FACILITATING CREATIVITY IN EDUCATION USING CONSTRUCTIVE FUNCTION-BASED MODELLING

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ABSTRACT
We describe the ways in which an approach to constructive shape modelling based on the Function Representation (FRep) can be used to facilitate creative thinking in artistic and technical education. This approach assumes the use of a simple programming language or interactive software tools for creating a shape model, generating its images and finally fabricating a real object of that model. It can be considered an educational technology suitable not only for children and students but also for researchers, artists, and designers. The corresponding modelling 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 artistic design and animation, computer graphics, programming languages, software development and experimental physics. Several application case studies in various areas of art, design, and technical education from different educational institutions and countries are presented.

KEY WORDS
Interactive geometric modelling, computer art, digital fabrication, FRep, HyperFun, Kinect.

1. Introduction
In the modern digital society, a new generation education technology is necessary with a particular emphasis on visual thinking to stimulate and facilitate creativity. Currently dominating geometric models in computer graphics are 2D vector graphics, 3D polygonal surfaces, and parametric surfaces. The problems of these models are well-known: non-precise shape and visual properties definitions, growing memory consumption, limited complexity, topological ambiguities and others. Such a geometric representation was reasonable and possible to handle by computers 30-40 years ago. Modern multiprocessor computers are able to deal with such complex data structures and mathematical models, which were unimaginable before.

The possibility to process and necessity of compact precise models with unlimited complexity have resulted in the development of the new paradigm of procedural modelling and rendering, where object's geometric shape and properties are evaluated upon request using procedural rules. One of the approaches to procedural modelling is to evaluate a set of real functions (or a vector-function) representing the shape and other object properties at the given point. A constructive approach to creation of such function evaluation procedures for geometric shapes was proposed and called the Function Representation (FRep) in [1] and then extended in [2] to the case of point attribute functions representing such object properties as material, colour, transparency, and others. The main idea of this approach is the creation of complex models from simple building blocks using operations similar to a model assembly in LEGO (see the illustration in Fig. 1). While the user operates on the high-level of abstraction, a modelling system is maintaining the final function evaluation procedure for the modeled object.

1.1. Function-based Modelling
One of the approaches to procedural modelling is to evaluate a set of real functions (or a vector-function) representing the shape and other object properties at the given point. A constructive approach to creation of such function evaluation procedures for geometric shapes was proposed and called the Function Representation (FRep) in [1] and then extended in [2] to the case of point attribute functions representing such object properties as material, colour, transparency, and others. The main idea of this approach is the creation of complex models from simple building blocks using operations similar to a model assembly in LEGO (see the illustration in Fig. 1). While the user operates on the high-level of abstraction, a modelling system is maintaining the final function evaluation procedure for the modeled object.

Figure 1: Constructive tree structure reflecting the logic of the object assembly (left), simple LEGO building blocks-primitives (top right), and a LEGO model assembled from those primitives (bottom right, http://www.fanedit.org).
It is worth to note that this approach corresponds to the constructionism learning theory introduced by Seymour Papert [3]. Application of this theory using computer technologies in educational practice is not always easy [4]. It is well known that constructive thinking lying in the basis of the LEGO construction toys enables children to learn notions that were considered as too complex for them. We have been developing virtual modelling and graphics tools rather than physical ones providing an extendible set of “building blocks”, which are deformable and modifiable on the fly. This approach assumes the model creation using a simple programming language or interactive tools with subsequent generating its images and finally fabricating a tangible replica of the created model. We believe that such an approach is of interest as an educational technology suitable not only for children and students, but also for researchers, artists, and designers. Earlier applications of this technology in education were reported in [5]. In this paper, we would like to present further experience and case studies in various areas of art, design, and technical education oriented towards facilitating creativity.

2. Function-based modelling and the HyperFun project in education

In the Function Representation (FRep) [1], a 3D object is represented by a continuous function of point coordinates through the inequality $F(x,y,z) \geq 0$. Time-varying and other multidimensional objects can be defined by a similar inequality. In an FRep modelling system, an object is represented by a constructive tree data structure (Fig. 1 left) reflecting the logic of the object construction, where leaf nodes represent primitives (building blocks) 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 via a small analytical expression or a short function evaluation procedure. The research results on various FRep primitives and operations are reported at the FRep Web page [6]. Later in [2], 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.

There are several projects adapting the FRep modelling paradigm: the general FRep modelling system HyperFun [7], the skeleton-based implicit surface modelling system BlobTree [8], and the function-based extension of VRML and X3D formats called FVRML/FX3D [9]. In this paper, we present a number of educational case studies based on various FRep software tools including HyperFun. The members of the HyperFun team, a freely associated group of researchers and students from different countries, have contributed to the case studies described in this paper.

Figure 2: Example of a HyperFun model fragment (left) and the images of the polygonized (middle) and ray-traced (right) model.

HyperFun [10, 7] is a programming language supporting all the notions of FRep modelling. This language was designed to be a minimalist one in order to allow non-specialist users to create models of complex geometric shapes. A model in HyperFun (see Fig. 2) can be constructed using traditional imperative programming statements such as assignment, iteration, and condition.
The functional expressions are presented using arithmetic and relational operators, standard mathematical functions as well as special built-in operators, which support fundamental set-theoretic operations (union, intersection, subtraction), and special FRep library functions.

The FRep library contains the most common primitives and transformations and is easily extensible. There are functions implementing traditional geometric modelling primitives (block, sphere, cylinder, cone, torus) and special implicit surface primitives (bloppy objects, soft objects, metaballs). More advanced primitives include convolution objects with various skeletons, pseudo-random solid noise primitives, and objects defined by parametric splines (cubic and Bézier). The typical transformations such as rotation, scaling, translation, twisting, stretching, tapering, blending are supported as well as some more advanced operations such as metamorphosis or non-linear deformations driven by control points. Details of the HyperFun language and associated freely available software tools can be found at the HyperFun Project Web site [7] and in corresponding publications [10, 11, 5].

FRep modelling, HyperFun language and supporting software tools have been taught on several levels of education starting from elementary schools to the postgraduate university level. The primary target was mathematical education at schools and universities combined with practical experience in modelling, computer graphics, animation, and visualization. More than a thousand school and university students in Japan, Russia, United Kingdom, Norway, France, Slovakia, Austria, Sweden, Albania, and United Arab Emirates, studied FRep modelling using HyperFun language in the following courses and exercises: computer graphics, shape modelling, visualization, computer animation, and compiler design. Examples of shape models created by students of different ages and qualifications can be found in the gallery at the HyperFun Web site [7].

Teaching FRep and HyperFun in computing classes can go through several stages. As HyperFun is quite a simple language it can be used for teaching the basics of computer programming. At the low level, all the mathematical and geometric modelling concepts can be hidden from students. At a higher level, the underlying mathematical and geometric concepts can be revealed in the courses of linear algebra and analytical geometry, computer graphics, solid modelling and other specialist disciplines. Finally, at the highest level, the HyperFun language can be used for modelling shapes with complex mathematical and procedural definitions by graduate and postgraduate students in different research areas. Another aspect of using FRep and HyperFun concepts and software is stimulating imagination and facilitating creativity in educating non-computer specialist users such as artists, designers and students in natural sciences. The case studies presented in this paper are intended to illustrate this branch of our educational practice.

3. Case studies in art, design, and technical education

3.1 Augmented Sculpture project

Augmented Sculpture project [12] illustrates a more complex and creative multilevel activity within our framework. In this project, we introduced and explored an original approach to computer-based sculpting that can be of interest for not only CG professionals but for art students and artists. The purpose was to develop a specific interactive environment with embedded computer-based means of sculptural representation to produce artifacts with a new aesthetics. Viewers experiencing these shapes within a virtual space can also benefit from this technology. One can start from an existing physical sculpture, then create its computer model and 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 world and then closes the loop bringing new computer models into physical existence.

The photographs of the sculptures by Russian artist Igor Seleznev were made available to computer-graphics students of the National Research Nuclear University “MEPhI” via the Web. To create initially sketchy computer models of the sculptures, the students were encouraged to write collaboratively and share the HyperFun code. They then formed groups of two or three to combine their efforts in developing more accurate models. The copies of 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. Finally, the students constructed geometric models of the sculptures in the form of programs in HyperFun language using the HyperFun for Windows toolkit, and then generated the final ray-traced renderings using the HyperFun for POVRay toolkit. Fig. 3 (top left) shows just one sculpture “Gymnast”, and Fig. 3 (top right) shows the ray-traced image of its computer model. Three frames from the animation sequence (implemented by another student who got an access to the code of the “Gymnast” model in
HyperFun) that brought the “Gymnast” to life are shown in Fig. 3 (middle). 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.

Another very interesting sculpting artefacts can be created using metamorphosis operation. Traditionally, metamorphosis is a complex task 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. In Augmented Sculpture project, students of the Hosei University in Tokyo had received from MEPhI students the Hyperfun code for metamorphosis between three sculpture models (“Gymnast” and two others - “Naked” and “Walking Androgynous”) that made it possible to generate a shape that was actually a weighted sum of all those sculptures. The Japanese students then produced the physical incarnations of that shape using rapid prototyping (RP) machinery and the process called ‘3D printing’. Fig. 3 (bottom left) shows three original sculpture models, fabricated using a SLA3500 RP machine. The result of the metamorphosis is shown in Fig. 3 (bottom right) fabricated using Laminated Object Manufacturing LOM (KIRA Solid Center).

The next stage of the project was concerned with using an experimental interactive modelling system allowing the artist to interactively navigate 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 [12]. We believe that projects like Augmented Sculpture are the way allowing professionals, artists and students to mix and work together thus encouraging them for exchange ideas and skills. A more detailed description of the project can be found in [12].

Figure 3: Augmented Sculpture Project: (top left) real sculpture; (top right) its HyperFun model; (middle row) frames of the gymnast animation; (bottom left) models of three sculptures produced by a RP machine; (bottom right) RP model of the “triangle metamorphosis”.

3.2 "Lifetime" animation

The National Centre for Computer Animation (NCCA) at the Bournemouth University is a leading educational and research school that is ranked as #1 in UK and provides the courses on undergraduate and graduate level in computer animation, visual effects and games. Its graduates can be found working at major studios worldwide and some Alumni have been awarded with Oscars and BAFTAs. On successful completion of “the major project” in the final year, NCCA’s undergraduate students have to produce a body of work (e.g., computer animation artefact) of professional quality mainly using industrial tools. Those tools are mainly surface-based and do not have FRep means, so our group has developed an FRep plug-in to Maya. Here we present a major project by a student Paul Novorol who created an animation called “Lifetime [13] using that novel tool.

The main idea for the short animation was to create a human life cycle using animated liquid wax based on a lava lamp. FRep tool allowed the author to handle a smooth flowing anthropomorphic object whose topology updated and changed frame by frame making it possible to form, blend and metamorph many different organic and complex shapes, within the same sequence. This animation could not be implemented using conventional tools, so the student who intended to work in industry as an artist had to learn some novel modelling concepts and
master a research software tool. Figure 4 shows four frames from the animation.

Figure 4: Frames of the “Lifetime” animation.

3.3 Kinect FRep Modeller

The Kinect FRep Modeller [14] is a group project of the masters students at NCCA. The goal of the project is software development to allow the users to manipulate objects and to perform constructive modelling with their hands rather than using a mouse and a keyboard. Fig. 5 illustrates the main concepts of the project. The core of the project technology is build around the Kinect sensor device [15] providing the depth data together with the video signal. This allows for tracking body motion including hand gestures (Fig. 5a). In the project, the hand detection is implemented through contours (Fig. 5b). The detected hands are represented on the screen for feedback by the blue and red cursors (Fig. 5c). A basic hand grab gesture has been implemented to perform such actions as selecting a primitive or operation from the menus, rotating the camera and moving the objects in the scene. An FRep library supporting the constructive modelling (Fig. 5d) has been implemented and includes basic geometric primitives and set operations. The current object is rendered using its surface polygonization. Several test models have been produced and the modelling process documented in the video available at [14]. The main intent of this technical project is to provide means for users to express their creativity by using their hand gestures to construct 3D shapes in a game-like environment.

3.4 Jewellery design and fabrication

The students were taken through the entire process, starting with the design concept on paper. After a few sessions in 3D software and HyperFun in particular, they
transferred their designs from paper to digital 3D models. A wax cast was made for each student’s 3D model using a Roland Modela MDX-20 desktop milling machine. Next the students used the special Art Clay material consisting of silver particles and organic binder to fill their casts, which were then dried, fired on a portable kiln, further polished and stylized by the students using traditional jeweller’s tools. More details on the technological process can be found in [16]. Each of the students who participated in the class ended up with a digital model and a real piece of silver jewellery from their original paper design.

3.5 SHIVA metamorphosis exercise

The EU sponsored SHIVA Project (Sculpture for Healthcare: Interaction and Virtual Art in 3D) brings together several computer science, educational and medical partners from UK and France. The main idea behind SHIVA is to give people with disabilities an opportunity to do something in the area of 3D modelling as a way of enhancing their creativity and expressing themselves. The project team develops computer-aided exercises to support a range of different patient activities.

One of the developed exercises allows for children with disabilities to perform a metamorphosis transformation between two arbitrarily selected 3D shapes (Fig. 7) [17]. The main design issue for this exercise is the simplicity and adaptivity of the graphical user interface, which is aimed to support the students with highly limited motor skills including those operating with a single switch (large push button, lever switch, eye-blink trigger). Typical computer-aided activities such disabled children are typing text and performing other simple tasks on the 2D surface of the computer screen. Providing them with the possibility to operate with 3D shapes is supposed to stimulate their imagination and to bring satisfaction from using the computer. There are several other exercises under development such as axis-aligned and free-form constructive modelling. The project aims to be completed with an exhibition, which will display the sculptures of the disabled students. This will be made possible through the use of desktop 3D printers.

3.6 Scientific visualization in physics education

Nowadays it is especially important for students in physics to have skills in computer modelling physical objects and processes that can be very helpful in their research work. As scientific visualization tools are widely used for analysis of computer modelling results, students in physics are often taught to visualize results of computer modelling as well. We describe here the experience of using HyperFun as a scientific visualization tool for analysis of various physical objects and processes that are the result of computer modelling work done by physics departments at the National Research Nuclear University “MEPhI” (Moscow, Russia). Most frequently the studied results of computer modelling are physical scalar fields. Students are taught to consider different static and dynamic spatial images of computer modeled scalar fields in the process of their analysis by means of scientific visualization.

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 computer modelling within students’ research work. Such description of the studied physical object was presented in a file in the form of numerical data that should be analyzed. The example of scalar field visualization is shown in Fig. 8. To obtain these results several additional file reading based primitives and attribute functions were added to the HyperFun FRep library and used within the resulting HyperFun model. The visualization presented in Fig. 8 was made through the Visualization Toolkit (VTK) based interface for HyperFun. These graphical representations of spatial scenes corresponding to the

![Figure 7](image-url)
second type superconductor computer modeled with Ginzburg-Landau equations help students to form statements about the physical variable under study, namely the scalar order-parameter field distribution in the selected space area.

One more example is “The Principles of Scientific Visualization” course, which is taught to graduate students in physics at the National Research Nuclear University "MEPhI". This course was developed by the “Scientific Visualization” laboratory with the close support of physics departments and the National Centre for Computer Animation, Bournemouth University, UK. The purpose of this course is studying the theoretical principles of scientific visualization and acquisition of practical skills in development of application software in scientific visualization. In general, the course aims to the development of the students spatial creative thinking while solving problems of scientific data analysis. So, this course teaches students to consider and manipulate the corresponding spatial images, make their visual analysis and interpret the analysis results in terms of the application area.

Figure 8: Scientific visualization example for the order-parameter field for the second type superconductor (Abrikosov vortices). Different approaches to scalar field visualization: a) isosurfaces; b) volume visualization with the scalar field defined on a rectangular domain; c) scalar field on a complex domain defined by one of the field’s isosurfaces. The field’s domain can be interactively cross-sectioned by the user with planes controlled by white handles.

The course includes the following three sections: scientific visualization concepts and capabilities, scientific visualization tools, scientific visualization applications. The second section includes introduction to HyperFun as well as other software tools that can be used for solving problems of data analysis by scientific visualization means. Students may write application scientific visualization software on the base of HyperFun in the practical part of the course. To support this, the HyperFun language was extended: the program functions of file opening, closing, reading, writing were added to the HyperFun API. An example of an application software on the base of these functions is given in the second section of the course. It should be mentioned that HyperFun was also used for the course multimedia training materials design that students have an opportunity to use.

4. Conclusion

Constructive function-based geometric modelling can be seen as a highly specialized subject interesting only for professionals. Our experience shows that it can be mastered and appreciated by students at different levels of education as an activity stimulating and supporting their creative thinking.

In a social context of the presented educational technology, we emphasize an active, creative and
collaborative character of the learning process presented in this paper. Indeed, the building of object models starts from rather abstract mathematical expressions, utilizes ready made building blocks in the form of library functions, then goes through interactive modelling in the virtual world, and finally results in the fabrication of physical artefacts. In this process, the learner obtains tangible instances of their creative designs. This can be considered a practical confirmation of the idea of the constructionism theory that learning is most effective when the learner creates a meaningful product actively using their imagination supported by advanced computer technology.

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References

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