

Reverse Construction of Cultural Heritage

C. Vilbrandt¹, G. Pasko², T. Vilbrandt¹, P.-A. Fayolle¹, M. Kazakov³, V. Adzhiev⁵, A. Pasko⁴, T. Kunii²
¹ University of Aizu, ² IT Institute, Kanazawa Institute of Technology, ³ Digital Media Professionals,
⁴ Hosei University (Japan), ⁵ Bournemouth University (UK)

Abstract

We give an overview of existing digital data structures, the mathematical representation of objects, and the approaches to computer modeling of historical objects of cultural significance. Corresponding problems and solutions with long term archiving of digital data structures, constructive modeling, and a real time interactive display of the cultural heritage objects are discussed, various examples and applications are given.

Keywords: Cultural Heritage, Digital Preservation, Constructive Modeling, CSG, Function Representation, Fitting, Virtual Worlds

1. INTRODUCTION

In this paper, we discuss the preservation of cultural heritage objects through the use of computer. By digital preservation, we mean not only the digital reproduction of the surface shapes and colors of existing objects and the digital reconstructive modeling of objects that have already been lost, but also the digital representation and archiving of all of the physical properties of a cultural object or site, thereby allowing for the conservation of objects and accurate physical reconstruction of artifacts, which can be lost due to unexpected events. This is a particularly important issue in the realm of cultural heritage, since objects may be easily demolished, as the recent destruction of the Buddha images in Afghanistan has powerfully demonstrated. The preservation of cultural heritage has attracted considerable attention in computer graphics, geometric modeling, and virtual reality communities.

Digital Persistence and Preservation

First, we discuss the issues concerning the persistence of digital data structures and the need for long term digital preservation of cultural heritage objects. Preservation of cultural heritage objects with digital processes is not only theoretically possible but highly desirable for the reasons reviewed below. We raise with diligence two problems critical to the implementation of digital archiving technologies. Then, we proceed to discuss applications of digital representation, modeling, and simulation technologies needed for digital preservation including real-time interactive access to cultural heritage objects for educational and artistic environments.

- (1) Since each digital reproduction copy is a perfect copy, digital reproduction has the potential to allow archiving of data into the distant future.
- (2) In very small amounts of space, large amounts of data can be stored, making it feasible to have many copies in many locations, thus assuring against loss due to unforeseen events.
- (3) Much historical data and many cultural objects can not be accessed publicly (because of the cost and overhead of display, exotic locations, etc.), whereas digital data can be publicly accessed on demand globally.
- (4) Transparent learning through constant interaction with cultural objects in real time simulations, both locally and globally, is perhaps one of the most promising benefits from

evolving digital modeling technologies.

- (5) Exponential evolutionary advancements of digital computational technologies will continue to provide more computational power and storage for less cost and space.

Digital archiving offers many benefits and has great promise, however there are several significant problems and possible solutions, which are discussed below.

Problem: Currently, digital data structures are dependent on the hardware, OS, and hundreds of copyrighted or patented application processes that involve a multitude of companies. Digital data dependencies are a great problem. Because of the exponential evolutionary advancements of digital computational technologies mentioned above, most hardware and software is updated every year. Over three years, the changes are significant, and after six or seven years, the original data can not be accessed.

Solution: Develop digital data structures that are robust and independent of hardware, OS, and application modifications.

Problem: The source code for most current digital processes is not open for public inspection. This means that not only the processes are not verifiable, but, without access to the source code of the processes, the data which is dependent on the processes will die. Processes and data can not be migrated into the future.

Solution: The source code for all of the processes must be open for public inspection, modification and testing, and transparency of all operations. This assures the accuracy of the verification of the data, at the same time allowing for migration into the future. Transparency of complex digital manipulations entrusted with the long term digital preservation of cultural heritage is an essential key element to the development and implementation of a digital preservation system.

Constructive Modeling and Engineering

We are proposing a paradigm yielding more than visible surface models for display. The basic mathematical shape representation in digital preservation should serve several purposes. It should reflect the logic of the object's construction, support modeling of parametric families of shapes, support specific and extensible modeling operations, generation of polygonal and other surface models, as well as voxelization, and serve for direct control of rapid prototyping machines with the precision needed to reproduce the modeled objects. Our approach is based on constructive modeling that reflects the shapes, logical structure, and physical properties of materials and processes for the cultural object or site.

Constructive Solid Geometry (CSG) [9] and *Function Representation* (FRep) [15] are practically applied as mathematical representations of the structure engineering at the same time providing for the independent robust data structures necessary for the digital archiving of cultural heritage objects and sites. Using CSG, one can begin by selecting simple shapes (primitives), specifying their parameters and positions in space, and then using them to construct more complex shapes by applying different set-theoretic operations. FRep is a generalization of traditional implicit surfaces, CSG, and other

shape models. It represents an object by a continuous function of three variables as $F(x,y,z) \geq 0$. The function can be easily parameterized to support modeling of a parametric family. In FRep, 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. Recently, a more general “constructive hypervolume” model has been introduced [16], 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.). HyperFun [1] is a minimalist programming language supporting all notions of FRep and constructive hypervolume modeling. In this paper, we present a number of cultural heritage-related works which have been done in the framework of the HyperFun, an international free software project on functionally-based shape modeling, visualization and animation (www.hyperfun.org). Members of the HyperFun team, a freely associated group of researchers and students from different countries, have contributed to projects described in this paper.

Examples of independent CSG based reconstruction of historical temples and FRep based modeling of traditional Japanese lacquer ware and modern Russian sculptures are given. We also recognize the cost problems associated with large amounts of labor in the reverse construction (reverse engineering through constructive modeling) of cultural heritage objects. Accordingly, we are seeking ways to reduce the amount of time and skill to make constructive engineering details. Therefore, we examine the application of fitting of a parameterized FRep model from a cloud of data points as a step towards automation.

2. CSG MODELING AND VIRTUAL HERITAGE: JAPANESE TEMPLES

Unfortunately, computer-aided two-dimensional drafting remains common practice in architectural and mechanical design. The benefits of using three-dimensional graphics techniques in constructing models are obvious. First of all, models can be manipulated to provide multiple viewpoints. Rotating a model can provide a better understanding of the physical relationships of the components of the actual structure, as well as the construction techniques involved. Moreover, three-dimensional models can replicate the actual construction of the building itself, including features normally hidden to the eye, such as interior bracketing, and the model can be deconstructed to reveal such hidden features. The description of our work below on the two Buddhist temple buildings in the Aizu region of Japan illustrates these benefits.

2.1 Constructive modeling of historical buildings

Considering the authors' experience in lost work and data due to obsolescence of software and hardware, the authors specified CSG representation as the most promising persistent data structure for modeling historical architecture of the Aizu History Project [3]. All parts of two Japanese historical buildings, the Golden Hall at Enichiji and Sazaedô featured in this paper (Figs. 1, 4), were created whenever possible with only CSG based entities. However, because CSG is limited in its range of shape representation and the overall size of each model was extremely large, the thatch roof of the Golden Hall and the double helix ramp inside Sazaedô had to be represented by a polygonal mesh. We used AutoCAD rel 12 software with Advanced Modeling Extensions (AME). AME is the implementation of CSG with the CSG tree history.

Furthermore AutoCAD rel 12 using AutoLISP allows for direct access to the CSG tree history and the creation of third party programs such as the creation of export programs for CSG data. The authors are creating a free source code HyperFun modeling module for AutoCAD rel 12. We have found many errors in the AutoCAD AME implementation of CSG. However, we only have access to the AutoCAD CSG data tree and not the source code for the AME CSG module.

The original modeling of Enichiji and Sazaedô began eight years ago on 386 and 486 Intel class machines using AME CSG. The computational demands using CSG representation were so high that sections of a single model had to be developed in many separate files on as many as four different machines. However, the authors knew that the exponential computational evolution would continue and, in a few years, we would be able to use one machine. There were significant problems in data creation and manipulation of sections of the buildings across separate files on different computers as the coordination was all manually done. When combining the files into one file, it is needless to say that this data overwhelmed even the fastest single system at that time. Now, the entire model of Sazaedô with polygon reduction can be handled easily in real time on current animation and rendering systems.

However, we have found errors in AME, such as the order of subtraction and union operations are not interchangeable in some cases and extrusion with taper is not accurate. Therefore, the quality of the AME CSG modeling database is in question. It will take more effort to extract the CSG data structure embedded in AME than it would to model the buildings again, but this is a part of our planned research. Since we started, the HyperFun modeling language based on function representation has been developed. The next step in our digital preservation research is the creation of a "CAD" style third party program for HyperFun in AutoCAD rel 12. This is the first step in developing a separate Synthetic CAD modeling system.

2.2 Golden Hall at Enichiji

The first structure that we modeled using the AutoCAD AME CSG system was the Golden Hall at Enichiji, a temple located at the foot of Mt. Bandai. Although Enichiji was the religious center of the region throughout much of the Heian period (794-1185), no buildings or images from that period are extant today. In order to produce a model of the Heian Golden Hall, the structure that housed the temple's most important Buddha-images, the authors relied on data introduced in archaeological site reports [4].

The construction of the Golden Hall model was a difficult task. At present the only solid information is the existence of seven foundation stones for pillars, demarking the north and part of the east walls. We have constructed the Golden Hall model (Fig. 1) using on-site measurements and some additional information.

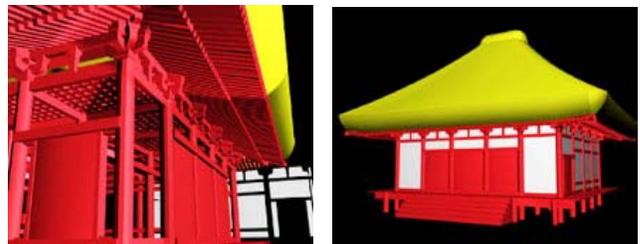


Figure 1: Golden Hall model

In addition to archaeological data, the model was based on standard temple-building practices of the eighth and ninth centuries [5]. We also took into consideration the snowy climate of the Aizu region, which dictated a steeper roof slope than is common in other areas of Japan. In addition, we consulted Yamagishi Seiji, a master *miya daiku* (shrine carpenter) and the scion of an 800-year carpentry tradition in this region.

2.3 Sazaedô Pagoda

Recently declared a National Important Cultural Property, Sazaedô, a pagoda built in 1796 in Aizu-Wakamatsu, is noted for its unique architectural feature, a double-helical interior walkway. The double helical walkway is part of an interior tower (Fig. 2). (For more details on the Sazaedô construction, including black and white reproductions of these figures and some others, see [22]. The drawings in the figures below were adapted from engineering blueprints done in 1965 by Kobayashi Bunji.)

The 3D CAD model can be used to display all components separately, so that the construction may be seen and understood. Even an actual visit to the site does not enable such views. For example, the entrance and its canopy are structures which can be better understood from the model than from a photograph or even from a visit to the actual site, since they are complex objects and access and sightlines are restricted [23].

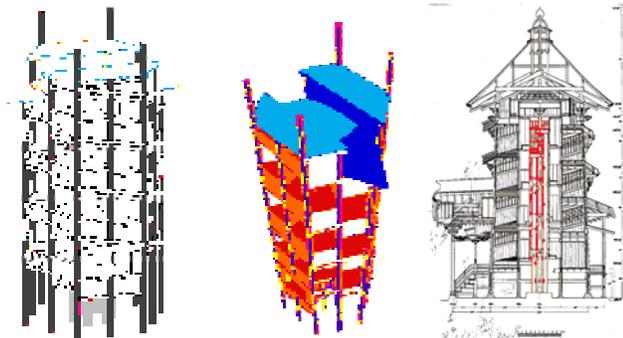


Figure 2: (from left to right) Interior tower in wire frame, interior tower colorized showing alcoves, drawing showing the location of the interior tower.

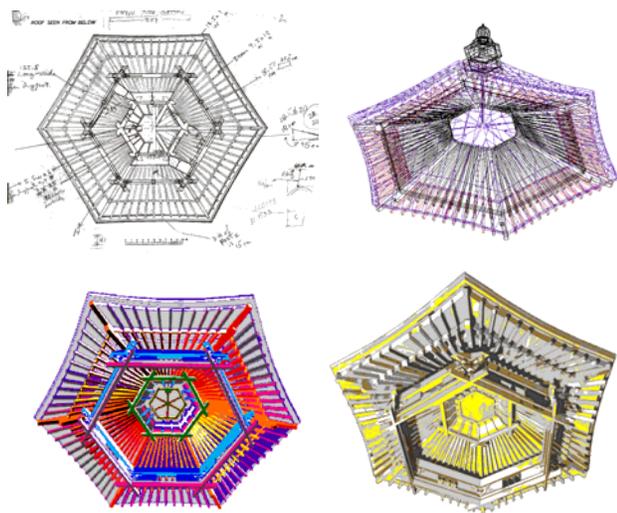


Figure 3: Sazaedô roof views

By using measurements from an engineering drawing (Fig. 3 upper left) of the roof, and supplementing them with measurements taken on site, a 3D CAD model was constructed, and is displayed in the wire frame view and the rendered views (Fig. 3). It is possible to select only one section from the single CAD model of the entire structure, and display it from multiple viewpoints and with various levels of detail. Because of the constructive approach, any part, such as the helical structure, may be rendered without displaying the other components, and an external shell may be fully rendered (Fig. 4).



Figure 4: Rendered model with helical structure and fully rendered exterior shell.

The models illustrated are virtual constructions using virtual lumber cutting, positioning and joining according to the specifications of the *miya daiku* based on empirical knowledge of the past. By virtual lumber cutting, positioning and joining, we mean that we create each piece of the temple from virtual parts that represent the shape of each piece of lumber in the same order that would have been used by the *miya daiku*. The virtual lumber cutting, positioning and joining empirically show the value of digital preservation of cultural heritage using constructive modeling. The 3D model has recently been used to produce high quality renderings of the interior of Sazaedô, as would be seen by a person walking through the structure, and to produce QuickTime and AVI movies of the journey through the temple (see <http://ggpl.org/saza2001>). We plan to enhance the current model by including 3D reproductions of the images formerly enshrined in the building. We also intend to develop VR facilities to allow the examination of these images independently, and to allow the viewing of parts of the structure that cannot be accessed in the actual building.

2.4 Virtual surfaces to synthetic objects

The *miya daiku* or shrine carpenter uses parts of the tree or piece of timber in a specific place or way to create what the *miya daiku* understands as a "living" harmonious structure. A simple example of this specific use of timber by the *miya daiku* is the fabrication of the main columns of the temple, which are cut from trees growing on four sides of a mountain. The orientation of these trees to the earth and to each other on the mountain is maintained as the columns in the temple structure. With the use of the constructive hypervolume model [16], we can reach beyond the virtual surfaces of a wooden object. In the future, with records of weather and growth rings of trees, we can synthetically grow a tree using volume modeling and fabricate synthetic pieces of

timber, using the same type of traditional *miya daiku* procedures, to create a synthetic representation of such ancient temple structures. Synthetic simulations of the *miya daiku* procedures in constructing traditional temples would not only archive the historical objects themselves but allow us a deeper understanding of the *miya daiku* craft.

2.5 Making history realtime - versus rendertime

In our research, we are exploring the use of optimized real time game engines as a method of viewing 3D content. These applications provide built in logic to handle basic world properties like gravity and collision detection. In addition, 3D games provide highly intuitive and efficient user interfaces, advanced network code for multi-user distributed environments, and an open coding environment allowing unlimited customization [24].

In real time simulation using gaming methods, a user can interact with the program, as well as with other users, in an immersive and entertaining environment. However, the restrictions imposed on a real time environment are significant. Even at relatively slow frame rate of ten frames per second (barely adequate for games), all computation for each frame must be finished within 100 milliseconds. Even on the most powerful gaming systems, this hardly allows for the level of complexity we might want in a historical simulation model. Such desired levels can be pre-calculated or calculated on demand by computational grids and presented as visualizations in various formats inside the real time game environment, transparent to the user.

Currently, at the University of Aizu Computer Arts Lab, we have modeled such a system using Quake [20] as the front end client and Povray as the backend server. Our test case is a model of the Enichiji temple. In order to provide an immersive environment, we have created a model of this temple which runs in Quake, and allows the user to climb the stairs, inspect the internal architecture, and move under, over, through or around the temple in full real time. At any location in the Quake environment, the user may choose a detailed Povray rendered visualization (Fig. 5).



Figure 5: Inside the Enichiji temple model: on the left is a view of the real time Quake model in low detail; on the right is a detailed raytracing delivered to the client in seconds after a view is selected.

Currently, we are working to incorporate the HyperFun geometric modeling language into the Quake game engine and Web technologies.

3. PARAMETERIZED FREP MODELING: LACQUER WARE

3.1 FRep modeling of Japanese lacquer ware

We illustrate here the preservation of traditional crafts such as lacquer ware (Japanese *shikki*) manufacturing using FRep modeling. The “Virtual *Shikki*” project [18] includes the following activities:

- Reconstruction of shapes and making parametric families of models of representative *shikki* items. A parametric family of models allows us to generate samples of a specific model with different sizes, width/height ratios, and so on, without repeating the entire modeling process, and to apply parameters fitting from the real object measurements and scanning
- Digitizing textures. There are technical problems of scanning colored textures from the surface of existing lacquer ware items.
- Producing 3D virtual objects and presenting them on the Web. [25] using Virtual Reality Modeling Language (VRML) (see Fig. 6).

The process of modeling *shikki* shapes included selection of representative items, measurements of the coordinates of control points, introduction of the basic logical structure of the model (primitives and operations), description of the parameterized constructive model using the HyperFun language, visualization, and selection or fitting parameters of the model. Development of some additional specific operations, for example, bounded blending [17] were required for adequate modeling of *shikki* shapes.

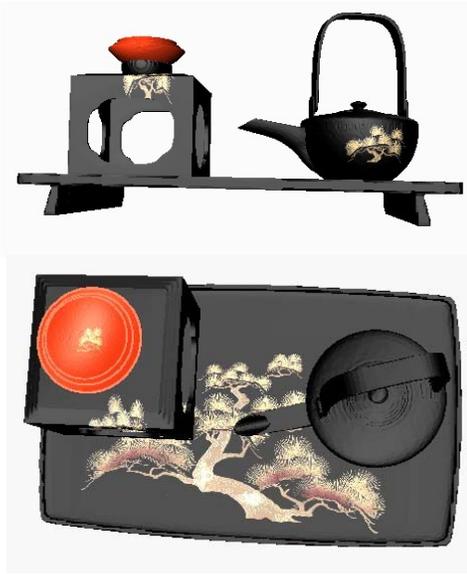


Figure 6: Front and top views of a Virtual Shikki object..

3.2 Fitting as an FRep modeling tool

Modeling specific shapes based on real world objects require a large amount of routine labor in measuring control points and fitting model parameters. Semi-automatic methods based on using 3D scanned points as control points and non-linear optimization for automatic fitting of parameters can be used to make the work of the modeler easier.

Some of the most useful methods for solving the problem of nonlinear optimization for fitting parameterized models in the least square sense are briefly discussed here and then applied to

the concrete example of the sake pot presented above in the Virtual Shikki case study.

3.2.1 Nonlinear least square approach

Given a parameterized FRep model that describes the global shape of the object, and a set of 3D points on or near the surface of this object, the task is to recover the best set of parameters so that the parameterized FRep model closely fits the data points. The 3D points, typically obtained by a scanner, serve as control points for the final shape of the object. The vector of parameters from the FRep model control the final shape and the best fitted parameters should give the closest possible model according to the information provided by the control points.

For estimation of general distance of the point cloud to the surface with the current vector of parameters, a fitness function is needed. The FRep model itself can serve for defining such an algebraic distance. The least square error, or error of fit, for the model is the sum of the square of the defining function at all points. Techniques of function minimization can be used with the least square error function. FRep models are essentially nonlinear, and so is the least square error. Therefore, local and global nonlinear minimization techniques are considered below.

3.2.2 Local methods for nonlinear minimization

The most traditional methods for solving problems of nonlinear least square fitting are Levenberg-Marquardt or Newton type methods [6,14,19]. Such methods rely on a local quadratic approximation of the function being minimized; this quadratic approximation is obtained by a Taylor series expansion of the function in the vicinity of the current vector of parameters. The algorithms of Levenberg Marquardt and Newton methods search iteratively for a privileged direction to go in the parameter space and a step length in that direction based on the information given by the gradient and the Hessian matrix of the function. For some parameter spaces with multiple local minima, such methods are likely to be trapped into a local minimum. Good initial parameters are very important, because they determine to which minimum the algorithm may converge.

3.2.3 Global methods avoiding local minima

In contrary to local methods for nonlinear minimization, global methods are intended to find the best possible solution to the optimization problem. The choice of the starting point in parameter space should cause less problems for these methods. Simulated annealing is one of these methods, that received a lot of attention for solving optimization problems, both in discrete and continuous spaces [8,11,13]. When trying to minimize a function usually only downhill steps are accepted, but in simulated annealing uphill steps can be accepted with a probability, initially close to 1 and decreasing to 0 with the temperature of the system. Methods based on simulated annealing may be a good alternative to classical direct methods in global optimum search among many local optima, but they are facing some major problem of efficiency: the objective function needs to be sampled a huge number of times before reaching convergence.

3.2.4 Hybrid methods for nonlinear minimization

In order to overcome problems of both methods presented in the previous sections, a two stage algorithm of nonlinear FRep fitting is proposed. At the beginning, a global method like simulated annealing is used to identify the vicinity of the global minimum, then a local, faster method, is applied, to extract the parameters that closely fit the 3D point set. Switching to a local method occurs when the error is below some threshold or when the parameterized model looks close enough to the data set. The result

of this two stage process is a method faster than a pure global method, and it can also avoid the local minimum.

3.2.5 Experiments

The two stage process has been applied to the fitting of the parameterized FRep model of a sake pot in the Virtual Shikki project. The initial set of control points includes 27048 3D points on or near the surface of the object (see Fig. 7)



Figure 7: Point data set used for reverse construction (black) and an intermediate shape during the fitting process (green).

The parameterized FRep model has four free parameters meaning the position of the object in the space, the radius of the main body, and the last one controlling the shape of the handle.

It took 347 seconds on a Pentium IV processor laptop for the two stage algorithm to converge to the global minimum. Most of the time is spent in the global minimization procedure (341 seconds). Fig. 8 shows intermediate steps of the evolution of the shape during the fitting process.

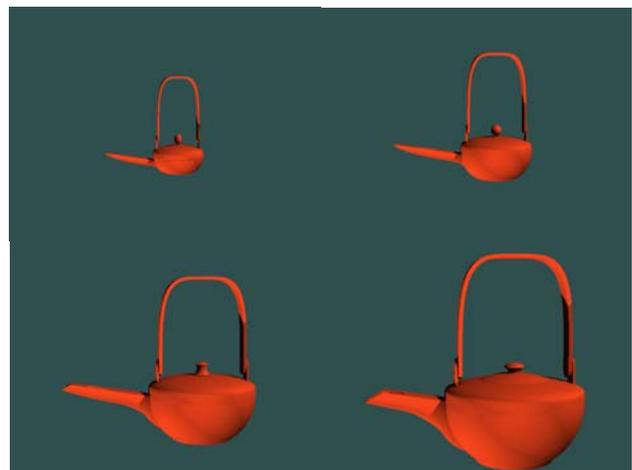


Figure 8: Evolution of the shape of the sake pot during the fitting process.

4. FRep ANIMATION AND INTERACTIVE EXPERIENCE: AUGMENTED SCULPTURE

In the Augmented Sculpture project [2] we investigate an original approach to computer-based sculpting. Starting with a physical sculpture, we produce its computer model and we manipulate this model to produce 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 artefacts 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>

Modern abstract sculpture is very much concerned with the exploration of novel non-trivial shapes and we believe that the computer technology being presented here can assist artists in their creative quest. 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 artefacts with a new aesthetic. Consequently, viewers experiencing these shapes within a virtual space can also benefit from this technology.

4.1 Real Sculptures and Their Models

Our case study is based on real (physical) sculptures created by Moscow artist Igor Seleznev (www.russian-art.org). Fig. 9 shows photos of two "real" bronze statuettes "Gymnast" and "Naked". First, it was necessary to construct the geometric models of the sculptures which have quite complex shapes with subtle features.



Figure 9: Physical Sculptures

"Gymnast" was modelled in HyperFun language using basic geometric primitives defined by equations as well as by the following set of FRep functions: non-linear deformations (hfBending3D), affine transformations (hfShift3D, hfScale3D, hfRotate3D) and blending (hfBlendInt, hfBlendUni). "Naked" was modelled using the following FRep functions: ellipsoids (hfEllipsoid), convolution surfaces (hfConvPoint, hfConvLine), affine transformations (hfShift3D, hfScale3D, hfRotate3D), blending intersection and union operations (hfBlendInt, hfBlendUni). Note, that so-called convolution surfaces [12] which are a class of implicit surfaces allowing for modeling complex non-regular forms were especially helpful.

Model building and debugging was carried out using the "HyperFun for Windows" toolkit, and the final ray-traced renderings (shown in Fig. 10) were generated using the "HyperFun for POVray" toolkit.

4.2 Animation of Sculptures

Once the model of a physical sculpture is created, one of the most natural things that the artist may wish to do would be to alter the material that could have been used to create the physical sculpture and to explore the visual appeal of such alternatives. To achieve this, within the functional framework, we may employ a texturing method based on the Hypervolume modeling techniques [16]. In [21] we have applied such a technique to the model of the "Naked" sculpture.

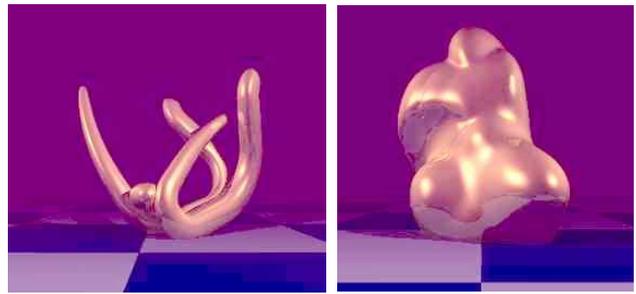


Figure 10: Images of models

What would also be quite interesting for an artist to do and, obviously, impossible without computer technology, would be to have the ability to animate a sculpture which being initially still, has internal (although hidden) dynamics and therefore a natural propensity to move. There is a traditional division in computer animation made between the modeling and the animation processes that leads to limitations of the forms that can be animated. The advantage of the FRep [15] is that one can work with both the shape and its animation simultaneously. So, time-dependent shapes can be modeled directly as four-dimensional (4D) objects with the subsequent generation of time cross-sections (3D frames) taken at discrete values along the time dimension. So, a 4D "space-time" FRep model defined by the inequality $F(x,y,z,t) \geq 0$ provides a natural solution to this problem.

Fig. 11 shows a few frames from a "Gymnast" animation sequence developed by A. Ogarko using HyperFun for POVray toolkit. The animation is available at the Project Web Page.



Figure 11: "Gymnast" animation

4.3 Metamorphosis

4D "space-time" modeling is just a particular case of multidimensional functionally-based modeling that allows us to accomplish non-trivial effects while modeling and animating. One important application of this type of modeling which is of great interest to both artistic and commercial animation is the problem of shape metamorphosis. Traditionally this is a complex problem that requires the animator to establish a set of correspondences between the initial and final key-shapes of a metamorphosing object. This process is quite cumbersome and it is incapable of dealing with key-shapes of differing topologies. In addition, using the traditional approach it is difficult to obtain intermediate shapes by interpolating more than two key-shapes. The HyperFun toolkit supports an original technique that allows us to successfully solve the metamorphosis problem using FReps to represent the key-shapes.

In the FRep framework, metamorphosis is performed almost trivially [7]. This framework is capable of handling key-shapes of differing topology and of generating intermediate shapes that exhibit genus change that may be composed of disjoint components. In this framework, a multidimensional object defined in abstract n-dimensional geometric space is given by an inequality of the form $F(x_1, x_2, \dots, x_n) \geq 0$. In parallel with this

“abstract world” there exists another “real world” which is populated by “multimedia objects”. A multimedia object can be seen as a multidimensional object with a set of 2D or 3D geometric coordinates (e.g. Cartesian, cylindrical, etc.), a set of dynamic coordinates (e.g. physical time), a set of photometric coordinates (e.g. colour, transparency, texture, etc.) and a set of audio or other “multimedia coordinates”. Both “abstract coordinates” and “multimedia coordinates” may assume values within given intervals.



Figure 12: Steps of metamorphosis

4.4 Augmented Sculpture Garden

The next stage of development of our computer-mediated-sculpture study was perhaps the most consequential one yet, namely the development of a system that allows the artist to experience real-time interaction with a virtual sculpture using a VR type interface with quite high level of user immersion. This system allows the user to navigate interactively through a so-called “Augmented FRep Garden” [10] which is a time-dependent scene composed of multiple objects (represented as volumes). In this virtual environment it is possible for the user to interactively edit, on the fly, the objects populating this environment as well as the processes that metamorphose these objects over time.

Let us describe how the user interacts with the model during the sculpting process.

- The user is able to navigate in the initial scene selecting an appropriate point of view.
- Once the point of view has been chosen, the user can begin the process of metamorphosis. The point of view can be changed at any time by interrupting the metamorphosis process. The metamorphosis is controlled by the position of the metamorphosis tool. Using this tool, the user can select a point inside the triangle and thus determine the corresponding current resulting shape. As the metamorphosis tool is placed close to one of the initial key-shapes, the result of the metamorphosis resembles this key-shape, although the other key-shapes also make a small contribution to the resulting shape as their weighting coefficients are not zero. This is an iterative process, which allows the user to arrive at an aesthetically pleasing resulting shape.
- Once the desired shape is arrived at, the user can further refine it using a carving tool. This tool can be immersed into the surface of the shape causing spherical indentations. This tool allows the user to both remove material from and to add material to the shape. It is even possible to design a new shape ab initio using this tool.
- The results of the carving process can be discarded by using the metamorphosis tool to select some other point in the metamorphosis triangle.

Fig. 13 shows just one frame from a recorded session of interactive metamorphosis and carving which can be downloaded from Augmented Sculpture Project Web Page.

Fig. 12 shows metamorphosis between two sculptures implemented as linear interpolation of the models’ defining functions with time as fourth variable. It is also possible to implement more complex “triangle metamorphosis, for instance, embracing 3 sculptures [2]. Animation sequence showing 5D triangle metamorphosis is available at Augmented Sculpture Web Page

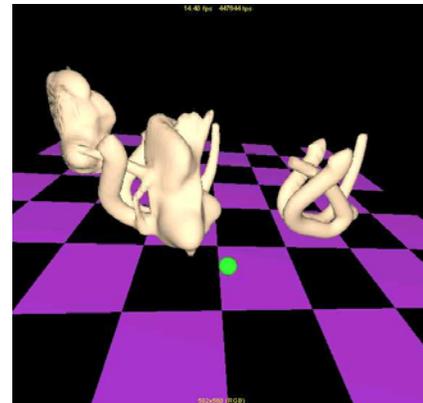


Figure 13: Metamorphosis on-the-fly

It is fairly easy to augment this system to simulate a set of carving tools with various shapes that allow the user to perform quite diverse and subtle operations on the resulting shape.

We are working on implementation of an interactive art installation where physical sculptures and their computer models described in this section are present in the same space allowing observers to interact with sculpture artifacts in real time thus immersing them into augmented reality.

5. CONCLUSION

We described an approach to digital shape preservation based on constructive shape modeling. We examined and selected Constructive Solid Geometry and Function Representation as shape representations that fit the purposes of long-term digital preservation. While this approach seems labor-intensive, it has several distinct advantages over methods based on automatic surface scanning and almost-automatic polygonal mesh generation. The purpose of a particular project should determine which method to use. If only visualization or animation from a distant viewpoint is needed, then polygonal mesh or other BRep models can be satisfactory. However, even a virtual walkthrough allowing close inspection of the object requires more accurate and detailed modeling. Constructive

modeling helps to reveal knowledge about a shape's logical macrostructure. The representation of three-dimensional surface microstructure (bumps, cracks, roughness) is also out of the range of BRep abilities, but it is possible to model it using FRep. FRep's major disadvantage, its labor-intensive nature, can be reduced gradually by introducing semi-automatic methods based on 3D scanning of real objects with acquisition of control points and non-linear optimization for automatic fitting of the parameters of the constructive objects as we have illustrated in this paper. Automation of the logical structure extraction will be investigated in our future work.

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