Cultural Heritage Preservation Using Constructive Shape Modeling

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Abstract

The issues of digital preservation of shapes and internal structures of historical and cultural objects are discussed. An overview of existing approaches to computer modeling of shapes is presented and corresponding problems are considered. We propose a digital preservation paradigm yielding more than visible surface models. Our approach is based on constructive modeling that reflects the logical structure of modeled shapes. Constructive Solid Geometry (CSG) and Function Representation (FRep) are examined and practically applied as mathematical representations, which fit the purposes of long-term digital preservation. The importance of open-source methods for digital preservation is also discussed. Examples of CSG based reconstruction of historical temples and FRep based modeling of traditional lacquer ware are given.

1. Introduction

This paper will discuss the preservation of cultural heritage objects through the use of computer techniques. By *preservation* we mean not only the digital capture of existing objects and the reproduction of objects that have already been lost, but also the archiving of digital data into the foreseeable future. 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.[1]

In this paper, we demonstrate two methods of modeling cultural heritage objects. Our first method, which we have used to model buildings from both archaeological data and on-site measurements, reveals how the actual objects were constructed. This approach could be used to parametrically augment the current "scan and mesh" approach that typically yields only visible surface models. Like most current methods of modeling, however, this approach relies on hardware and on proprietary software packages that may conceivably become obsolete and unusable even before the modeled objects themselves are destroyed. Accordingly, we next propose and demonstrate a new paradigm for cultural heritage preservation that avoids such pitfalls. This paradigm is based on constructive modeling, which reflects the logical structure of the shapes reproduced. We illustrate this method with models of ancient Japanese temples and traditional Japanese lacquer ware.

2. Digital Preservation of Cultural Heritage

Computers may be used to preserve cultural heritage in the following ways: [1]

1) Digitizing text and images from existing documents;
2) Reconstructing lost cultural artifacts such as paintings or temples in digital form using existing documents (photographs, drafts, written evidence) or archaeological findings;
3) Reverse engineering and digital representation of the shape and texture of existing three-dimensional physical objects (sculptures, buildings, natural environments, etc.) based on measurements and 3D scanning;
4) Archiving digital representations of reconstructed and reverse engineered objects;
5) Using digitized and reconstructed images and models for presenting cultural heritage as virtual objects, animations, games, multimedia documents, and Internet sites.

2.1 Approaches to cultural heritage preservation

Let us discuss and compare different approaches to computer-aided preservation of the shapes of culturally valuable objects. In the general case, a shape can be considered a point set in a multi-dimensional space. Thus, not only external boundaries, but also internal structures of objects as well as their time and other parametric dependencies can be subjects of digital preservation.

Measurements and drafting

Existing shapes are typically documented by measuring them and drafting 2D representations of them. Computer-aided drafting methods may be used, and logically extended in the "measurements and modeling" paradigm described below.

Measurements and modeling

This approach is especially valuable if the real object has been lost, destroyed or damaged, and is documented only by previous measurements and drawings. The goals are to create a 3D model of the object that is as complete as possible, and to represent its internal structure, design logic (showing how components are interconnected or layered), and history of the shape construction, as well as time-dependent aspects and other parametric dependencies.

De facto standard industrial modeling tools are usually based on the so-called *boundary representation* (BRep) of 3D objects. In particular, BRep can be based on a polygonal mesh approximation of the object surface. This modeling scheme is only partly appropriate for achieving the modeling goals described above. BRep data structures do not reflect the object's internal structures (e.g., material distribution) or design logic. Parameterization of BRep models is quite limited. Only simple time-dependent parameterization of BRep is allowed, which does not change the object topology. A *constructive modeling* approach can be an alternative. It is based on the construction of complex objects using simple primitive elements and combining and transformation operations. This approach is supported by the Constructive Solid Geometry (CSG) and the Function Representation (FRep) methods discussed in the following sections.

Scanning

There exist several well-developed technologies for automatic non-contact acquisition of 3D point coordinates on the visible surfaces of objects. These technologies are based on lasers, structured light, sound, and stereo imagery. Archiving of the raw data (the measured point locations) is preferable in any case to archiving shapes inferred from this data. Moreover, the raw data itself can be the best way of actually representing the surface, as was shown in the Digital Michelangelo project.[2] The authors' dataset of range images obtained with laser rangefinders provided 18:1 storage savings with no loss in information, if compared with the equivalent polygonal mesh. A special viewer based on range images was developed. The project authors claim that "if one only wants to view a 3D model, and not perform geometric operations on it, then it need not be represented polygonally."

Scanning and meshing

Traditionally a polygonal mesh is generated on the basis of the rough data. This can be necessary especially if the measurement equipment does not provide point coordinates directly. For example, in the Pietà Project [3] the scanner consisted of six black-and-white cameras capturing images of a striped pattern projected on an object. Accompanying software computed a triangle mesh from the captured images using principles of stereo computer vision.

Scanning and modeling

Scanning can provide a set of reference control points for manual modeling or the full point cloud can be used for (semi-)automatic model generation. An example of the latter case is voxel model generation from a set of range images.[4] The potential of an automatic search of a simple model structure and parameters fitting of an implicit surface model on the base of range data was illustrated in the work of S. Muraki.[5] In the case of unknown initial estimation of the model structure, evolution of shapes using techniques such as genetic algorithms can be applied, in the manner of the reported experiments with CSG [6] and analytically defined implicit surfaces.[7] Here, the overall distance from the shape surface to the scanned points can serve as an optimization criterion. In this work, we use measurements and constructive modeling of parameterized shapes oriented towards automatic optimization of shape parameters and further genetic evolution of shape structures.

2.2 Problems of cultural heritage preservation

Most current methods of modeling, including the first approach demonstrated in this paper, rely on proprietary software packages using data formats embedded in operating systems and hardware platforms. Since it is difficult, and in many cases illegal, to access the data directly, it is impossible to verify the application's operations independently and difficult to translate or provide interoperability or migration across platforms. Thus, proprietary software violates basic scientific requirements for rigorous proof of the accuracy of data gathering methods, research procedures, and digital processes. These methods and procedures must be open to inspection and inquiry in order to assure that cultural artifacts have been accurately modeled, and it should be possible to perform independent verifiable evaluation of the results of a given study. Moreover, information must be disseminated and archived using an open and understandable data format and a stable storage medium that provides secure storage and retrieval, at a reasonable cost, for the near and distant future.

Most digital information technology presently in use fails to meet these basic requirements. Proprietary methods and processes make it impossible to know how a given process works, what it accomplishes, and whether or not the results are reproducible. This snarled and secretive situation limits the life of the data, often to a period shorter than the life of the artifact itself. It should be self-evident that concealed and unverifiable procedures are unacceptable for archiving data. Academic exchange and research are diminished, when commercial proprietary products and data formats are accepted and used in academic circles a*s de facto* standard tools with little other choice.

Computer models of cultural heritage sites and artifacts are made with the specific purpose of preserving these objects for future generations. Thus it makes little sense to create models using software and data formats that may become obsolete, unusable, or unavailable. Accordingly, a crucial feature of our second approach discussed in this paper is its development and utilization of open-source software. This approach should contribute to the production of secure and long-lasting digital archives for cultural heritage preservation.

Problems with current shape modeling systems are not limited to the issues of proprietary data formats, methods, and processes. In addition:

- Inaccurate and poorly-defined data structures prevent migration to future hardware and software upgrades.
- Violation of well-established norms, such as the right hand rule with Z-axis up, conflict with standard scientific and engineering procedures.
- Data is not accurate enough to make models that are consistent at every level of detail.

The last two problems are minor and are easily remedied. However, issues of proprietary and embedded procedures, mono-directional processing, loss of originating source data, loss of constructive primitives, and loss of the order of construction procedures are serious barriers to the creation of archival quality digital data.

Digital migration problems that occur when core processes are embedded in a given computer platform can be addressed by the abstraction of the core digital process to the level of a virtual machine, such as in the use of the Java Virtual Machine (JVM). The problems of proprietary software that plague archival data processing and storage are also understood and well defined; they are being addressed by nonprofit groups such as GNU.org and sourceforge.org. Development of the Linux OS has also addressed these issues.

On the other hand, geometric modeling procedures and the fundamental mathematical base for 3D shape modeling, volume rendering, and multidimensional modeling are not well known or understood in the digital archiving community. These are core issues in the development of digital archives. Basic geometric modeling procedures, the retention of originating data attached to these procedures, the retention of the order of constructive events, and the modeling and embedding of physical dynamic attributes of 3D models for the creation of synthetic processes and simulations will change the way we look at digital data.

3. Shape Representations

In the following section, we describe two major shape representations and discuss them from the practical modeling point of view. Then, the function representation is discussed as a new promising direction.

3.1 Boundary representation and Constructive Solid Geometry

There are several different ways to represent solids digitally. Each representation has to provide determination of point membership: given any point it must be possible to determine whether it is inside, outside, or on the surface of a solid. In this section, we describe basic representational schemes: Boundary Representation and Constructive Solid Geometry. Formal definitions and more details on solids and solid representations can be found elsewhere.[8,9]

A solid can be represented by its boundary. To define a boundary surface one can introduce points (vertices), curves (edges), and surface patches (faces), and stitch them together (Fig. 1 upper). This boundary representation (or BRep) has two parts (Fig. 1 lower): topological information on the connectivity of vertices, edges, and faces, and geometric information embedding these boundary elements in three-dimensional space. Topological information specifies incidences and adjacencies of boundary elements. Geometric information specifies coordinates of vertices or the equations of the surfaces containing the faces. The boundary of the solid is a two-dimensional manifold. Each point of the boundary has a neighborhood with one-to-one correspondence to a disk in the plane.

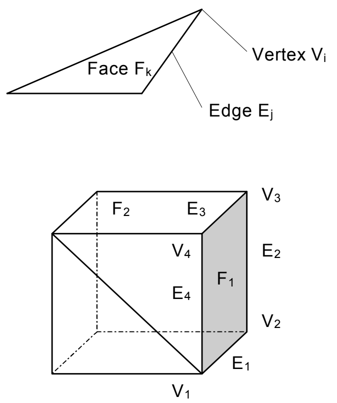

Figure 1: *Boundary representation of a cube is based on surface faces (triangles and/or quadrangles), edges, and vertices.*

Local modifications of the boundary are performed using tweaking operations such as moving the vertex, edge, or face. Topological modifications are performed using Euler operators, which include adding and removing vertices, edges, and faces. These operators satisfy Euler's formula and thus ensure topological validity of the resulting solids.

From the practical modeling point of view, wire frame or BRep is used for visualization of CSG or FRep defined objects. Currently, most commercial modeling programs use BRep not only for visualization but also for mathematical definition of objects. Systems based on this approach are exceedingly complex and prone to error. The objects made in this manner may be aptly described as polygons with holes and should not be considered archival quality digital objects. In the practice of modeling with these systems, wire frame is convenient for finding the center of arcs and circles and thus indispensable to the creation and editing of entities, and BRep is helpful during the creation and editing of entities and necessary for rendering the entities. Hybrid systems using BRep based interaction and visualization together with mathematically rigorous representation are needed for quintessential digital modeling of objects.

Constructive Solid Geometry.

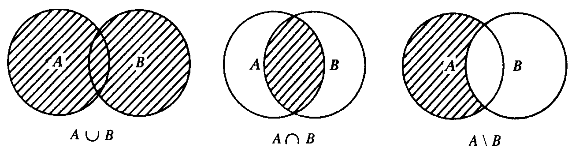

Figure 2: *Set operations between two 2D disks: union ( ), intersection ( ), and subtraction (\). The result of each operation is shown as a hatched area.*

Using the modeling paradigm called Constructive Solid Geometry or 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 union, intersection, or subtraction set operations (Fig. 2). Traditional CSG primitives are the block, the cylinder, the cone, the sphere, and the torus. Linear transformations (translation and rotation) can be used together with regularized set operations. A regularized set operation includes removing lower dimensional parts of the standard set operation result such as dangling surfaces, curves or points.

A CSG object is represented as a binary tree (or CSG tree) with operations at the internal nodes and primitives at the leaves (Fig. 3). The point membership classification algorithm defines whether a given point is inside, outside, or on the boundary of the solid. This algorithm recursively traverses the CSG tree starting from the root. In the nodes with linear transformations, the inverse of the transformation is applied to the current point coordinates. When the recursion reaches the leaves, the point is tested against the corresponding primitives. Then, the classification results are combined in the internal nodes with set-theoretic operations.

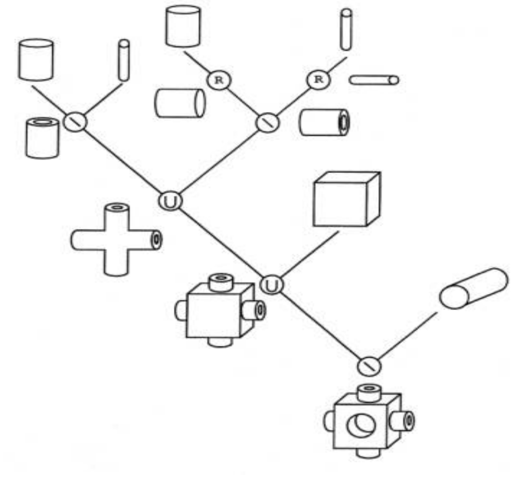

Figure 3: ***Example of a CSG tree. Operations: R (rotation), \ (subtraction), (union).***

From the practical modeling point of view, CSG inherently provides a constructive history, which allows interactive editing of sub-elements. If a complex object is created with CSG, its constructive primitives and the order in which they were processed can be accessed; CSG modeling can be called bi-directional. Furthermore, CSG allows for surface calculations of area and mass calculations of weight, volume, and centricity. The disadvantage of CSG is its limitation in geometrical representation; it is not suitable for producing organic shapes. Thus, though it performs well in its representation of most architecture, it would not do for sculpture.

IGES (Initial Graphics Exchange Standard) is the U. S. national standard for exchange of data between dissimilar CAD systems. Over the last twenty years, IGES has failed to include in its standards support for the translation and exchange of CSG 3D data, whose primitives and procedures are well defined and understood. On the other hand, STEP protocol (International Standard for the Exchange of Product Model Data, ISO 10303 standard) supports CSG, but this part of the protocol is quite rarely used nowadays. A suitable protocol should, at least, support CSG.

3.2 Function representation and the HyperFun modeling language

The basic mathematical 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, generate polygonal and other surface models, as well as voxelization, for visualization, animation and virtual objects presentation on the Web, and serve for direct control of rapid prototyping machines with the precision needed to reproduce the modeled objects**.** We propose to use so-called function representation (FRep) as our basic mathematical model.[10] FRep is a generalization of traditional implicit surfaces [11] and CSG. It represents an object by a continuous function of three variables as $F(x,y,z) \geq 0$. A point belongs to the object if the function is positive at the point. The function is zero on the entire surface (called usually an *implicit surface*) of the object and is negative at any point outside the object. 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, see Fig. 3) reflecting the logical structure of the object construction, where leaves are arbitrary "black box" primitives and nodes are arbitrary operations. Function evaluation procedures traverse the tree and evaluate the function value in any given point. Algebraic surfaces, skeleton-based implicit surfaces, convolution surfaces, procedural objects (such as solid noise), swept objects, and volumetric (voxel) objects can be used as primitives (leaves of the construction tree).

Many modeling operations are closed on the representation, i.e., generate as a result another continuous function defining the transformed object. These modeling operations include set-theoretic operations, blending, offsetting, non-linear deformations, metamorphosis, and projection. A new operation can be included in the modeling system without changing its integrity by providing a corresponding function evaluation or space mapping procedure.

In FRep, there is no difference in processing soft objects, CSG solids, or volumetric objects. This allowed researchers to solve such long standing problems as metamorphosis between objects of different topology, sweeping by a moving solid, controlled blending for all types of set-theoretic operations, collision detection and hypertexturing for arbitrary solids, and direct modeling of space-time and multidimensional objects.

The HyperFun language [12,13] was introduced for teaching and practical use of FRep modeling. It is a minimalist programming language supporting all notions of FRep. The following tools are available for processing HyperFun models: a polygonizer that generates a polygonal mesh on the surface of the object and exports it in the VRML format; and a plug-in for the POV-Ray ray-tracer that helps to generate high-quality photorealistic images. Application software deals with HyperFun models through an interpreter, which evaluates the defining function at any given point.

FRep also naturally supports 4D (space-time) and multidimensional modeling using functions of several variables. We are investigating approaches and tools for further utilization of multidimensional models. The main idea is to provide a mapping of such objects to a multimedia space with such coordinates as 2D/3D world space coordinates, time, color, textures and other photometric coordinates, and sounds. Deeper connections between multimedia space and geometric multidimensional spaces should be investigated in the context of computer animation, computer art, and cultural heritage preservation applications.

HyperFun was also designed to serve as a lightweight protocol for exchanging FRep models among people, software systems, and networked computers. The average size of HyperFun files is 5K. This allows for efficient implementation of a client-server modeling system in which a client can run simple interface tasks and generate HyperFun protocols to be sent to the server. The server site can be a powerful parallel computer or a computer cluster that performs time-consuming tasks such as ray-tracing, polygonization, or voxelization.

It is quite easy to learn and use HyperFun on the beginner's level. It does not require deep mathematical knowledge. High-school level geometry and common sense in constructing and using building blocks are enough to start modeling. The authors have had the experience of teaching HyperFun to first year university, high school and even junior high school students.

The open and simple textual format of HyperFun, its clearly defined mathematical basis, its support of constructive, parameterized and multidimensional models, its support by free modeling and visualization software, and its ease of use make it a good candidate as a tool for the digital preservation of cultural heritage objects.

4. Constructive Modeling in Cultural Heritage Preservation

4.1 Constructive modeling approach

We propose the use of FRep and CSG as its subclass as the basis of constructive shape modeling procedures in cultural heritage preservation. The ultimate goal of this work is to create a synthetic CAD modeling system based on constructive modeling principles and to apply it to cultural heritage preservation purposes. The system could have a hybrid character including CSG and FRep as primary representations and BRep and voxels as auxiliary ones. The multidimensional modeling system would allow not only for the three-dimensional coordinates, but for additional variables such as time, and other physical properties of an object. The proposed system would have a FRep construction tree and be capable of accurately modeling not only the shape or volume of a given object and its physical attributes, but also the dynamic relationships between objects and object processes.

Recently FRep has been applied to represent not only point set geometry, but also material distribution and other properties of arbitrary nature (optical, physical, statistical, etc.).[14] The proposed synthetic CAD system defining a volume and describing mixed materials within that volume will allow for the support of 3D printing processes, which require a great deal of volumetric data that polygonal mesh systems cannot provide.

The synthetic CAD modeling system that uses HyperFun will be a completely free and open source software package, just as is HyperFun itself. The proposed system will meet the basic tenets of the rigorous proof of operations required by scientific study. The proposed system's data will be abstracted and the constructive processes and procedures will be embedded within the digital data structure. These constructive processes will be bi-directional and verifiable and uniquely based on material-based procedural textures. Using this approach, the logic of hidden structural elements and the uniqueness of a historical object can be captured. The data resulting from the proposed system will have a lifetime suitable for long term archiving.

The proposed CSG and FRep based system is computationally intensive and will need to use clusters of networked computers. By comparison, present-day systems based on polygonal meshed data structures would be viewed much the same as paper data of the past. The proposed system for archiving applications steps beyond the indexing of simple and fragile paper based data structures of the past toward complex robust and active data structures of the future.

In the following, we illustrate our experience with application of CSG and FRep to practical problems of cultural heritage preservation.

4.2 Constructive modeling of historical buildings

Considering the experience of data loss, the authors specified CSG as the most likely data format for modeling historical architecture with any possibility of archival quality for the Aizu History Project.[15] All parts of the two historical buildings, the Golden Hall at Enchiji and Sazaedô, featured in this paper 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 the models was extremely large, the thatch roof of the Golden Hall and the double helix ramp inside Sazaedô had to be represented unsatisfactorily by a polygonal mesh.

In using CSG, computational requirements dictated that sections of the model be developed in many separate files on four different PC based systems. 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 on several different platforms. Even now, the entire model of Sazaedô cannot be handled easily at one time in present day animation and rendering systems. The efforts the authors experienced using CSG in commercial products on single computer systems with the hope of creating digital archival data seems wasted. It is doubtful that even this CSG constructed data will live through the next several decades because of the proprietary nature of the commercial software and the unknown quality of the CSG database. It may take as much or more effort to extract the CSG data structure embedded in these proprietary programs as it would to reconstruct the buildings from original data.

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. Our work on two Buddhist temple buildings in the Aizu region of Japan illustrates these benefits.

Golden Hall at Enichiji

The first structure that we modeled using the 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.[16]

Figure 4: *Structural view*

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. A base of piled stones also stretches along the north and east walls, and remains of a retaining wall abut the (surmised) southwest corner. This information has led archaeologists at the site to conclude that the building measured five bays from east to west and four or five from north to south. We have constructed the Golden Hall model as a five by four building (Figs. 4 and 5).

Figure 5: *Normal view*

In addition to archaeological data, the model was based on standard temple-building practices of the eighth and ninth centuries.[17] 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.

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 that takes visitors from the front entrance to the top of the structure, then over and down to the back entrance. The double helical walkway is part of an interior tower (Figs. 6a, b and c). (For more details on the Sazaedô construction, including black and white reproductions of these figures and some others, see Vilbrandt, Goodwin, and Goodwin, 1999.[18] The drawings in Figs. 6c, 7c, 8c and 9a were adapted from engineering blueprints done in 1965 by Kobayashi Bunji.)

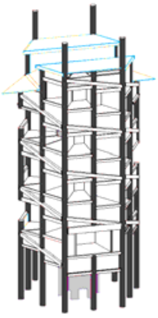

Figure 6a: *Interior tower with image alcoves - wire frame*

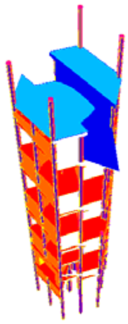

Figure 6b: *Interior tower - colorized*

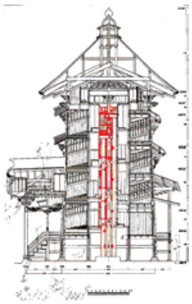

Figure 6c: *Full drawing showing the location of the interior tower .*

The 3D CAD model can be used to display such components separately, so that the construction may be seen and understood. Even an actual visit to the site does not enable such views.

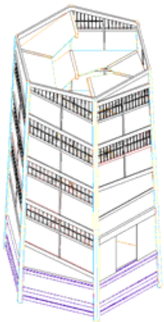

Figure 7a: *Exterior tower with walls added - wire frame*

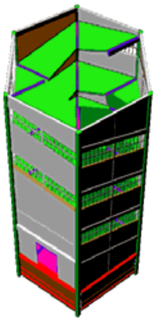

Figure 7b: *Model of exterior tower with walls - colorized*

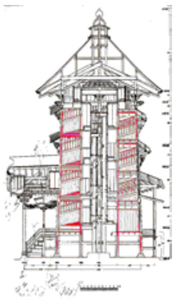

Figure 7c: *Full drawing showing the location of the exterior tower*

The interior tower is housed in an exterior tower, with a separate support structure (Figs. 7a, b and c).

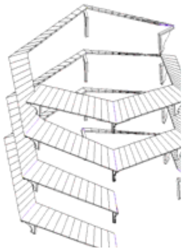

Figure 8a: *The exterior tower overhang - wire frame*

Figure 8b: *The exterior tower overhang - colorized view*

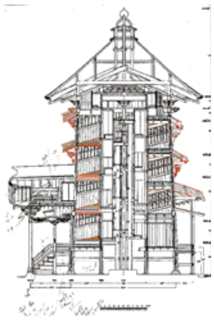

Figure 8c: *Full drawing showing the location of the exterior overhang*

The tower exterior shows helical overhangs protecting the windows from direct sunlight (Figs. 8a, b and c).

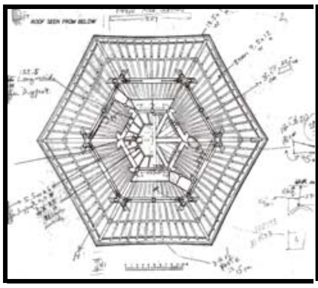

Figure 9a: *Roof - engineering drawing*

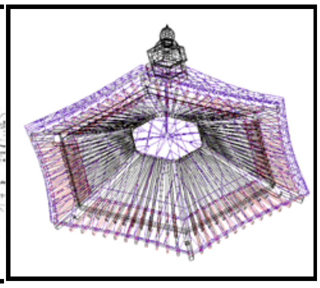

Figure 9b: *Roof - wire frame 3D CAD model*

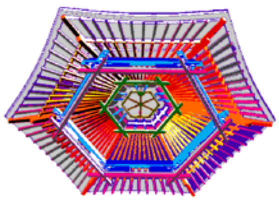

Figure 9c: *Roof - false color CAD Model*

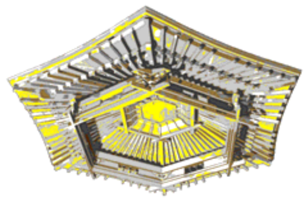

Figure 9d: *Roof - Rendered 3D CAD model, from below*

Fig. 9a is an engineering drawing of the roof shown from below. By using measurements from this drawing, and supplementing them with measurements taken on site, a 3D CAD model was constructed, and is displayed in the wire frame view (Fig. 9b) and the rendered views (Figs. 9c and 9d).

The entrance and its canopy are structures which can be better understood from the model (Figs. 10b, 10c, and 10d) than from a photograph (Fig. 10a) or even from a visit to the actual site, since they are complex objects and access and sightlines are restricted.

Figure 10a: *Entrance canopy photograph*

Figure 10b: *Entrance canopy – wire frame CAD model*

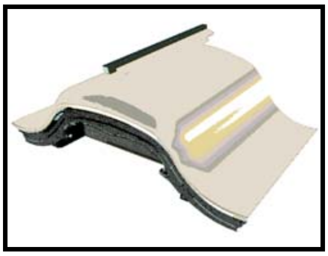

Figure 10c: ***Entrance canopy rendered***

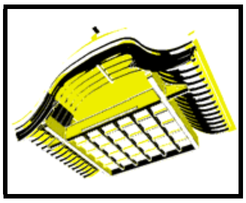

Figure 10d: ***Entrance canopy – alternate view***

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 (Figs. 11a, b and c).

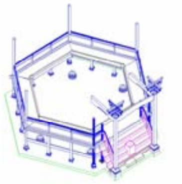

Figure 11a: *Wire frame of the base*

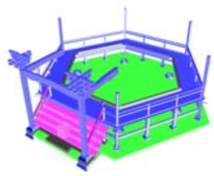

Figure 11b: *Colorized CAD model of the base*

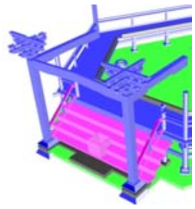

Figure 11c: *Base – details of the supports*

Because of the constructive approach, any part may be rendered without displaying the other components, as shown in (Fig. 11d), and an external shell may be fully rendered (Fig. 11e).

Figure 11d: *Rendered model showing helical structure*

Figure 11e: *Fully rendered view*

The models illustrated above are virtual constructions using virtual lumber cut, positioned and joined according to the specifications of the *miya daiku.* This empirically shows 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,[19] and to produce QuickTime and AVI movies of the journey through the temple. 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.

4.3 Constructive modeling of Japanese lacquer ware

Digital preservation of crafts heritage

As subjects of computer-based preservation efforts, traditional crafts such as pottery, embroidery or lacquer ware require special treatment. First of all, any craft is a living tradition, not a fixed set of inherited items. At the center of the tradition are masters with knowledge of essential craft technology, which is often not presented in written form. While computers may be used to preserve this technology or even to enhance it, computer-based technology is sometimes considered not to support, but rather to rival traditional crafts, giving rise to psychological and economic conflicts. However, the decreasing number of masters, fading technologies, and economic difficulties for crafts and their practitioners validate the necessity of computer-based preservation. The production of traditional Japanese lacquer ware or *shikki* suffers from the problems mentioned above, as well as from additional economic pressure due to cheap production of plastic look-alikes. In this section, we demonstrate how computers can help to preserve traditional crafts such as *shikki* manufacture, using a practical example of FRep modeling, conversion to polygonal BRep, and Web presentation of *shikki* items.

Virtual Shikki

When making actual *shikki*, parts of an item are produced manually using thin pieces of wood, which are then assembled, painted in different colors, and covered by natural lacquer or *urushi*. There is a great variety of *shikki* items: boxes, small drawers, stands, cups, bowls, sake pots, chopsticks, notebooks, and even ball pens and pencils. These items are quite different from one another in their topology, geometry, and texture.

The "Virtual *Shikki*" project includes the following research and development activities:

Reconstruction of shapes and making of 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.

Digitizing textures. There are technical problems of scanning colored textures from the surface of existing models.

Producing 3D virtual objects and presenting them on the Internet. The Virtual Reality Modeling Language (VRML) is often selected for Web presentation of 3D virtual objects. However, VRML has well-known drawbacks such as huge data files and long downloading time. Other Web3D data formats and browsing tools should be considered. The purpose of our virtual *shikki* presentation on the Web is to allow people to appreciate the beauty of shapes and textures from a remote location. This is important from both cultural and commercial points of view.

Producing animations and other multimedia presentations of traditional and virtual lacquer ware. The basic mathematical representation of 3D models should allow easy transformations and metamorphosis of shapes, thus enabling effective animation.

Implementation Issues

The process of modeling *shikki* shapes included the selection of representative items, the measurement of the coordinates of control points, the introduction of the basic logical structure of the model (primitives and operations), the description of the parameterized constructive model using the HyperFun language (see above), visualization using ray-tracing and polygonization, comparison of the obtained shape and control points with those of the original, modification of the construction, and selection of parameters of the model.

Some additional specific operations--for example, bounded blending--were required for adequate modeling of *shikki* shapes. A blending operation generates a smooth transition between two given surfaces. Blending operations for FRep were formulated by Pasko et al.[10] for all set operations (union, intersection, difference) between two solids. However, this formulation of blending suffers from the resulting surfaces being offset (expanded or contracted) everywhere in the space. This is not acceptable in modeling lacquer ware shapes, because blending should not affect original surfaces outside the specified area of influence. To satisfy this requirement, we proposed and implemented bounded blending operations,[20] illustrated in Fig. 12. A sake pot is shown in Fig. 12a with the circle showing the region of bounded blending. Fig. 12b shows the union of the initial pot spout and the ellipsoidal shape (the left bottom part of the pot body) which are to be blended. The cylindrical bounding solid is shown in Fig. 12c. The blended shape resulting from the bounded blending operation should completely reside inside this solid. The resulting blend satisfying this requirement is shown in Fig. 12d.

The implementation of the three first stages of the project, namely modeling shapes, digitizing textures, and presentation of virtual objects, includes the following:

1) Creation of several 3D computer models of traditional Japanese lacquer ware items. The basic modeling tool was HyperFun language.[12,13]
2) Generation of polygonal models using HyperFun Polygonizer[13] and export to VRML (Virtual Reality Modeling Language) format.
3) Decimation of polygonal shapes using different software tools to produce VRML models as small as possible in size.
4) Scanning of color textures directly from lacquer ware objects with planar surfaces and from photographs.
5) Texturing of polygonal models using standard VRML authoring tools.
6) Generation of images and creation of the website.[21] Several snapshots from the web site are shown in Fig. 13. Each image at the site is hyperlinked to the corresponding HyperFun model and the VRML model, which can be downloaded and visualized using any VRML viewer such as the CosmoPlayer. See an example of the sake set VRML model in Fig. 14.

The average size of a VRML file is 100-500 Kb. However, the size of the sake set file (Fig. 14) is 4.5 Mb (uncompressed ASCII version). On the other hand, no HyperFun models for any lacquer ware item exceeded 5 Kb. Thus we can conclude that HyperFun provides a high level of compression and should be considered as a lightweight network protocol in the future.

We found that VRML files are too memory expensive, especially in the case of complex shapes and sets. Other and more compact Web3D formats should be considered in the future. A more radical solution would be to transfer small HyperFun models to the user's computer and provide a browser able to unfold a polygonal or other representation suitable for interactive visualization.

Modeling specific shapes required a large amount of routine labor in measuring control points and fitting model parameters. Semi-automatic methods should be introduced based on 3D scanning of real objects for acquisition of control points and non-linear optimization for automatic fitting of parameters.

5. Conclusion

We proposed an approach to digital shape preservation based on using constructive modeling. We examined and selected Constructive Solid Geometry and Function Representation as shape representations that fit the purposes of long-term digital preservation. Constructive Solid Geometry (CSG) was used in modeling the Japanese temples Enchiji and Sazaedô with its unique internal structure. Traditional Japanese lacquer ware was modeled using FRep.

While the approach proposed here 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 a visualization 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.

Perhaps the most important advantage of the FRep geometric protocol is its open and simple textual format, making it highly suitable for long-term digital preservation and for the exchange of models among systems and people. 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. Automation of the logical structure extraction will be investigated in our future work.

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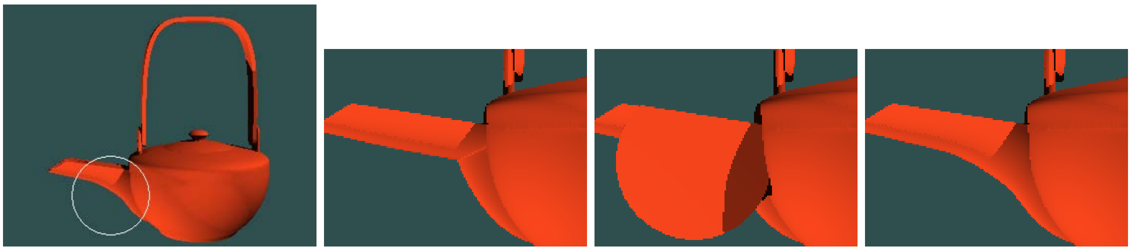

a b c d

Figure 12: *Bounded blending operation: a) sake pot with the region of blending circled; b) initial pot shape without blending; c) pot and cylindrical bounding solid; d) resulting pot shape with bounded blending.*

Figure 13: *Snapshots of the "Virtual Shikki" Web site with images hyperlinked to the HyperFun and VRML models of corresponding lacquer ware items.*

Figure 14: *VRML model of the sake set examined using the CosmoPlayer software.*