Solid Modeling for Heritage Documentation

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SUMMARY

As opposed to solid models, line and surface models have been widely used in heritage documentation because they are easier to build and less bulky. This paper explores the solid modeling approach as a tool for heritage documentation. As an application example, the process of modeling the Gereza, a fortress at Kilwa Kisiwani in Tanzania is discussed. The authors suggest that a solid (volumetric model) is more suitable than conventional models for the representation of an open building with an exposed interior structure. Comparative analysis of line, surface and solid models is given. A combination of laser scan and photogrammetry data was used as input for the creation of a 3D solid model on CAD.

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1. INTRODUCTION

1.1 Object Representation for Documentation of Historical Sites

Today, three-dimensional computer models play an important role in engineering, design, education, entertainment, tourism and many other areas. There are several reasons why computer models have become the preferred mode of representation. As compared to physical models, computer models are cheaper to build and can be easily stored and retrieved when needed. Further, compared to analogue ones, three-dimensional digital models are easier to modify. In applications to historical sites, computer models provide a virtual model shop where structures can be studied and experimental reconstruction of partly ruined or extinct monuments can be carried out.

Three-dimensional modeling for documentation of historical sites is somewhat different from engineering design in that it follows the reverse engineering approach as opposed to forward engineering. Reverse engineering seeks to produce a credible representation of an already existing object. This involves the acquisition of precise object measurement and the transfer of measurement to a modeling system. Forward engineering produces a model of a non-existent object as a design process prior to manufacture. In this case, the designer supplies measurements of the object based on his or her objectives and the design requirements. In heritage documentation, this is only applied in virtual reconstruction. Apart from the reverse-versus-forward-engineering distinction, three-dimensional modeling for heritage documentation follows the same general pattern manifested in engineering design representation.

There are several kinds of three-dimensional computer models employed in engineering. The type of model one chooses to use depends on the purpose of the model. In general, three-dimensional computer models are classified as wire-frames, surface models and solid models. The wire-frame is the first topological level above the point cloud level, making distinct the edges and corners of the object. The surface model is the second level, providing information not only about edges but also the surface area spanning the edges. A solid model – the third level up provides information about the boundaries of the object as well as the enclosed volume thus creating a better understanding of the structure. Wire-frames and surface models have been widely used in heritage documentation because they are easier to build and less bulky. In this paper the authors explore the alternative of using solid modeling given the added advantages this representation has over surface models.

1.2 The Solid Modeling Advantage

As compared to wire-frames and surface models, solid models are very useful because they do not only describe the boundary of the object but its interior as well. The data structure of a solid model incorporates topology (connectivity information) documenting how vertices, edges and surfaces of the model join together. In addition material properties can be assigned to solid models thus allowing other forms of engineering analysis to be carried out. It should be noted that, although thus far documentation of historical sites has been viewed in terms of providing a basis for visualization, these added advantages will extend the value of the documentation and are essential to researchers studying historical buildings of from an engineering perspective.

Figure 1: Broken, free standing walls inside the Gereza

In addition to the potentials of solid modeling in general, this paper presents solid modeling as the solution to the challenge of modeling a particular kind of historical buildings. Kilwa's monuments were built of coral rag with lime mortar. Over the past centuries most of the buildings have been reduced to open roofless structures with freestanding walls. The walls have been badly eroded leaving rough edges and honeycombed surfaces that pose a challenge to standard CAD modeling. Using an approach based on constructive solid modeling (CSG), a technique is developed to create a solid models of highly irregular coralline walls based on object's surface data. Solid modeling of such complex structures affords researchers a study model that can be sliced horizontally or vertically to reveal interesting spatial relationships.

2. BACKGROUND: A BRIEF HISTORY OF KILWA KISIWANI

Kilwa Kisiwani was first settled around 800 AD, and by 1320 it had grown into one of the most prominent trading centers of the East African Coast. Its splendid buildings include mosques, palaces and ordinary residential buildings. Kilwa supplied timber, ivory and other African products to Southern Arabia, the Persian

Gulf and locations as far as India and China. Kilwa's trade to the North reached Egypt and other Mediterranean countries. For quite some time, Kilwa also controlled the coast to the South as far as Sofala beyond the Zambezi mouth; a harbor from where gold mined in Zimbabwe was exported. Around the 15th Century, Kilwa faced growing competition from Mombassa and Malindi to its North and at the beginning of the 16th Century it was invaded and subdued by the Portuguese who built the Kilwa fortress in 1505 to signify their dominance over the island. When leaving the island after a short occupation the Portuguese reportedly razed most of the original fortress – the present fortress is largely an extension of the original structure by Omani rulers who revived Kilwa and ruled there during the 1800s. First structures of the Great Mosque were built in the 11^{th} century and expanded significantly in subsequent centuries. Other than for some reconstruction in the 15th century, the present mosque has retained its original form (Sutton 1998). After some economic revival in the late 18th Century, Kilwa faced a new period of occupation by Omani rulers based in Zanzibar at the beginning of the 19th Century. In 1840 the last Sultan of Kilwa was deported to Oman, thus ending the dominance of Kilwa. (Chittick 1974).

3. DATA ACQUISITION AND PROCESSING

A combined laser and photogrammetry approach, supported by control points determined by theodolite observations was chosen for the modeling of the Gereza. This hybrid approach has been found effective and less time consuming in a number of studies. (Borg, 2002, Lapointe, 2001). Laserscanning provides detailed surface information, while photogrammetry allows the extraction of edges and other features.

3.1 Processing Photogrammetry Data

In the early stages of the photogrammetric processing of image data for modeling of the Gereza, a data structure was developed to streamline the acquisition and presentation of photogrammetrically acquired points. The data structure was instrumental in photogrammetric digitization of feature points with Australis software (Fraser and Edmundson, 2000) and subsequently transferring these points to a CAD system for line drawing. The following workflow was adopted:

- An approximate CAD model was created using tape measurements of the Gereza's ground plan.

- The working model was used to label (code) each point according to its location within the structure, the feature type and the location on the feature, according to a pre-designed data structure; for instance, EGl-1 (Figure 6) refers the first point on the left side of the gate in the East wall, or EWPW1_1 refers to vertex 1 of window 1 on Eastern wall, parapet 1. Further points are labeled in a sequence that follows the outline of the window in clockwise direction, and named EWPW1_2 and so forth. These labels, which identify individual points uniquely, are allocated to points during the 3D digitising with the Australis software. In previous digitising processes, points had only allocated sequential numbers and were manually linked in CAD. In this approach, the identification of individual points in a large densely populated point cloud proved extremely difficult and sometimes impossible. In the newly adopted approach, the file of labeled coordinates, generated in Australis, was translated into a corresponding Lisp feature file, by means of an in-house program (*Aus2lisp*) for the automatic generation of AutoCAD feature descriptions from an ASCII xyz-file. Once imported into the CAD system, the points of a feature are automatically joined with lines according to the number sequence of their labels. The new coding method combined with automated transfer into CAD, proved a significant improvement on the previous approach and the features of the Gereza's East Wall were successfully plotted on AutoCAD with this method.

3.2 Processing Laserscan Data

Before the creation of a model, laserscan point cloudsrequire pre-processing , such as the registration of adjoining point clouds into a common reference system, the thinning out of unnecessary points and the elimination of irrelevant for- and back ground points. With increasing availability of laser scanners it has become important to develop techniques for the pre-processing of laser scan point clouds and for the creation of solid models from object surface points. The solid model generation proposed here is meant to be a step in this direction.

The data structure coding system applied for photogrammetric feature extraction was employed to the laserscan point clouds as well. In this case, however, entire wall sections are treated as units named following the data structure coding pattern.

The speed and efficiency with which 3D data of large surface areas can be acquired through laserscanning makes the technique very appropriate for capturing surface detail. An alternative method of generating dense point clouds are the well established photogrammetric image matching and feature extraction techniques.

In the hybrid approach photogrammetry provides information about object edges for wire frame modeling while laser scanning supplies surface detail.

4. SOLID MODELING BASICS

"A solid model is a digital representation of the geometry of an existing or envisioned object." (Rossignac). Solid modeling was developed in the seventies in response to the search for a valid and unambiguous engineering representation that in principle supports any and all geometric queries that may be asked of the corresponding physical object. (Shapiro, 2001)

The mathematical foundations of solid modeling are Euclidean principles and differential and algebraic geometry. Data structures and algorithms for efficient solid modeling computations were developed in the nineteen seventies as a research project at the University of Rochester.

“The real world artifacts and the associated processes are abstracted by *“postulated”* mathematical models. The space of mathematical models and operations serves as the definition for the corresponding data type (class) that can be represented on a computer (in more than one way) by a representation ‘scheme’. Formally a representation scheme can be defined as a mapping from a computer structure to a well-defined mathematical object.“ Requicha, 1980.

There is a number of existing solid modeling representation schemes. The following list is by no means exhaustive but provides a summary for the purpose of this paper.

- Boundary Representations:
  In boundary representation the object is defined as the union of its boundary faces that should be non-overlapping. The faces, in turn, are defined by curve functions defining the edge, and surface functions defining the points spanning the edges. B-rep data structures therefore document each vertex, edge and face plus their topology.

- Constructive Solid Geometry (CGS):
  In this scheme an object is expressed as a collection of primitives i.e simple shapes like cylinders, cones, blocks combined using Boolean operations. Primitives may be instantiated several times and used with different parameters, positions and orientations. CSG data structures store objects in form of a tree with Boolean operators (union, intersection and difference) at the nodes and primitives as the leaves. While some nodes represent Boolean operations others perform translation, rotation or scaling. (Requicha 1980)

- Spatial Decomposition
  In spatial decomposition an object is represented as a collection of small non-intersecting cellular units. There are several kinds of spatial decomposition schemes including spatial occupancy, cell partitioning and octree.

In this work we adopted a hybrid modeling approach based on CGS. Several potentials of CGS are important in the process of finalizing the model and deriving other representations from the model. These potentials include Boolean operations, slicing and sectioning.

5. FROM POINT CLOUDS TO SOLID MODELS

Although several methods of solid modeling of complex objects exist, to the author’s knowledge, none uses surface point information as input. Solid modeling of complex irregular objects from so-called 3D images is discussed in a number of available literature sources: Marsan (1999) presents a summary of recent techniques. In medical and similar applications, 3D images are obtained from CT scans and represent the object completely by describing its interior and exterior by means of voxels. A voxel is the smallest cubical unit of space or simply a volume pixel. Data acquisition through CT scans, is, for obvious practical reasons, not suited to the documentation of monuments. Point clouds can be generated either through photogrammetric processing of images or as a product of laser scanning.

Figure 2: Photograph
(entrance gate to the Gereza's)

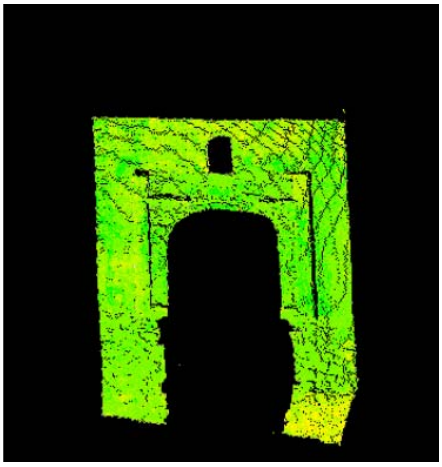

Figure 3. Laserscan image
(entrance gate to the Gereza's)

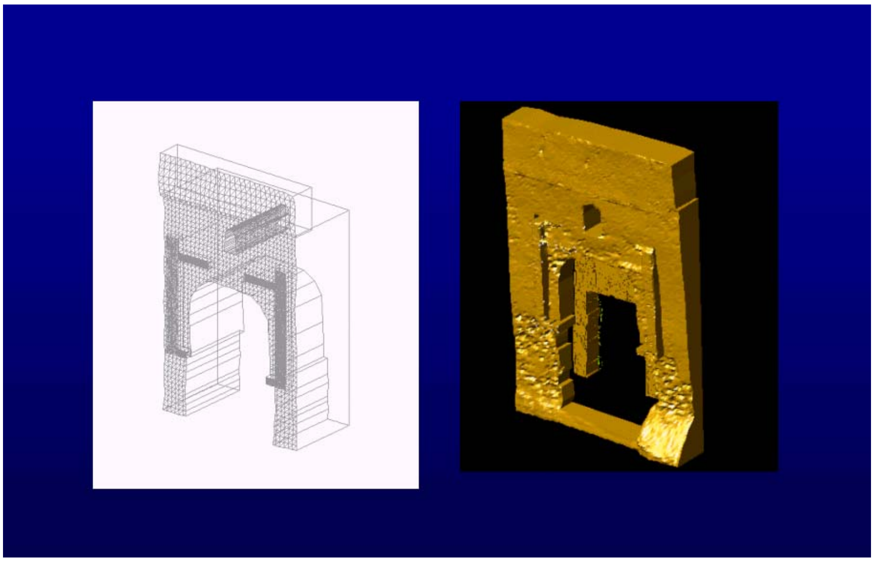

Figure 3. Wire frame
(entrance gate to the Gereza's)

Figure 4. Solid Model
(entrance gate to the Gereza's)

5.1 The Modeling Process on CAD

In the initial stage of the modeling process the desired model is considered as a solid crust or shell of the object. The difference between the crust and a surface model is that the crust (shell) is a solid object with some thickness. This solid can be sectioned, sliced, joined to another solid through the union operation or punched through (windows and doors) using the subtraction operation. Once the shell has been generated the next task is to fill it with solid material to produce a full solid object. Again the filling-in is possible through the use of Boolean and other solid modeling operations inherent in CGS based systems.

In summary, the solid model is created following these steps:

- A laser scan point cloud is displayed in CAD in dxf format (data exchange format).
- A section of a laser scan point cloud is isolated and saved as an independent file.
- This new dxf segment of the laser scan point cloud can now be converted into xyz format and used as input for the creation of a DTM using krigging algorithms – in this case *Surfer* software was employed. The 'density' of the DTM can be increased, if necessary.
- A three-dimensional polyline is used to create two triangles from each rectangular cell of the DTM. Each triangular unit is then swept by a given thickness to create a unit solid. The whole process is automated by as an AutoLisp program. Boolean union is used to join individual triangles into a single solid.

6. DERIVING OTHER PRODUCTS FROM SOLID MODELS

For restoration purposes, it is useful to represent a building in detailed 2D drawings in form of plans, elevations and sections, in addition to the 3D model. These 2D representations are essentially abstractions of the real object and given the right type of 3D model can be derived directly from the model. In this regard a solid model is superior to wire frames and surface models because it provides a useful resource from which other representations can be extracted through slicing, sectioning subtraction and other constituent operations of solid modeling.

Another important advantage of solid modeling for heritage documentation is the ease with which the model can be modified and extended in case digital reconstruction should be considered. Overall, documenting a historical site using solid models as opposed to wire frames and surface models offers considerably more potential in addition to visualization.

7. CONCLUSION

Although the documentation of Kilwa Kisiwani is a process in its early stages, certain trends are beginning to consolidate and show the direction forward. Among these are the advantages of combining theodolite, laser and photogrammetry surveying techniques,an approach given full treatment in Ruther 2003 and Borg, 2002. In the course of the Kilwa project, it has been established that, while wire frame and surface models may sufficiently and economically cater for visualization needs pertaining to documentation of historical sites, solid modeling is a better approach – one that adequately addresses the needs for documentation as guideline for restoration work and basis for virtual reconstruction of historical sites. A notable disadvantage of laser, solid models of complex objects are bulky and more time consuming to generate than wire frames and surface models. However, with computers becoming more powerful, it is projected that documentation of historical sites will benefit from adopting a solid modeling approach because of its many advantages.

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