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Solid Models of Archaeological Data

Paul Reilly

IBM UK Scientific Center

Athelstan House, St. Clement Street,
Winchester, SO23 9DR, UK

Starting with a brief overview of leading state-of-the-art applications of advanced graphics in archaeology, this paper will describe a current research project, in which archaeological deposits, such as layers, pits and artefact distributions, are modelled using solid modelling rendering techniques.

It is argued that besides producing pictures, solid models may enable the investigator to explore and navigate through multi-dimensional datasets by exploiting the geometry and structure implicit in the model. The research has important implications for the ways in which archaeology is taught and presented to the public.

考古学データのソリッドモデル

ポール　レイリー
アイ・ビー・エム英国サイエンティフィック・センター

コンピューターグラフィックスが考古学においてどのように使われているかの現状についてまず概観し，層やたて穴，遺物の分布などの考古学的包含層をソリッドモデルのレンダリングによってモデル化する研究について述べる。

ソリッドモデルは可視化以外にも，モデル内に潜在するジオメトリーや構造を見つけながら，さまざまな次元のデータ群の中に何か新しい知見を獲得することを可能にするもののようである。このような研究は，考古学が一般に考えられているものと密接な関係を持つ。

Solid models of Archaeological Data

Paul Reilly, IBM UK Scientific Centre[1]

Introducing the Technology

Solid-modelling systems facilitate some of the most sophisticated computer graphics currently available. These should not be confused with other graphics systems which produce pictures of "solid-looking" objects. "Face models", for instance, are composed of a set of rendered polygonal panels, which give the object the appearance of being solid but which do not actually conform to a truly enclosed solid shape.

Solid modelling systems were developed mainly by engineers to perform analysis functions on the resulting models. This criterion excluded the use of face models since the engineers required a process intrinsically geared to the production of representations of solids rather than relying on the user to create the required set of faces. Today, most solid models are based on one of two data structures, and often both are present (Woodwark 1986). The "boundary" model is similar to the face model, except that the faces, edges, and vertices of the model are linked together into a structure which is assured in its topological consistency. That is to say, there are no extra or omitted faces, edges, or vertices of the object. The "set theoretic", or "constructive solid geometry" (CSG) model, on the other hand, is defined as the combination of simple or primitive solids (eg. spheres and blocks), using operators derived from set theory (eg. union, difference and intersection). One of the most important properties of these modelling systems is that they very suitable for supporting picture generation.

It needs to be stressed, however, that the graphical capabilities of solid modelling systems represent just one area of usage. These systems also embody large volumes of structured three-dimensional information which can be exploited to establish links to many different kinds of database to provide powerful and flexible archival, training and analytic tools. The potential of solid modelling in archaeology, within an integrated multimedia paradigm, for the analysis and presentation of primary archaeological material, is even greater when we consider that the latest trend in archaeological data visualisation is toward the use of free-form digital solids. In connection with this, a further aim of this paper is to suggest how the use of simulated three-dimensional archaeological formations can assist the development of new recording and analytical tools for understanding actual archaeological formations. Such facilities could play an important role in helping students to understand better the nature of archaeological features as well as being an excellent vehicle for demonstrating the relative benefits of applying different exploration scenarios.

Introducing the Archaeological Applications

Boundary models have only recently begun to be applied in archaeology, whereas set theoretic models have a longer pedigree (see Chapman 1991 for a more detailed discussion of the relative merits of the two types of systems for the archaeological user). Since the mid-1980s, we have witnessed steady advances in the application of solid modelling techniques, particularly set-theoretic methods,

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[1] IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, SO23 9DR, UK

to elucidate ancient monuments, with Roman and Romanesque building complexes being most popular subjects in Britain (eg. Blake 1990; Cornforth and Davidson 1989; Cornforth et al 1990; Delooze and Wood 1990; Dew et al 1990; Haggerty 1990; Holliman 1990; Lavender et al 1990; Reilly 1989; Smith 1985; Woodwark 1991), but a wider range of architectures is being explored in, for example, Egypt (Boccon-Gibod and Golvin 1990, 8 – 19), Greece (Cornforth et al 1990), 1990), Japan (Ozawa 1986; 1989; Oikawa 1990) These projects can be characterised as collaborative affairs in which archaeologists and computer scientists establish a symbiotic relationship. Of course, both parties usually have different perceptions and expectations of the benefits of this relationship. The archaeological motivation behind the earliest projects was essentially to explore the potential of this sort of technology to illustrate monuments. By contrast, the computer scientists hoped to overcome certain technological problems in modelling complex objects.

Equipped with a detailed model and some facilities with which to view all its many aspects, the earliest projects were still restricted to generating a relatively small number of views because of limited processing resources. There is little doubt that these early solid model reconstruction projects were successful in a number of ways. (As I have reviewed these early pioneering projects elsewhere (Reilly 1989) I need not rehearse this material here).

The archaeologists involved in many of the earliest projects had already formed fairly firm ideas about what the archaeological remains would have originally looked like before they even considered building the computerised model. In effect, the solid models were really only a means of actualising these ideas in a visually compelling way. The obvious step of introducing the modelling at a much earlier stage in a project, and exploiting it as a malleable conceptual aid in the initial data interpretation process itself, was gradually made during the investigation of the rather minimal remains of an early medieval Manx chapel and burial ground known as 'Malew 18' (Reilly 1988a, 187 – 216). Here, experiments to incorporate a number of features – identified through several survey techniques – into a coherent solid model brought to light flaws in the initial interpretations. What emerged was that, because the human modeller was forced to define explicitly the size and three-dimensional location of each feature in the model, inconsistencies were soon exposed. The result was that attention had to be continually directed back to details in the data. Besides speeding up the process of exposing and rectifying faulty thinking, the model building also had the effect of targeting key points in the complex where logical stratigraphic (ie. relative geo-chronological) relationships might be resolved. This is clearly essential information in order to understand the development of the complex.

From around 1988 onwards the number of teams developing solid model applications in archaeology started to grow noticeably. Groups have begun to concentrate their efforts on particular aspects of the modelling process, especially user interface problems and photorealism. Another avenue being developed is that of exploiting the data visualisation potential of these modellers at a much more fundamental stage of the data capture and analysis process. Human-computer interface problems in model definition and assembly are clearly important issues. Unwieldy-looking text file input methods are common, but are not attractive to many non-programmers. Consequently, more sophisticated, user-friendly methods are being sought. However, some interesting issues appear in the wake of this process of making modellers both easier to use and more widely available. For instance, the possibility of establishing libraries of architectural elements (or entire monuments) and consistent methods of model definition suggests that discussions on standardisation are inevitable (cf. Eiteljorg 1988). Sophisticated textures are rapidly becoming required features in computerised archaeological reconstructions and consequently greater photorealism is a significant research component of several interesting projects. This objective is the principal driving force behind the technological side of the work is in both the development of novel algorithms and new, ever-more powerful, processing capability. Lighting and texture are currently the main topics being explored. Probably the most notable recent example of the widespread use of texture, some incorporating permeable elements, appears in a three-minute animated tour of a model of Edo Castle, Tokyo. The Fujita Corporation together with IBM Japan has accurately reproduced the Grand Hall of Edo Castle and its "Pine-Painted" Walkway using Fujita's COMPASS computer graphics system. The animation, rendered using the IBM Japan Tokyo Research Laboratory's Rendering Subroutine Package (RSP), was broadcast as part of the *Kasuga-no-Tsubone* series on a channel of the Japanese public broadcasting station NHK (Nihon Hoso Kyokai). This beautifully detailed model illustrates Edo Castle as it probably appeared in Tokugawa period (1603—1867), the period of the Shoguns (see Miyata 1990; Nikkei Computer Graphics 1989a; 1989b for graphics).

Relating Analyses and Theories to the Underlying Data

All the above projects are undoubtedly promoting the image of archaeology to the public and provide computer scientists with a fascinating test-bed domain. Another set of projects hope to achieve these desirable effects while trying to harness the power of solid modelling to help deal with some fundamental problems in the collection and understanding of archaeological data and to find ways of enabling people to see how interpretations relate to the actual material remains encountered.

This has always been a critical problem for archaeologists. Generally speaking, every effort is made by the excavators to record all relevant details concerning the nature of the deposit. The criteria defining what constitutes a relevant detail are always subject to review, and there is often a tendency is to err on the side of caution, even when there is no clear idea about why certain details could be important. This is not to say that practitioners necessarily lean towards an empirical attitude to archaeological nature. Rather, a pragmatic tendency towards the cautious approach, combined with an ever-increasing range of allied and subdisciplines who are interested in a wide range of different facets of buried archaeological formations, has lead to a veritable explosion of data. Unfortunately, many of the methods of recording (ie. textual description, drawing and photography) are constrained by the limitations of the available technology, particularly the paper interface. For by projecting aspects of a three-dimensional space on to two-dimensional planes information is lost and the effectiveness of these tools is therefore circumscribed. A severe limitation is the strict view dependency. Nevertheless, they are founded on a long tradition of convention and are useful records. Scale drawings and black-and-white photographs also have the major attraction of being comparatively cheap to mass reproduce.

That the first computerised systems for recording and handling archaeological contexts should have inherited many of the characteristics of the traditional paper interfaces is not very surprising (eg. Alvey 1989; 1990; Rains 1989; Stancic 1989; Weiss 1989, 314−317). These first-generation computer-based site recording systems enhance considerably existing single context and other planimetric recording procedures (eg. Harris 1989) by providing greater freedom to isolate and combine (ie. phase) contexts in smaller time frames, and their relevance and utility is undoubted. They can, moreover, be adapted to fulfil the role of supplying an extra dimension to the shape of the contexts which the section drawing managed with only partial success. In principle, at least, any section can be generated from the planimetric data, providing that it is accompanied by sufficient three-dimensional surface readings. Preliminary experimentation indicates that more flexible records are feasible. In fact, developments in several technologies are creating a climate which could herald major improvements in what and how archaeological material is recorded, structured, analysed, presented and disseminated. These are hypertext, or integrated multi-media systems, and three-dimensional modelling (including so-called virtual realities). Both embody techniques for representing and exploring data. (cf. Cornforth et al 1990; Loveria and Kinstler 1990; Wilson 1988).

A multi-media approach is being used at Pompeii, the Roman city buried by the eruption of the volcano Vesuvius in A.D. 79. At Pompeii there has been a heavy reliance on graphics as an interface to the Pompeii archives. The most important navigation method through this colossal hypertext databank is via digitised maps of the city and its environs (Gullini 1989; Martin 1988; Moscati 1989; Zingarelli 1989). Solid models are employed to help reveal and explain the structure of dertain buildings, such as the Stabian bathes. such as the SITAG project on Sardinia (SAPPSN 1989, 31). The idea of combining various data sets – databases, surveys, reconstructions etc – is also being explored by Australian researchers, working on the Syrian El Qitar project (Ogleby 1988), and by Americans working on material connected with the Puruvian Inca city of Machu Picchu (Chohfi 1990).

Virtual Archaeology

Impressive though such enormous projects are, a gap still remains between the interpretation and the original data. It is not always readily apparent how one gets from the dig to the interpretation. Reconstructing archaeological sites is just one aspect of archaeological research. Understanding the subtleties of the raw data is, if anything, even more important to archaeologists themselves. By constructing detailed models of the excavated material, archaeologists can re-excavate the site and search for evidence which escaped attention during the actual dig (at least to the tolerances imposed by the original investigative and recording methods used). Research of this kind clearly has major implications for how archaeological excavation and interpretation is taught as well as performed.

Experimentation with virtual archaeological formations may lead to new insights into data recording and analysis. The key concept here is "virtual", an allusion to a model, a replica, the notion that something can act as a surrogate or replacement for an original. In other words, it refers to a description of an archaeological formation or to a simulated archaeological formation. (A simulated data set will normally be shaped by the criteria used for recording an actual formation). The problem is therefore to identify the quintessential components of the archaeological formation under investigation, since these must have implications for the styles of data representation and information handling that are possible. It may turn out that in many cases archaeologists need not record in any greater detail than present-day standards demand. However, archaeologists must always pose and try to answer such questions as: "to what level of detail can one record?" or "at what level of detail must one record?" The overall archaeological objective of developing virtual environments must be to provide insights into the understanding of archaeological formations by the addition of the powerful resources of the computer: a synergistic relationship. A number of studies are exploring the potential of simulation methods for establishing such a relationship.

Lately, attention has begun to be focused on modelling archaeological formations as they appear in the field. The challenge is no longer only to model buildings with simple geometry, but to model those amorphous humps, bumps and hollows, typically found in the course of fieldwork. Set theoretic solid modelling methods were introduced into the investigation of the Early Bronze Age settlement site at Klinglberg-St.Veit in the Austrian Alps (Reilly and Shennan 1989). Normal methods of planning, levelling and sections through features, such as post-holes and pits, were used throughout the excavations. Nevertheless, attempts to build three-dimensional models of the deposits from the recorded data were in vain. Even though the excavators used the highest current standards of archaeological excavation, survey and recording, it could not be said that they produced a true three-dimensional record. The unavoidable conclusion is that most archaeological excavation recording has still a long way to go yet before excavators can claim that they record archaeological features in a manner that allows their full three-dimensional form to be reconstituted.

The first tentative steps towards building solid models of typical archaeological remains, as they are found in the field, took place in the Mathrafal project, where an integrated programme of non-destructive surveying techniques (ie. topographic, magnetometer and resistivity) was applied to identify the critical areas of the site where the minimum amount of excavation would yield the maximum amount of useful information. By mapping the geophysical survey data onto face models of the site's topography as colour-codes, the identified geophysical anomalies could be compared to local topographic features. As in the Malew 18 project the combined data sets showed some interesting details and a solid model reconstruction of several identified features, such as a building, kilns and a palisade, was built (Arnold et al 1989).

At this time, scalar fields, which could be handled with the same operators (ie. union, difference and intersection) as other Winsom primitives (ie. plane, cube, sphere, cylinder cone, ellipsoid and torus), were developed to enable chemists to look at equipotential surfaces around molecules. A regular grid of three-dimensional values defines the location of field properties including membership of the set of points inside a complex shape (Burridge et al 1989, 561 – 562). A variant of the fields primitive made it possible to integrate a solid model of the site's surface morphology with reconstructed components derived from the analyses of the non-destructive geophysical surveys (Arnold et al 1989). In combining the interpretation with the measured data, it is very easy to see how the two categories of information relate to one another. At the same time attention is redirected to unexplained features or anomalies which are left exposed.

The extra freedom that the field primitive introduces into the modelling arena has an important implications for archaeological field recording methodologies, especially when we take into account parallel developments in other technologies which could conceivable converge in an integrated, seamless and multidimensional multimedia information environment. A project, known as Grafland, has attempted a few tentative steps towards achieving this goal, by creating an imaginary archaeological formation. Grafland is a simulated three-dimensional solid model of an archaeological formation containing layers, pits, post holes, cuts, recuts and so forth, and is a direct descendent of the data exploration and teaching experiments pioneered in research simulations like Clonehenge and educational initiatives like SYASS. It is intended to illustrate, in broad terms, how archaeological site-recording systems such as HINDSITE (Alvey 1990), might be extended through the use of a multidimensional representational tool, like a solid modeller, to be further enhanced by enabling links to a wider hypertextual system of the Pompeii kind. Advances in modelling free-form solids mean that archaeologists can experiment with new recording strategies which supersede the traditional view dependent conventions. Solid models do not exclude the continued use of the well-established conventions; such schema could be extracted from the solid model definition. Most of the cut features in the Grafland model are composed of compound CSG shapes, such as cylinders and spheres or parts thereof. However, some of the contexts have been modelled as if a real irregularly shaped feature had been found with artefacts deposited it. Of course, much more complex models are possible.

The purpose of Grafland is to demonstrate that archaeologists can produce less abstract records of buried archaeological data than has hitherto been normal. Rather than reduce the record to a series of single context plans and sections, each context is defined as a three-dimensional solid which can be examined from any aspect or sectional view. Once in this form it is susceptible to novel methods involving transformations and interactions which open the way for new knowledge to be created and insights about the nature of three-dimensional deposits and their recording to be gained.

A Grafland animation sequence has been generated to illustrate the composition of the model excavation. The animation brings out several key points. To begin with, the multiple views of the model demonstrate the principle of constructing true three-dimensional solid models of archaeological formations is feasible and provides a superior record and database for further research. Allied to this, archaeologists can present larger volumes of complex data to a wider audience in more meaningful ways. This should enable archaeologists to explain better how their interpretations derive from the data. Perhaps most important of all, data exploration and analysis are promoted still further. Visualisation can be exploratory — in the sense that the researcher may pan through the data looking for loci of activity and other evidence. In other words, searches can be spatially organised, with the structure of the solid model being exploited as an efficient high-level spatial index. Conversely, the visualisation can be more attribute directed. For example, if the modeller labels, or provides pointers to and from, component features it is possible to isolate specific and associated stratigraphic components using standard database functions. An example might be a model in which all the cut feature between layer α and layer β are isolated and displayed in order to study the different routes by which residual material could have travelled in getting from α to β. The solid model description has the additional benefit of having valuable quantitative details, such as volumetric information about contexts, implicit in the model definition.

Prospects

It seems then that the various technological and intellectual threads discussed above are coalescing. A logical extension of the hypertext concept is to integrate solid models of the kind outlined into a multimedia environment, not only as theoretical reconstructions, or even three-dimensional models of the recorded features, but as user interfaces for data interrogation and navigation. Hyperlinks could be introduced between the solid model and other data sets associated with the object of interest (eg. image, audio, video, DVI and text). A three-dimensional cursor could provide one possible interface, allowing users to "point" at part of the model to discover what is being looked at and whether further information is available.

The convergence of these technologies, solid modelling and hypertext, opens up many interesting avenues which need to be explored in order to make the one archaeological record acceptable to those interested in preservation through recording, research, education and presentation.

In the area of "digital solids", in which free-form solids are modelled, we are witnessing exciting new developments. Already, modellers can extract feature data from sets of medical scans (eg. those produced in CAT) to build three-dimensional models of patients (eg. Tyrell et al 1990). Medical tomographic data is analogous to the geophysical scans produced from devices such as the "Ground Pulse Radar", which is apparently capable of registering even small archaeological features many metres below the ground (Addyman and Stove 1989). However, there are two significant differences between the nature of the data embodied in medical and archaeo-geological scans, each of which represents a considerable challenge to routinely modelling and analysing archaeo-geophysical formations. First, the sheer volume of data is enormous and is already pushing hardware and software processing requirements. Second is the problem of feature recognition and extraction. Building models from scans of patients is made simpler because there already exists a considerable amount of a priori knowledge about the nature of human physiology.

At the moment feature extraction is difficult with straightforward geometric models (eg. Jared 1989). Looking for meaning in a virtual sea of heterogeneous three- (or more)-dimensional data is one of the key problem-areas currently being addressed at the leading edge of the modelling world. However, there are many situations where non-destructive investigations would be a great boon for the profession. Developing these methods may help in delicate situations where, for instance, excavation might be regarded as profaning a sacred site. Equally, they should encourage us all to think more deeply about the physical nature of what it is we are investigating. Archaeologists should look forward to progress being made in multi-dimensional solid modelling with particular enthusiasm.

In the meantime, Grafland-like models might be used as controlled data sets to devise and assess different excavation, recording and analysis scenarios. They may even prove helpful in evaluating the strengths and weaknesses of pattern recognition procedures.

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