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Multi-dimensional GIS: exploratory approaches to spatial and temporal relationships within archaeological stratigraphy[1]

1 Introduction

All archaeological phenomena are located within a time-space continuum. The need to recognize the infinite multi-dimensionality within that continuum has been argued elsewhere (Harris/Lock 1995). This paper focuses on those aspects of multi-dimensionality which are relevant, indeed fundamental, to the recording and interpretation of archaeological stratigraphy. It will be argued that since the first attempts to scientifically record excavations, and even with the application of modern analytical techniques such as the Harris Matrix and various digital database or CAD methods, the three-dimensional representation of stratigraphical archaeological units and the relationships between them has been an illusive goal. It was not until very recently, with the advent of software that can store and analyse three-dimensional volumetric forms, that the technological capability has existed to achieve that aim.

The growth of GIS applications in archaeology over the last few years has been remarkable (Allen *et al.* 1990; Lock/Stančič 1995). It is now very apparent, however, that the continued imposition of a two-dimensional abstraction of reality within GIS represents a serious deficiency and has limited the uptake of GIS, particularly within archaeology. This two-dimensional emphasis in archaeology is partly due to the continuation of traditional manual and 2-D CAD-based approaches to the handling of archaeological spatial data in the form of maps and plans. The continuation of this into GIS presents severe limitations in functionality when examining multi-dimensional data. To date, where an application warrants the inclusion of a third or fourth dimension, such as depth or time, then the approach has been to construct, integrate, and analyse within a stacked vertical series of two-dimensional geographies. Often, 2.5-D graphics are achieved by draping two-dimensional coverages over a wire-frame Digital Elevation Model of a landform or other surface. Such quasi three-dimensional graphics should not be confused with true three-dimensional functionality which incorporates three independent axes along x, y and z (Raper 1989a).

Given these constraints it is not surprising that the majority of GIS applications in archaeology have occurred at the inter-site, regional scale. It is here that GIS functionality is at its strongest in identifying distribution patterns and exploring latent relationships between sites and their environs. Time, and subsequently change through time, is represented by a series of period coverages. We demonstrated such an approach several years ago with the analysis of 500 sq. km of landscape around the later prehistoric site of Danebury, England (Lock/Harris forthcoming a). This study organised the archaeology into seven period coverages spanning approximately five millennia. The temporal analytical capabilities are thus crude when compared to the potential of three-dimensional functionality which we presented in a later paper (Lock/Harris forthcoming b). The latter approach details a probability model which allows for the combination of disparate pieces of archaeological site information of varying date and accuracy. This effectively results in a series of 'columns' representing the third, or temporal, axis showing the probability of use for each site at any point in time.

At the intra-site scale there are relatively few applications of GIS. Again temporality is generally treated as a categorical variable and analysis mirrors the standard manual procedures using phase plans. This is illustrated by the study of excavations at the Romano-British town at Shepton Mallet, England (Biswell *et al.* 1995) in which seven archaeological phases are condensed into three periods for analysis and discussion. In this paper we seek to explore the recording and interpretation of excavated units through the use of GIS for it is within the three-dimensional world of stratigraphy that the real limitations of current approaches and technologies are most manifest.

2 Recording archaeological stratigraphy

The principles of archaeological stratigraphy were adopted from the ideas of 19th century geologists and based on the Law of Superposition as viewed in vertical stratigraphical sections. Pioneers of objective excavation recording methods, such as Sir Mortimer Wheeler in the 1930s, retained the vertical section drawing as their main tool for the interpretation of stratigraphical relationships. This places the analytical emphasis firmly on vertical relationships which equate with temporal development in terms of archaeological interpretation. The limitations of this approach are implicit in the attempts of Wheeler to record in the horizontal dimension through the development of his 'box' method of excavation. By recording horizontal surfaces at succeeding depths, together with conjoined vertical sections running in different directions, Wheeler was essentially attempting to record the three-dimensional spatial and temporal relationships that occur within the volumetric space that constitutes archaeological stratigraphy. It is argued below that despite the development of analytical tools such as the Harris Matrix and computer-based recording systems, the limitations of modern stratigraphical recording methodologies are the same today as those experienced by Wheeler five decades ago. The essential three-dimensional volumetric form and three-dimensional relationships of strata, or 'contexts', are coerced into two-dimensional recording and analytical frameworks.

The move toward area excavation during the 1960s, with the corresponding reduction in the importance of sections, was one attempt to address the three-dimensional complexity of deposits 'from the top down'. It was not until the mid-1970s, however, and the introduction of the Harris Matrix that a methodology designed to represent such complexity became available. Despite the subsequent impact of the Harris Matrix, not least the stimulation of considerable discussion concerning the theory and practice of stratigraphical recording and interpretation, it is still a tool incapable of representing the true multi-dimensionality of the data being analysed. In the first, and only, collection of papers addressing wide-ranging applications of stratigraphy generally, and the Harris Matrix in particular (Harris *et al*. 1993), the Matrix is claimed to have 'changed the paradigm of stratigraphy from a two- to a four-dimensional model' (*ibid*.: 1). This claim is based on the assertion that a section shows two dimensions of each deposit (thickness and length) while the Harris Matrix shows four dimensions by adding width (horizontal extent) and time (relative ordering). This said, it is difficult to see how the symbolic representation of contexts within a Harris Matrix, usually by standardized boxes containing a context number and joined by lines, represents the thickness, length and width of each individual context. However, while this is a powerful tool for establishing the relative ordering of a stratigraphical sequence and displaying it symbolically, its primary limitation is that it remains locked into the confines of the two-dimensional diagram.

Closely related to the methodology of the Harris Matrix is that of single-context recording in which the plan, stratigraphic relationships, and descriptive characteristics of each context are recorded individually. While this approach eases the interpretation and recording of the stratigraphic sequence context-by-context, an unexpected improvement has been the application of computer-based methods resulting in new means of display and visualization. Such systems, Hindsight for example (Alvey 1993), utilize the layering capabilities of CAD software to record each context as a separate drawing (layer), link it to a database record, and then produce composite plans by overlaying selected layers. This not only reproduces a conventional composite plan in digital form but also enables the creation of exploded stratigraphical sequences to show vertical relationships. As noted by Alvey (*ibid*.: 221), there has been a reluctance to adopt the Harris Matrix by some archaeologists because of the necessity to reduce three-dimensional volumes of soil, with concomitant three-dimensional relationships, to two-dimensional symbols with two-dimensional relationships. The advantage of exploded stratigraphic columns, such as produced by Hindsight, is that the relative shape and size of each context is retained, albeit only in plan and without any depth, while portraying their horizontal and vertical relationships in a very simplistic manner.

The use of CAD software for excavation recording is becoming commonplace. These applications are almost always confined to two-dimensional drawings despite claims to the contrary. Alvey (1993) refers to the Hindsight exploded column as 'the 3-D model' and Beex (1995) combines CAD plans and sections to produce a (hollow) box-like representation of an excavation trench referred to as 'a full three-dimensional reconstruction' (*ibid*.: 106). As will be demonstrated, it is misleading to claim three-dimensionality for software that does not have independent x, y and z axes. Such truly three-dimensional software has been used by Reilly (1992) to demonstrate the visualization powers of volumetric solid modelling and rendering as applied to hypothetical stratigraphy. The difference between a true 3-D approach and the CAD work is immediately obvious in the ability of the former to slice volumetric contexts along any of the three axes to reveal the interior. Even so, Reilly's work emphasizes that the visualization approach lacks the analytical functionality associated with GIS and topological relationships.

3 Multi-dimensional GIS

The archaeological emphasis on two-dimensional representation of three-dimensional phenomena through the use of scientific visualization, CAD/CAM, 2.5-D techniques, and solid volume modelling, is indicative of the search for approaches to manipulate and analyse archaeological phenomena in three dimensions. While these approaches possess powerful capabilities for exploring multi-dimensionality, they lack the full functionality provided by the use of three independent axes and true 3-D capabilities. To date, however, GIS has been firmly rooted in a two-dimensional abstraction of reality. Quasi 3-D approaches used in GIS, in which the third dimension is treated as a variable, should not be confused with true 3-D systems in which multiple attribute data may be recorded for any unique combination of three-dimensional space represented along three independent axes. Necessarily, real-time dynamic visualization of graphical images, solid volume rendering, mathematical modelling, and database management must remain important features in any 3-D system, but what is needed in addition is the fundamental common topology. Three-dimensional topology would permit spatial queries such as 'what is next to', 'what surrounds', 'what is above, below, to the side of', 'what is the value of the object at this location', and 'what are the relationships between this feature to surrounding features'. In addition, spatial analysis and 'what-if' modelling can also be pursued. In instances where multiple property values exist in three-dimensional space then 3-D GIS would be particularly apposite for archaeologists seeking to address the long-standing issues of how to handle multi-dimensional data which have both depth and temporal dimensions.

The development of software which possess the characteristics of true three-dimensional functionality has largely spawned out of the commercial world of petroleum and gas exploration (Fisher/Wales 1992; Raper 1989a, 1992; Smith/Paradis 1989; Turner 1989). Geology has substantive needs for three-dimensional capability especially for oil and gas exploration and reservoir analysis, coal seam modelling, hydrogeology, contaminant plume analysis, and hazardous waste site evaluation (Mahoney 1991; Smith/Paradis 1989; Turner 1989; Turner/Kolm 1991). Three-dimensional GIS applications in geology are also sometimes referred to as Geoscientific Information Systems (GSIS) to distinguish them from their 2-D counterparts (Turner/Kolm 1991: 217). The underlying needs of geologists has been to construct spatial models of continuous surfaces and to understand and model the spatial relationships between structural units and the interaction between them, as for example in the flow of fluids (Fisher/Wales 1992). Like archaeology, geology shares many similar needs with regard to portraying and analysing three-dimensional data from a variety of spatial data sources and seeking spatial relationships between stratigraphic units and features. Traditionally, geologists have relied heavily upon 2-D representations of subsurface features such geological maps, cross sections, fence diagrams, block diagrams, and isometric surfaces (Jones 1989; Kirk 1990). A three-dimensional interpretation of this data has invariably been inferred from combinations of these 2-D representations. Analytical capabilities and simulated 'what-if' scenarios have therefore remained limited. The development of software to digitally represent geological structure for oil and gas exploration has opened the door toward extending 2-D GIS capability into the realm of true 3-D.

Currently, there exist three basic approaches to representing multiple property data which vary continuously across a three-dimensional volume. These approaches are based on data structures using volumetric or geocellular methods (Jones 1989); surface piecewise patches welded by parametric polynomial functions (Fisher/Wales 1991); and triangulated tessellations (Belcher/Paradis 1992; Smith/Paradis 1989). For the most part three-dimensional GIS data structures have their counterpart in 2-D GIS representational structures. The move from 2-D planar to 3-D solid geometry is only now becoming possible because of the widespread availability of 3-D graphics software and the hardware needed to support 3-D graphical display. Three-dimensional capability adds considerable storage and computational overheads to GIS software and the continued development of more powerful computer architectures and 3-D visualization capabilities has contributed considerably to the growth potential of 3-D GIS.

The voxel data model, which provides the basis for Dynamic Graphic's Earthvision software, involves the 'spatial occupancy enumeration' of a cube or other regular polyhedral cell by an object (Belcher/Paradis 1992; Denver/Phillips 1990; Jones 1989; Pack/Bressler 1990). A voxel is defined as a rectangular cube bounded by eight grid nodes. In the 2-D GIS world this representation has its immediate counterpart in the 2-D raster data model. These representations may comprise a three-dimensional array of voxel centroids with associated attribute data, or an array which defines the exact region of space occupied by an object. Mathematical representations of property surfaces based on each grid node's value can be calculated using three-dimensional minimum tension algorithms.

Jones (1989) refers to the extensive storage demands of such data structures and their spatial inexactitude because of the dependency on the size of the regular voxel cell and the lack of precise spatial boundaries between objects. Such concerns have been levelled equally at raster GIS data structures, particularly in comparison with the vector data model alternative. In the same way that raster compression techniques such as run-length encoding and variable cell decomposition, such as bintrees or quadtrees, have been developed to overcome these limitations (Samet 1984, 1989; Shaffer *et al.* 1990), so too are similar techniques applicable to the 3-D data model. Thus the use of octrees, based upon the regular and recursive decomposition of voxels into homogeneous units, have been developed for 3-D data structures (Kavouris/Masry 1987). Octrees provide good addressing procedures which can be enhanced through the use of tesseral addresses (Diaz/Bell 1986). They also possess good set operation capabilities and the ability to integrate and link other types of volumetric data such as point, line, and polygonal-solid data (Kavouris/Masry 1987). Storing boundary data at minimal voxel resolution is, however, less satisfactory, though as Jones (1989: 23-28) points out the use of 'flat' voxels, vector octrees, and multi-resolution representations provide differing mechanisms to overcoming these problems. A number of geological applications have utilized Earthvision or earlier software versions for mapping subsurface mine fires (Vasilopoulos 1989), atmospheric applications, oceanographic studies (Manley/Tallet 1990), and petroleum resource analysis (Belcher/Paradis 1992; Fried/Leonard 1990; Lasseter 1990).

A second data structure approach has been to spatially define objects in terms of their geometry and boundary surfaces (Houlding 1988, 1989; Jones 1989). Three-dimensional component modelling, as utilized by Lynx Geosystems software, has been developed to meet the needs of the mining industry by defining extensive irregular seam deposits (Houlding 1989). Component modelling of solid shapes is achieved through combining 3-D solid modelling and geostatistics to define upper and lower stratigraphic surfaces. By using surface descriptions, component modelling seeks to overcome perceived boundary and data storage limitations of voxel-based models (Houlding 1988). The modelling process is based on establishing a set of triangular platelets in which plate vertices are obtained from known control points based on geological elevation and seam thicknesses (Houlding 1989). In the use of such tesselations, component modelling draws close comparison with 2-D Triangulated Irregular Network (TIN) tessellation methods. Plate thickness, size, and orientation are determined linearly along the axes defined by the vertices. Upper and lower seam boundaries record local variations in thickness and also define continuous and possibly irregular surfaces. Volumetric calculations are based on the triangular plate facets and seam thicknesses and irregular solids can be intersected volumetrically. Aggregated regional units can be constructed from the set of tesselations and the problems generated by discontinuities such as faulting are relatively easily handled by using control points at the seam-fault intersection. The complexity, variation, or even simplicity of a geological structure, can be captured by varying the density of the control points and by defining the specific control points which make up plate vertices.

A third approach, employed as one of their approaches to solid modelling by Intergraph Corporation, involves the construction of 3-D surfaces and solids through the use of mathematically defined surfaces. NURBS (Non-Uniform Rational B-Splines) can describe large complex surfaces by a single uniform mathematical form. The technique was originally developed to define large complex surfaces for use in the design of complicated machine and industrial parts (Fisher/Wales 1990, 1992). It has since been extended into medical and physical research. Since the same common mathematical method is used to represent all entities in the system, the functional integration of geo-objects, surfaces, defined solids, and attributes can be achieved. The method combines wireframe, surface, and solid modelling and has been largely explored in the context of geological applications (Fisher/Wales 1990, 1992). The basis for NURBS rests upon the use of low order polynomials to describe small, relatively simple, sections of a surface based on a series of known data values. The use of piecewise parametric polynomials overcomes many problems which arise from seeking to fit a global surface through all known data points: not least the problem of oscillations which arise from the use of higher order polynomials (Fisher/Wales 1992: 88). These low-order polynomial patches are subsequently 'quilted' and stitched together by the use of mathematical parametric polynomial B-splines. These splines also overcome patch edge irregularities and discontinuities by using control points near the edges of the patches to produce a smooth continuous surface along the 'knot' vector.

4 Three-dimensional GIS and archaeological stratigraphy

To demonstrate the potential capabilities of 3-D GIS for archaeological applications a series of 3-D archaeological structures, stratigraphical units, and relationships were explored using Dynamic Graphic's Earthvision software. The selection of a voxel-based minimum tension algorithm was initially perceived by the authors as being best-suited to meet the needs of archaeologists. Certainly the heavy focus of available 3-D GIS systems on geological applications, surface generation, and volumetric assessment was not initially considered to be fully sympathetic with the needs of archaeology. The voxel model was, however, viewed as more flexible in its potential ability to deal with the variety of archaeological phenomena although many of these decisions were based on preconceptions and have yet to be validated or dismissed. The decision was also made to focus in this paper on intra-site applications even though the use of 3-D GIS for inter-site archaeological applications promises to open up a significant research frontier which for reasons of scope will not be considered here. The Earthvision software comprises a number of interactive software libraries which enable data input, editing and manipulation, surface and volume modelling, grid and analytical operations, mapping, and 3-D visualization. Data input comprises x, y, z coordinates and property values. This varied according to the subject matter as to whether coordinates defined leading vertices along horizontal or vertical profiles of an object or were randomly distributed, as in the use of the bore-hole data. Minimum tension modelling was used to calculate a three-dimensional grid which formed the basis from which to define specific volumes or solids. In a number of instances the model was constrained in x, y, or z so that the polygonal solid matched the boundaries of predefined stratigraphic units. In this way the boundaries of certain units could be delimited where applicable by curtailing the influence of data values in adjacent layers or volumes. For example, in a number of instances the boundaries of certain volumes were forced to conform to the surface boundaries of units existing above or below the solid. In other cases the model was unconstrained and allowed for freely calculated, nonconforming boundary surfaces.

The examples used for this paper were selected primarily to demonstrate some of the basic capabilities of 3-D GIS. Studies of a more analytical nature which demonstrate the greater functionality of these systems are yet to be undertaken. Of greatest import in the following examples, over and above developing data encoding and modelling within the system, is the use of the real-time dynamic visualization capabilities available within the systems. We urge readers to bear these powerful capabilities in mind as the following examples are introduced.

In all, three examples are utilized to demonstrate the application of three-dimensional GIS to stratigraphic recording and analysis (shown as Figures at url: http://www.geo.wvu.edu/www/4dgis/welcome.html). The first example portrays a stratigraphic sequence representing a wall with associated foundation trench in which the wall subsequently collapses and is covered with extraneous debris. The example is taken from a standard and well-known text on archaeological excavation techniques (Barker 1994: 230). The Harris Matrix and exploded stratigraphic units were used to define the superpositional relationships and the units were reproduced within the 3-D system. The example, though simple in appearance, conceals numerous complexities in the way in which solid forms are constructed, classified, rendered, and displayed. The importance of visualization as an analytical tool is amply demonstrated when a series of these cut-away images are displayed and azimuth, perspective, and rotation are applied in viewing the solid geometry. The example demonstrates slicing capabilities in which layers or stratigraphic units are stripped away to expose other 'hidden' units, the surrounding undisturbed land has been 'removed' so as to expose the construction more clearly. The ability to peel away solids to reveal underlying solid geometry and unit relationships is further demonstrated in the following examples. Volumes for these units can be calculated, though again it should be stressed that these examples do not demonstrate the full functional capabilities of multi-dimensional GIS for these capacities are only slowly being developed. It should be borne in mind, however, that these stratigraphic units possess topological relationships which provide the basis for going beyond purely visual analysis to apply the full range of GIS functions in the third dimension.

The second example, also taken from Barker (1994: 228), is a section of Norman construction within Worcester Cathedral, England. The stratigraphy beneath the Norman structure is complex although within the software the spatial and temporal relationships between contexts are clearly visible from the cross-sectional views. As demonstrated before, the capability exists to remove undisturbed ground and surrounding contexts to reveal the intricate 'spatial footprints' of the holes, graves, and columns. In many respects, reconstructing structures and archaeological contexts as in the first two examples are among the more difficult features to reconstruct in a voxel-surface system such as Earthvision. The features are geometrically well-defined and solid-surface models must be forced to replicate these as accurately as possible. The interpolative capability of the system is thus constrained to operate within well-defined margins.

The third example is of a dataset representing the results of an area survey around a suspected Romano-British settlement (provided by James Dinn of Hereford and Worcester Archaeological Unit). Here the interpolative and visual capabilities of the system are fully employed. The data are based on a number of irregularly spaced bore-holes distributed across the site. The layers generated comprise present-day ground surface, Romano-British ground surface, a prehistoric ground surface, and three soil horizons, extending in total to a depth of over one meter. The 3-D interpolated surfaces are sliced and cut to reveal the spatial extent and the relationships within and between the historic landscape surfaces and the soil horizons. The dynamic representation of this data as slices are made in the X, Y, and Z planes provides a powerful interpretative capability. Furthermore, the ability to slice based upon a unit's value, or isosurface, contributes even greater understanding to the interleaving that existed between the historic surface features and recorded soil horizons. In addition to these horizons, phosphate and magnetic susceptibility readings were recorded indicating concentrations, or 'hot spots', of possible human and animal activity. Again, progressive slicing in the major planes as well as by isosurface, reveal fascinating insights into the complex three-dimensional patterns and relationships present in the data. The patterns revealed in the phosphate and magnetic susceptibility analyses can be correlated with the Romano-British and prehistoric ground surfaces. The dual representation of both depth and temporality is displayed well.

5 Conclusion

Given the limited analysis intended for these demonstration projects perhaps the most impressive capability to arise from the experience of encoding and building the 3-D representations lies in the importance of dynamic visualization. The ability to strip away surrounding materials and contexts, and to examine information within these volumes is an extremely valuable process. Unfortunately, this experience does not reproduce well within the constraints of image reproduction displayed here. The graphical interactivity of the system to rotate, change azimuth, to slice and view the stratigraphic units in x, y, or z dimensions or combinations thereof, to produce 'chairs', and to undertake a variety of other graphical manipulation, provided an extremely valuable aid to exploring and understanding the sequences displayed. Furthermore, one of the most valuable visualization techniques was the ability to strip away features and stratigraphic units based upon the value of the isosurface. Thus, for example, the Romano-British ground surface and its relations with other adjacent temporal land surfaces could be identified with relative ease as the surrounding surfaces were stripped away based upon their isosurface value. Similarly, the varying densities of phosphate or magnetic susceptibility could be identified based on the incremental stripping away of lesser or greater concentrations of surface values. The combination of these visualization techniques provided a very powerful interpretive user-environment and in their own right represent a major addition to the archaeologist's arsenal of tools.

Other reflections on the role of 3-D GIS for analysing archaeological stratigraphy are more mixed. This response is due in part to the limited analytical role afforded the GIS because, with the exception of the Hereford and Worcester study, the spatial relationships of the various contexts had been predetermined at an earlier point during the excavation and recording process. It is normal practice to record a context's stratigraphical relationships on-site and any subsequent analysis is usually limited to ordering those relationships to form the Harris Matrix. As a result, the spatial techniques enjoyed by users of 2-D GIS, specifically to buffer, overlay, cluster, classify, and to undertake spatial analysis, are available in the 3-D environment and yet their utility is likely to be very project specific and limited to intra-site applications. Where appropriate the power of the 3-D system for spatial analysis will be considerable, for example the ability to seek spatial relationships between artifacts at the intra-context level could be substantial. In other instances that utility will be more limited, certainly in comparison with the utility of the 3-D graphical tools, because of the nature of the excavation process itself. The full impact of 3-D GIS capability will certainly have to be evaluated beyond the current confines of an end of project analysis stage. The potential to develop linkages to the Harris Matrix would also appear promising, but again, if this is predetermined at the excavation phase then such capability is likely to be somewhat redundant. GIS capability to handle three-dimensional data is not far from being a reality and is likely to unleash many exciting and innovative avenues of enquiry for archaeologists. Though this paper has focused primarily on intra-site stratigraphy several other application areas in archaeology are apparent, not least in the extension to 3-D inter-site temporal analysis (Harris/Lock 1995). Such technological capabilities portend the possible enhancement, if not replacement, of traditional hand-drawn or CAD-generated plans and sections by three-dimensional GIS. Further development is clearly required to explore the functional capabilities of GIS, such as buffering, overlay, and networking capabilities, in the third dimension. A major constraint continues to be the age-old problem facing archaeologists to obtain precise recordings of archaeological phenomena whilst contending with the very real resource pressures which exist, particularly in modern rescue excavation work. Such financial exigencies, however, should not completely dampen the pursuit of innovative archaeological investigation.

note

1 For the figures, please refer to the CAA World Wide Web server on http://caa.soton.ac.uk/caa/CAA95/Harris/.

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