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Semantically Enhanced 3D: A Web-based Platform for Spatial Integration of Excavation Documentation at Alken Enge, Denmark

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ABSTRACT

The photorealistic and geometrically accurate 3-dimensional representation of excavations, provided by image-based modeling, has the potential to transform the process of excavation documentation, making it easier to share observations with other researchers. Paradoxically, however, spatial representation lacks the ability to convey archaeological interpretations. By example of excavations in Alken Enge, Denmark, this paper explores how a web-based 3D platform is able to facilitate the collaborative exchange of 3D excavation content and how the integration of spatial and attribute data into one common event-based data model may be advantageous. This includes enhancing the semantic value of field-recorded 3D models by segmenting the geometry using various techniques, such as 3D projections and machine learning. Accordingly, the paper demonstrates a framework for interactive 3D models, which includes attributed classification based on segmented 3D content correlated with traditional raster, vector, and textual data, delivering a spatially integrated platform for collaborative research.

Introduction

The promise of 3D photogrammetric field recording is currently out of alignment with archaeological practice. The photorealistic and geometrically accurate representation of excavations, provided by technologies such as Structure from Motion (SfM), has the potential to transform the process of post-excavation interpretation, making it easier to share observations with other researchers. Paradoxically, however, the spatial representation lacks the ability to convey archaeological interpretations, as existing solutions usually only provide surface geometry and texture. The advent of HTML5 and WebGL means that browsers can interactively render and manipulate 3D content, leading to a distinctly different approach to data management. The potential of online frameworks changes the file-based paradigm, which for decades was the premise for digital field recording. Not only are thousands of desktop databases, spreadsheets, and GIS tables a legacy we are forced to deal with; but more files are being produced every day. In addition, the increase of new file formats related to the spatial management of complex data such as 3D-data, challenges not only data archival procedures, but also affects the premise for collaboration. Rather than enforcing new standards for 3D content, this paper seeks to focus on the development of tools and frameworks for data management and exchange of 3D content. This includes the scientific augmentation of 3D representations through supervised segmentation and classification and harvesting of file-based field documentation.

By example of the excavations at Alken Enge, Denmark, this paper discusses how a web-based 3D platform is able to facilitate the collaborative exchange of 3D excavation content almost instantaneously and how such a platform, based on a philosophy of integrating all spatial and attribute data into one common event-based data model, may be advantageous to interpretation. This paper focuses particularly on how we may use custom algorithms to enhance the semantic value of field-recorded 3D models by segmenting the geometry. Accordingly, the paper demonstrates a framework for interactive 3D models, which includes attributed classification based on segmented 3D content correlated with traditional raster, vector, and textual data, delivering a spatially integrated platform for collaborative research.

The Photogrammetric Toolbox of Digital Archaeology—Going 3D

The growth of digital archaeology has introduced photogrammetry as one of the most promising additions to the archaeological toolbox, and it is evolving into one of many standard tools for archaeological field recording. In particular, the use of SfM is considered an affordable and efficient way of generating highly detailed, photo-realistic, and geometrically accurate 3D models for excavation documentation (Huggett and Guo-Yuan 2000; Pollefeys et al. 2001; Katsianis et al. 2008; Ducke et al. 2011; Dellepiane et al. 2013; De Reu et al. 2013, 2014; Dell’Unto 2014; Powlesland 2014; Forte 2014; Forte et al. 2015; Berggren et al. 2015; Dell’Unto 2016). Supplemented by laser scanning and precise measurements by differential GPS and total station with integrated GIS or CAD-solutions, it has the potential to provide everything archaeologists need in terms of accuracy and speed of acquisition. Nevertheless, it is frequently debated what exactly it is that photogrammetry, and 3D-recording in particular, offers in terms of revolutionizing excavation recording or even how
it contributes to the creation of new knowledge compared to more traditional recording methods (Hodder 2000; Losier et al. 2007; Berggren et al. 2015; Dell’Unto 2016; Forte 2014). Photographs as media—and digital photography in particular (Morgan 2016; Bateman 2008, 2006; Morgan and Wright 2018)—are comparable to the 2D-representations we know from traditional paper drawings, but inherently provide a more precise portrayal of the observed situation. Photographic evidence is, however, limited in its ability to carry the semantic annotations and classifications, which are used to convey the archaeological interpretation. Subsequently, recurrent use of photos and digital photogrammetry for field recording becomes a determining factor for the way archaeological documentation is used and managed. For instance, a fundamental facet is the acceptance that all digital documentation tends to be derived from something else. Consequently, rectified, processed, or digitized photos are something fundamentally different compared to a paper drawing—they are snapshots of the observed reality, yet require a level of manipulation in order to be useable for documentation. The clear advantage of a photo-realistic representation of an excavation is the way it strengthens the unambiguous distinction between observation and interpretation. This in turn requires that we are able to track and account for changes to data, and special attention is required regarding the management of digital excavation data. In a world of digital archaeology, photographic evidence may be considered one of the most essential assets for collaborative efforts. In particular, this is the case if we focus on the ability to share and discuss archaeological observations, rather than accepting derived interpretative delineation, which is the norm for archaeological GIS or CAD representations. It does, however, lead to a question of how photorealistic 3D-representations may improve or affect the collaborative preconditions, provided that a suitable framework for the exchange of data exists.

Archaeological visualization

Despite a series of 2D and 3D archaeological applications in the early 1990s, such as Hindsite (Alvey 1989, 1993), the interactive and collaborative potential of 3D visualization were not thoroughly addressed before the early 2000s, by which time technological developments had introduced 3D representations into archaeological fieldwork. In 2004, the VITA system (Benko et al. 2004) demonstrated a multi-user, off-site visualization system for archaeological excavations. This was followed by an increasing number of visualization as well as immersive and virtual reality applications (Bobowski et al. 1991; Mills and Baker 2009). Several of these tools had great potential, but were generally lacking in their ability to combine visualization capabilities with a solid database management system for spatial and stratigraphic data. In the last decade, two diverging trends have developed, which may be traced back to the methods by which excavation data is managed and produced. On the one hand there has been a focus on the possibilities of online infrastructures and the interoperability provided by the semantic web (May et al. 2008; Binding et al. 2008; May et al. 2012), while there has been a parallel focus on off-line, file-based desktop applications (Dell’Unto 2016; Katsianis et al. 2008). The latter are closely linked to the extensive use of GIS or CAD in the archaeological pipeline. Both trends, however, testify to a departure from basic dissemination of cleaned and synthesized data, towards an aim of more extensive on-site collaboration and metadata management.

Desktop 3D GIS

Geographic Information Systems (GIS) are traditionally and inherently 2-dimensional, and use various geographic projections to represent and visualize mapping to a sphere (Wheatley and Gillings 2002; Conolly and Lake 2006). Any 3D recorded or modeled content is traditionally represented in GIS using what is characterized as 2.5D or quasi-3D to simulate the appearance of being three-dimensional. 2.5D representations use, for instance, extrusion of Digital Elevation Models (DEM) or interpolation of elevation data to represent facets in a triangulated irregular network (TIN). In these cases, 3D-information is not an independent variable, and representations are subject to the same premise of 2D-projection onto a mathematical description of the globe. Having a true 3D-GIS-solution, however, provides for a non-predetermined visualization, potentially making the excavation process more reflexive and contextual (Berggren et al. 2015; Dell’Unto 2016: 309). This allows researchers to engage with field recording and spatial representations in novel ways and readress the archaeological record with new research questions. In practice, several archaeological projects now make use of the recent developments of 3D capabilities in ESRI’s ArcGIS—and in particular ArcScene desktop applications. With 3D Analyst extensions it is possible to directly import, visualize, and analyze 3D surface models in combination with more traditional vector and raster GIS datasets (Dell’Unto 2016: 311). This use of 3D GIS in support of archaeological interpretation has been employed at major excavations projects such as Çatalhöyük (Forte 2014; Forte et al. 2015; Berggren et al. 2015; Hodder 2000; Dell’Unto 2016), while its analytical capabilities for visibility analysis has been explored in ancient Pompeian houses (Landeschi et al. 2016). Other options are becoming available as open source projects such as QGIS, and GRASS GIS are also integrating true 3D capabilities, for instance through the use of voxel modeling (Liebworth 2008; Merlo 2016; Oreno 2013). Common to these solutions is the possibility to merge and visualize different data types. Instead of vectorizing using 2-dimensional surfaces, which is common practice when employing georeferenced drawings or orthophotos, it is possible to draw in 3D, using the 3D model as a canvas to which the delineated polygons will conform (Kimball 2014; Dell’Unto 2016). Without doubt, this affects the archaeological preconditions for collaborative interpretation by integrating traditional and innovative 3D practices, while increasing accuracy and realism of documentation; delivering a richer and more complete record.

Online interactive 3D

The inherent limitations of commercial desktop GIS, which also affects its collaborative potential, is the lack of interoperability, due to the need to install proprietary and expensive software. Recent advances in free open-source systems, such as QGIS with its database connectivity, geojson support, and Python API, offer high-level interoperability, while the introduction of industry standards as HTML5 and WebGL means that ‘being online’ is profoundly affecting the
preconditions for archaeological documentation, collaboration, dissemination, and visualization. This is perhaps most evident in the evolution of national sites and monuments databases, which were relatively early adopters in making data accessible for the public (Hansen 1992). Now it is usually not only to disseminate archaeological data online, but to include far more interactive and immersive access to data. Furthermore, the support by all major web-browsers for client-side scripting and hardware accelerated graphics, as well as cross-platform designs, means that complex spatial content is now available on devices ranging from smartphones to desktop computers. This is a technology which has already seen applications in other disciplines such as geology (Herzig et al. 2013) and palaeontology (Michaux et al. 2015), and has immense potential for archaeology.

The capabilities of 3D interactive visualization, now being exploited by archaeological institutions to present artifacts and cultural heritage, make extensive use of the services provided by companies like Sketchfab (https://sketchfab.com/museums) (Means 2015). However, for archaeological use, such proprietary services are often limited in their data integration capabilities, due to their generalized application without the essential requirement for customization of data integration. For such purposes, two archaeological projects stand out.

MayaArch3D (www.mayaarch3d.org) is a web-based virtual research environment for documentation and analysis of complex archaeological sites, which integrates 3D models of cities, landscapes, and objects with associated, geo-referenced archaeological data in a 2D/3D WebGIS (Agugiaro et al. 2011; Auer et al. 2014; Agugiaro 2014). It offers an innovative database and system architecture, which is one of the first examples of combining 3D models and traditional GIS online. Likewise, its vast analytical capabilities are commonly seen only in powerful desktop GIS solutions. The project focuses on the eighth-century Mayan Kingdom, and makes extensive use of WebGL and JavaScript for the visualization of 3D models while a PostgreSQL database with PostGIS extensions is used for storing both 2D geometry and 3D objects (Auer et al. 2014: 35). An interesting feature of the MayaArch3D is its capabilities for storage and management of segmented models, given that a segmented model is a prerequisite for embedding semantic information. By effectively annotating and classifying individual parts of a 3D model, its potential as an information-carrier approaches that of the archaeological drawing, while retaining the additional detail and realism gained from photogrammetric recording. The segmentation process is done manually by Maya researchers using a hierarchical system of semantic object classes and several levels of subclasses, and allows users to access elements of 3D models as individual features, rather than one continuous 3D surface, which we have otherwise become accustomed to.

Another project, which is proving its value by enabling web-based 3D capabilities and data repository integration, is the ADS 3D viewer (Galeazzi 2014; Galeazzi et al. 2016). The viewer is actually two separate instances: an Object Level 3D Viewer and a Stratigraphy 3D Viewer, each seeking to accommodate different user needs. The stratigraphy viewer allows the exploration of the sequence of layers in an archaeological stratigraphical representation, while the Object Viewer mimics much of the functionality of more general 3D implementations.

The ADS 3D Viewer (http://archaeologydataservice.ac.uk/research/3D_Viewer.xhtml) is built on top of the Archaeology Data Service’s data repository, and therefore demonstrates a strong link between visualization and data. The development represents a customization of the 3D Heritage Online Presenter 3DHOP (Pottenzian et al. 2015), taking advantage of its high level of detail compared to other solutions such as Unity or Adobe 3D. It also uses the Nexus open source library for multi-resolution and progressive loading, which is advantageous for transferring large quantities of mesh-data for client-side/browser 3D rendering.

Apart from the common navigation tools for rotating and exploring 3D models, the 3DHOP Viewer also offers tools for interactive illumination, distance measurements, and sectioning, providing valuable tools for collaborative exploration of data. The integration with the ADS Archive is achieved through 3D hotspots, which are clickable points in 3D space that allow annotation and links to relevant data records in the vast archaeological repository and grey literature at the ADS.

At present, a distinct difference exists between such online viewers, which are semantically linked to synthesized and harmonized archival data, and the requirements for an online infrastructure for visualizing ongoing field work documentation. Such data tend to be much more ad-hoc, derived, and intermediate. The common denominator is obviously the visual component, but for fieldwork it is inevitably much more closely linked to the documentation pipeline, and in the case of 3D photogrammetric documentation—the Structure from Motion workflow.

Alken Enge—A Structure from Motion Workflow

In 2012, Aarhus University in collaboration with Museum Skanderborg and Moesgaard Museum reopened the archaeological investigations of the Alken Enge wetlands in central Jutland (Hertz and Holst 2015; Holst et al. 2018). Alken Enge constitutes an area of almost 40 ha situated at the outlet of the Illerup River into Lake Mossø. The Illerup River Valley is world-renowned for its weapon sacrifice, comprising more than 15,000 artifacts, mainly weapons, dated 200–500 A.D. (Ilkjer 2002). Like the Illerup River Valley, Alken Enge was investigated during the late 1950s by archaeologist Harald Andersen as drainage work had unearthed significant amounts of finds; but unlike the weapons and personal equipment of an Iron Age army found further upstream, the Alken Enge site produced more than a thousand scattered human bones. Radiometric dating places them prior to the weapon sacrifice; in the first half of the first century A.D., yet the bones all point to young males, many of which had battle wounds, clearly pointing towards acts of war. The presence of post-battle bone trauma, as well as four human pelvic bones threaded on a branch has led to theories concerning human sacrifice and rituals in the aftermath of battle.

The very challenging excavation conditions were well known from the excavation in the 1950s and 60s (Andersen 1956) as they were excavating bog peat to a depth of over 2 meters and working below the water table of the neighboring Lake Mossø. As with any wetland excavation, it required technical solutions for controlling the water level while maintaining the anaerobic and humid preservation conditions. Furthermore, the stratigraphy of the different geological and archaeological deposits was extraordinarily complex. Reviewing the traditional paper documentation of the 1950s created concern that such methods were not able to convey a sufficient level of detail. Despite being remarkably meticulous and precise, even across large distances, Harald...
Andersen’s traditional recording did not fully account for the stratigraphic complexity and deposit sequence, nor did it clearly visualize the arrangement of human bones, scattered on the ancient lakebed. The paper documentation was generally limited to one or two plan drawings of each sector, with annotations of find numbers and levels of all bones and major pieces of timber (FIGURE 1A).

Having pioneered the development of digital photogrammetric documentation in Denmark in 2002 and 2003 at Skelhøj (Holst and Rasmussen 2013; Johansen 2003; Scollar 1998), followed by experiments with digital stereo photogrammetry for the creation of simple 3D models of complex data (TopCon Imagemaster), Unit of Archaeological IT and Aarhus University established a documentation pipeline and workflow, centered around the consistent use of photogrammetry based on SfM. This was in part inspired by the documentation and interpretation process at Çatalhöyük (Hodder 2000; Forte et al. 2015), while the introduction of SfM and the move to 3D was essential to accomplish digital photogrammetric recording under these circumstances. Traditional digital photogrammetry is limited to the geometric rectification of photos based on measured and georeferenced ground control points, which only works well on completely level surfaces. The situation in Alken Enge was far too complex and the large quantities of timber that had floated around in the prehistoric lake and river, and even in situ standing wooden structures, would protrude any level surface and result in distinct perspective distortions or ‘Escher-effects’ on all orthogonal representations (FIGURE 2).

From the outset, a combination of VisualSFM (Wu 2016) and MeshLab was employed to create textured 3D-meshes, which were then projected through a top-down orthogonal viewport with the purpose of generating a true orthophoto that could be georeferenced in ArcGIS using measured ground control points. Later, this workflow was enhanced and simplified using Agisoft PhotoScan and its built-in processing capabilities for generating geometrically true orthophotos. It is important to acknowledge that the primary argument for adopting 3D documentation in this case was the precise generation of 2-dimensional, rectified orthophotos, which could be used as a more detailed substitute for traditional paper drawings. Meanwhile, the ambitions rapidly grew to an evident concern about how to manage 3D data—and not least—how to put it to proper use and harness its full potential. Fortunately, the photo documentation workflow was kept consistent throughout the successive excavation campaigns, which meant that new ideas and more advanced processing capabilities could be introduced progressively and retrospectively.

The complex stratigraphy (FIGURE 3) did not encourage a single context approach (Harris 1989; Roskams 2001) as the hundreds of geological deposits and erosions, brought on by 2000 years of lake and river dynamics, were intertwined with organic material, branches, and timber. Furthermore, the oxidation of the peat resulted in almost instantaneous discoloring, making it impractical to excavate only one context at a time. Instead, by relying on the observations made by Harald Andersen in the 1950s as well as test pits in 2008 and 2009, a documentation strategy was established, aimed at documenting predefined levels, which were determined by the prevalent hypotheses (FIGURE 4).

**Conceptualizing a digital approach**

One of the main challenges of applying digital excavation strategies is factoring in the human equation. Archaeologists
are generally very fond of arranging field recording by way of numbers and lists, and it is an important part of manifesting how they think and work (Roskams 2001; Lucas 2011; Carver 2009; Carver et al. 2015). This way, every drawing, photo, sector, feature, context, stratigraphic unit, or find are assigned unique numbers that assist in organizing and relating the

Figure 2. A 2D-rectified excavation orthophoto, showing pronounced geometric distortions or ‘Escher-effects’ of protruding wooden structures (a). The same problem visualized through first-generation Google Earth imagery (b & c) (Google Maps, 2010; Chris Silver Smith http://www.nodalbits.com/bits/google-maps-fixed-escher-effect/).

Figure 3. Photomontage illustrating the difficult excavation documentation at Alken Enge and the complex stratigraphic sequence in the section profile.
individual elements of field recording. In a digital approach, however, this makes proportionally less sense, as the amount and different types of recorded data increase substantially; for instance the thousands of photos and control point measurements used for photogrammetry. Accordingly, a 3D model is something significantly different compared to a hand drawing; and is derived from a combination of many types of inputs. The immediate solution would be for the computer to keep track of numbering the documentation elements automatically. This procedure was evaluated during the test pits in Alken Enge in 2009, and resulted in a significant increase in human error. When employing an arbitrary number, human beings are much more likely to make mistakes, compared to when using a methodical naming convention. As a result, the digital approach at Alken Enge called for a naming convention of semantic numbering that would introduce a principle of spatial awareness at the level of human-computer interaction, while retaining a degree of machine- readability, which would allow for automated procedures for data processing. This is not unlike the aims of the KAP Recording System (Roosevelt et al. 2015), which seeks to provide a logical and internally consistent system of recording and managing spatial and aspatial information in a digital, 3D field recording pipeline. The KAP system uses a tripartite nested system of record identification, which includes area, spatial context, and sample IDs. At Alken Enge, concepts of Documentation Events and Data Collections were introduced in support of the collaborative efforts of many people working at the same place at the same time (FIGURE 4). This also addressed the derivative nature of digital data, and recorded the historic dimension of the documentation process (Jensen 2012; Holst 2013). Para and meta-data were explicitly contained within the documentation, and it was explicitly articulated how interpretations and visual representations evolve over time, as new data and new knowledge become available (Jensen 2018).

A square meter grid covering the research area was extended from the old excavation areas, and partitioned into sectors of 8 x 4 meters, corresponding to where trenches could be placed. The naming-convention conceived, was based on a hierarchy of Data Collections and Documentation Events. Starting from the origin of the grid, every sector was considered a Data Collection with its own unique D-number. The first digit being the relative sector position in the north direction, while the second digit shows the sector position in the east direction. The predefined levels would add intervals of 10, leaving room for inserting intermediate documentation levels when necessary. For instance, D1060 would translate to the sector immediately east of the origin, at level 6, which would usually correspond to the bone deposits on the lakebed (FIGURE 4). This proved to be an intuitive way of relating to the precise individual sectors and stratigraphical levels of the excavation, and provided a vocabulary for efficient communication between archaeologists. Furthermore, it provided an immediate validation of the numbers, as it could usually be deduced as a description of the relative location, rather than an arbitrary number. Within each Data Collection one or more Documentation Events would take place. Documentation Events were designated by the creation date in the format B[YYYYMMDDI] with the prefix B and a suffix [1], meaning that the complete identifier of an event would be something like D1060B20130615A. These events would usually encompass the entire pipeline of the documentation process, ranging from photos, measurements, processing, and vectorization, as well as the written record of archaeological interpretation and description. The outcome was an efficient way of keeping related documentation material combined and accessible for processing. The different Data Collections would act as containers for different visualization purposes and help users navigate the excavation both horizontally and vertically, and piece together minor documentation units to form coherent sections and plans; for instance one particular level or combination of sections. The individual sectors were excavated consecutively, providing main profile walls in an east-west direction at intervals of 4 meters, which could be correlated and allowed for hypothesis validation against the observed layers (FIGURE 4).

At first glance, it may seem irrational to be concerned with numbers and the designation of elements in a world of computers and digital archaeology. More than anything, it is likely to be a testimony to a limited archaeological methodology in the scope of computer-human interface, and how distinctions are made between human- and computer-generated data. Furthermore, what archaeologists assign numbers to, does not necessarily correspond to a physical or even spatial entity, which is why it is an extremely complex and sometimes
arbitrary relationship to model. With semantic numbering, the inherent risk of human errors while assigning numbers is reduced as the assigned identifiers include a conceptual and spatial component. When errors eventually do happen, the consequence is nevertheless greater as ‘meaning’ has been assigned as part of a unique number, and cannot easily be changed. However, if we are to interpret data, a vocabulary and designation of different elements are a fundamental requirement, and a necessity for collaborative discussions.

**3D Segmentation and Annotation**

As discussed above, the main motivation behind the early adaptation of 3D photogrammetric recording using either stereo photography and later SfM at Alken Enge, was the shortcomings of traditional photo rectification. Although flat surfaces are usually a core ideal of field archaeology, in reality it is virtually impossible to achieve, and the geometric distortions of having an uneven surface projected onto a 2D-plane are often considerable. Paradoxically, the target of flat surfaces contradict the whole idea of 3D documentation. Meanwhile, apart from the wow effect of having an interactive 3D-representation of the documentation, the adverse consequence of not aligning our documentation end-goal with the capabilities of 3D-recording means that the geometrically highly detailed documentation is often reduced to a 2-dimensional orthophoto, which may be vectorized and treated like a traditional paper drawing. This is for the most part how 3D SfM is applied to field archaeology at the moment—as a tool for creating very precise distortion-free documentation photos. It worked very well in Alken Enge. However, it also meant not dealing with 3D documentation on its own terms. Three objectives were defined, targeting explicitly the inability to exploit the full potential of the 3D representations.

Firstly, the development of a flexible solution for integrating archaeological interpretation and 3D geometry was considered the main challenge, and the lack of dedicated software, which allow for embedding classification data into the 3D-models was regarded as a severe limiting factor. By segmenting the geometry, and splitting it into its constituent parts corresponding to individual archaeological entities, an enhanced level of interaction with field-recorded 3D models as well as augmented semantic value could be achieved. Secondly, an integrated database was needed, which could hold not only the 3D data and its associated classification data, but also provide para-data tracking associated with the documentation pipeline, using the data model principles of event-based recording. Thirdly, an online infrastructure for textual as well as spatial data was needed to accommodate the cross-disciplinary exchange of data and collaborative interpretation.

The digital documentation produced at Alken Enge followed a predefined pipeline involving a number of teams, each responsible for individual steps in the process. Documentation Events of varying size, which by function is very similar to the more traditional concept of Stratigraphic Units, were excavated by trowel and photographed for SfM processing using ground control markers, which were measured by total station. Within half an hour, an orthophoto was generated, printed to scale on paper, laminated, and used in the trench for delineation and interpretation by the archaeologists. This process was later streamlined and made more efficient using High Performance Computing (Stott et al. in press). The orthophoto sketch was eventually scanned, georeferenced, and vectorized using ArcGIS. To efficiently manage the incoming data, the documentation hierarchy of Data Collections and Documentation Events was recreated as a folder structure on a file server, and all related and derived files were organized accordingly.

**Ortho-projection through Point-in-Polygon**

The 3D content was stored in its native proprietary file formats (mainly Agisoft PhotoScan project files), and finally exported to open ASCII .ply Stanford Triangle Format with associated bitmap texture in .png format.

Having GIS vector data representing the archaeological interpretations, as well as 3D models, offered an opportunity to use the vector polygons to embed archaeological classification into the 3D models themselves. This process was in part inspired by the work by Wulff and Koch (2012), who demonstrated methods for projecting each triangle in a 3D mesh into a vectorized drawing to determine the archaeological entity to which it belonged, thereby segmenting it into discreet elements. For the Alken Enge project a Python script was developed to automatically parse the 3D model. Instead of triangles, it would match each 3D vertex of the mesh against the polygons in the ArcGIS Shapefile. The algorithm used, was a simple Point-in-Polygon routine, which would efficiently segment the mesh into individual .plys for each polygon, named according to the attribute identifier from the GIS-data. Accordingly, all vector-color data, face-indices, and texture coordinates were retained and transferred (FIGURE 5A).

The segmentation process is not limited to top-down projections, and in the case of Alken Enge, where vertical sections were used extensively to keep track of individual layers and stratigraphy, a combination of local 2-dimensional coordinate systems were used to project vectors onto vertical sections. An interesting observation was made, during the first tests of Point-in-Polygon segmentation by 2D vectors on the Alken Enge excavation data. There was excessive focus on segmenting the 3D model according to the individual finds, such that the actual surface on which the finds were placed was almost overlooked. However, it also needed segmentation. For practical purposes, any such ‘background’ or surface mesh would usually be much larger than any segmented find, and it was decided to simply segment any geometry, which was not inside a polygon into 1 square-meter blocks, so that they could be managed and loaded, alongside the segmented objects, at a comparable speed.

**Mesh normal vector refinement**

Due to the nature of projecting an orthogonal vectorization onto a 3D surface, there are some noticeable limitations to the segmentation process, which were also identified by Wulff and Koch (2012: 95–96). The main issue concerns how protruding objects or convex sides may inadvertently be segmented alongside neighboring entities as a result of the 2-dimensional projection. One positive thing is, however, that in working on surface geometry as produced by SfM, overlapping geometry within one Documentation Event is relatively rare. Furthermore, it is possible to employ the face-normal-vectors—i.e., the ‘way’ each triangle in the mesh is facing—to identify sections, which are perpendicular to the orientation of the projection and use them to refine...
each segmented object. The face-normal-vector may be progressively computed by its three vertex coordinates as part of the segmentation process, or derived from the original ply (FIGURE 5B).

Voxel envelope and support vector machines

Whereas both of the above use the archaeological interpretation as a starting point for the semantic segmentation, another option is to turn the process upside down. This means allowing the computer to suggest archaeological entities on the basis of predefined criteria for geometry and texture.

One solution is to convert the surface geometry into a volumetric model. By generalizing the model into a voxel matrix, of a fixed value of for example 1 cm, it is possible to make continuous sections through the model, and identify closed loops, which correspond to physical entities protruding from the surface, and refine the proper extend for a 2D vector representation (FIGURE 5C).

Another option is to employ Support Vector Machines (SVM), and disregard geometry as the defining basis for segmentation altogether, and instead focus on color and texture. For SVM to work, a training dataset is needed, but due to their heterogeneous appearance, the human bones from Alken Enge were not the best subject for this procedure.

The vertical sections with hundreds of layers, reflecting the sedimentation sequence in the wetlands, are however characterized by some distinct differences, as are the postholes which penetrated the sandy lakebed. A combination QGIS using LibSVM and OpenCV through the Monteverdi and Orfeo Tool Box plugins allows the use of existing vectorizations in combination with orthophotos to segment flat geometry on basis of feature or context color and texture (FIGURE 5D). In both cases, a starting point with machine assisted processes for the segmentation and classification of features is an interesting basis for collaborative evaluation and analysis.

Fragmented Reality in a 2-Dimensional Representation

The Alken Enge project involved a number of interdisciplinary scientific partners with individual aims of analysis, who would feed into the overall questions regarding the site. For example, how were the deposits created and what is the context of the prehistoric landscape, what had happened to the human bones, and were the people local or foreign? Additional overarching methodological questions regarding the dynamics of water levels in a wetland area in terms of preservation conditions and decomposition of organic artifacts were also in focus. All these aspects have a geographic and spatial component, as is usually the case with archaeology. However, the various disciplines also applied different methodological approaches to scientific questions, and, in turn, an array of different tools and procedures. Consequently, the project faced a challenge in dealing with data fragmentation. This was particularly the case when working with desktop GIS, which produces a multitude of intermediate and supporting files for each dataset and with SfM, which takes hundreds of input photos. To accommodate this variety, Documentation Events were defined for each individual data contribution, including information and metadata describing the method of analysis and software used. During the excavations, an interesting observation was made regarding the workflow, which relates directly to what may best be described as a paradigm of file-based thinking. Archaeologists have become accustomed to using primarily desktop applications for doing digital archaeology, and the conflation of spreadsheets, photos, GIS, and CAD tables all contribute to a workflow, which is of limited flexibility. In terms of collaboration, this also means that infrastructure in support of file-sharing becomes a priority, but leads to a discontinuity where data very easily becomes fragmented. When it comes to the 3D content, another level of discontinuity exists, which relates to the human-computer interface being almost exclusively 2-dimensional. We interact with a 3D model, through a...
2-dimensional projection onto a computer screen, and conversely, we aim to shape 2-dimensional surfaces by trowel and shovel in the real world, which may be visualized by the available tools. As more online solutions are introduced to the documentation pipeline for data entry and recording, and more immersive means of human-computer interface become available, one cannot help to speculate how this online thinking will affect the workflow; but also what it means for 2D vs. 3D archaeological thinking (Benko et al. 2004; Eve 2012).

Having immediate access to an interactive online 3D representation of an ongoing excavation has far-reaching implications. Not only does it affect the collaborative preconditions of archaeological fieldwork, but it is associated with a paradigm shift in archaeological recording, represented by the adaptation of fully digital methods, workflows, and data (Berggren et al. 2015; Roosevelt et al. 2015). A web-based 3D platform facilitates the exchange of knowledge, for instance between archaeologists and geologists, regardless of terminology and tradition, and instead focuses on the photo-realistic and geometrically accurate visual representation, and the individual researcher’s perception and interpretation thereof. It helps archaeologists account for depositional sequences and stratigraphic observations while the excavation is on-going, and provides an immediate three-dimensional spatial context to all finds and features. All observations, interpretations, and derivatives go together in one internally consistent management system, which reflects the excavation process and the iteration of hypotheses, and which is accessible globally.

**Database and scraping**

For the Alken Enge project, an online database was developed and used for direct data entry in the field. At the time of the excavations, the requirements for managing 2D and 3D content were ambitious enough that it was regarded too complex to achieve by a purely web-based solution. Development therefore began of a cross-platform client application with an online PostGIS enabled PostgreSQL-database, compiled for both Windows and Mac computers (ArchaeYA). It had a Python 3.4 core and used Qt5 support libraries for the user-interface and OpenGL rendering. During development it became clear, however, that a dedicated desktop application, was not necessary to fulfill the requirements of 2D and 3D navigation. These criteria could be met using HTML5 enabled browsers and JavaScript instead. ArchaeYA was replaced by a solution—Archeo (Jensen 2017a)—which included a flexible custom-built user-interface, resembling the original client application, but written in PHP with a MySQL database back-end. The database is subsequently undergoing continuous development and being repurposed to suit other projects’ needs. PHP was chosen based on its open source philosophy, availability, and support from almost any webhosting company, while MySQL was also chosen for its support for geometry data-types. Consequently, all field recorded observations regarding finds and contexts were immediately available online, while associated GIS-data would be uploaded to the database as Well-Known-Text (WKT), following open standards and best-practices for archiving (Archaeology Data Service 2015). The hierarchy of Data Collections and Documentation Events was recreated as a folder structure on a file server, while a Python script was developed to act as a scraper. The ArchaeoScraper module will iterate through any folder structure, and build SQL insert statements on the fly, based not only on file contents, but using the folder hierarchy and naming conventions to insert the required relations between database records:

Different folder structures, naming conventions and file types are treated according to one of several predefined XML schemas. GIS vector files are interpreted and transformed from any native coordinate system using proj4 libraries to a common web-friendly WGS84 projection (EPSG: 4326). All JPEG photos are furthermore parsed for embedded EXIF-data regarding exposure, focal length etc. The 3D content based on ASCII .ply files with associated .png bitmap textures, is also parsed and added to the database as JSON-data, including vertex, face, and normal data as well as texture-coordinates. Finally, database records are inserted for each segmented 3D model, and appropriate database relations are created to ensure database integration between not only 2D vector data and 3D models, but also the textural classification data.

For practical purposes, a transformation was applied to all coordinates, effectively shortening them. This made for more efficient storage and helped avoid problems when visualizing using a GPU, with limited floating point precision, which would result in ‘blocky’ geometry. Finally, the script creates a checksum calculation for any interpreted file, and adds it to the database as a reference to the source file, meaning that it is possible to trace back any scraped data to the original file.

The scraper effectively combats the data fragmentation brought forth by the file-based documentation, and furthermore allows different collaborators to work with the tools they usually do. For instance, almost any GIS, CAD, and 3D software may be used to generate documentation data in a file-based folder structure, as long as it is done according to a well-defined schema of folder structure and file types for harvest by the scraper (FIGURE 6).

**An online 3D viewer for segmented data**

The most obvious advantage of a web-based database and 2D/3D viewer is perhaps that, unlike desktop applications, which require software installation of required dependencies on the user’s computer, JavaScript APIs are loaded alongside the web page, and the necessary code is executed on the client browser, without the need for any pre-installed browser add-ons. The Archaeo 3D viewer takes advantage of the open source three.js JavaScript APIs, which provides a wrapper for all the common OpenGL functions. Using the database Documentation Events, 3D data is loaded directly from the MySQL database to the client browser as JSON text, where it is parsed and combined to build renderable, segmented 3D models. Using WebGL for visualization of 3D models does however have some implications, as pointed out by the MayaArch3D project (Auer et al. 2014). It relies exclusively on the client browsers JavaScript engine to interpret and execute the code, and client computer hardware and—not least—network speeds quickly become a limiting factor, when transmitting the millions of vertices, face indices, and texture-coordinates, which make up a 3D model. Contrary to desktop applications, browser JavaScript has limited memory management, meaning that it is very easy to completely deplete all available memory when loading large or complex 3D scenes.
The 3DHOP-Viewer addresses these limitations by utilizing the Nexus file format for transferring 3D data (Ponchio and Dellepiane 2015). It allows for progressive multi-resolution loading, which means that the 3D model is rendered in increasing detail before the entire file has been downloaded to the client. In the case of the Archaeo 3D viewer, the 3D models are queried and transmitted as segmented elements, giving the appearance of progressive loading as each part is rendered as soon as it is transferred. Furthermore, the use of asynchronous loading through JavaScript effectively allows for more segments to be downloaded simultaneously. A segmented mesh of around 250,000 vertices, including texture bitmap is usually completely downloaded in less than 10 seconds, which is an acceptable speed for most uses.

Unlike the ADS 3D and MayaArch3D viewers, the Archaeo 3D-viewer does not explicitly distinguish between archaeological objects/finds and stratigraphy, but allows for the segmented data to be accessed as either. Due to its special attention to the photo-realistic excavation documentation, it is targeted at the visualization of Documentation Events. This also means that the user has an option to choose to either display 3D objects as individually segmented objects or as part of a larger documentation unit. Different 3D representations of the same element are therefore accessible independent of the entire 3D Documentation Event to which it belongs. It does however have the adverse effect that individual segments load at very different speeds, according to their complexity, i.e., number of 3D primitives (vertices, faces, etc.).

Compared to the ADS 3D Viewer, which makes use of clickable hotspots to provide the linking to associated data, the Archaeo 3D-Viewer provides a different level of semantic classification, as each individual segment is directly selectable from the mesh. This has the clear advantage that it resembles the way people are used to interact with 2D vectors in GIS and CAD—much like selectable polygons, but may not be as intuitive as visible hotspots are—depending on the target audience. It does, however, provide an integrated link between 2D GIS-data and 3D model-data as well as semantic classification, all in the same data model, and it is possible to overlay the associated segmentation vector onto the 3D-model, visualizing the para-data surrounding the segmentation process (FIGURE 7).

**Combining 2D, 2.5D, and 3D**

The combination of 2D and 3D in a web GIS solution for archaeology is rare, but has been realized by MayaArch3D for instance (Agugiaro et al. 2011; Auer et al. 2014; von Schwerin et al. 2013, 2016). One of the more elaborate projects uses semantically structured 3D models for archaeological site management at Pompeii (Apollonio et al. 2012), while Auer (2012) has demonstrated the analytical capabilities of WebGL-based web GIS.

The Archaeo database employs the open source leaflet.js JavaScript libraries for visualizing 2D components; mainly GIS-derived vector data. This provides for a lightweight, flexible, and customizable mapping interface, which integrates not only web-service background map data (WMS and WFS), but allows for spatial queries into the 2D geometries in the MySQL database. Another challenge was highlighted by the extensive use of soil sections at Alken Enge by both archaeologists and geologists. It was a challenge, which is easily overlooked and leads back to the legacy of archaeological 2-dimensional methodology, namely how to manage vertical sections.

Vertical sections are commonly featured as separate datasets, detached from the rest of the spatial documentation—this applies to both traditional analogue drawings and GIS. The 2-dimensional projection, which is perpendicular to the usual top-down projection is incompatible with any GIS projection, and is therefore predominantly managed as separate datasets in local, vertical coordinate systems. The necessary information is, however, usually available to perform a scientific augmentation of the 2-dimensional profile sections, and arrange the sections in their proper place and orientation in...
3D space, albeit as flat 2D-surfaces. The same applies to both 2D rasters, such as orthophotos and 2D vectors. In the case of georeferenced orthophotos, a GIS world-file will usually contain information about proportions, while the associated GPS or TPS-measurements provide the necessary data for placement and orientation. The properties (origin/orientation/scale), which are automatically harvested and derived by the ArchaeoScraper, and used to automatically ‘raise’ and unwrap the 2-dimensional profiles at their proper location in 3D-space (FIGURE 8).

Conclusions—The Collaborative Potential of Online 3D Frameworks

As a case study, the Alken Enge excavations are atypical in terms of the type and complexity of archaeological and geological deposits. In fact, excavation complexity is often the primary rationale for employing an SfM workflow; for instance at recent excavations at Star Carr (Milner et al. 2013) and Çatalhöyük (Berggren et al. 2015). For the more ordinary excavation situations, i.e., large-scale surface recording of soil features and postholes, the stratigraphic
component is less complicated and the use of 3-dimensional documentation provides limited extra information. The consistent use of photogrammetry should, however, not be understated as its visual constituents offer unique collaborative capabilities—3-dimensional or not.

In the case of Alken Enge, the interdisciplinary collaboration between archaeology and geology was very rewarding in terms of understanding and discussing how different events in the past led to the creation of individual stratigraphic sequences, but also in recognizing how individual scientific disciplines approach the same material evidence differently. In particular, the divergences between an archaeologist’s and a geologist’s interpretation of a soil section, and how differing professional traditions shape the documentation outcome, became very apparent. Archaeologists focus on evidence of human activity, while geologists are looking for physical processes. In either case, documentation and interpretation is a matter of identifying the abstract notion of something, which is not necessarily a physical entity like an object or artifact, but a context of some previous human action or natural event (Jensen 2017b; Madsen 2003). For the purpose of recording these observations in their entirety, we may make use of online frameworks as more than dissemination outlets, and accommodate documentation of the entire process of knowledge creation.

In practice, the use of Documentation Events demonstrates the kind of real-time collaboration which online 3D visualization makes possible. In particular, it offers the virtual presence of researchers, who are physically distant, but who are able to give their informed opinion, based on an interactive 3D-visualization, while an excavation is ongoing. Thus, different versions of the same 3D-documentation are submitted and correlated, but segmented and annotated individually according to different interpretations. There is no one ‘real’ interpretation, but a series of Documentation Events, which provide input to a common Data Collection.

The combination of online frameworks and photogrammetric 3D documentation also has implications for the more general excavation methodology. While the majority of excavations adhere to some level of single context archaeology, the use of Documentation Events acknowledges the subjectivity of archaeological interpretation, and the fact that hypotheses should not be set in stone, but be open to re-interpretation and used to guide the excavation progress. A consequence of traditional single context recording is that individual archaeological features easily become ‘locked’ into the concept of a stratigraphic unit, which is fixed in time and space, and documented only once, before it is removed to reveal the next context in the sequence. Furthermore, 3D photogrammetric recording tends to include more than the archaeological context itself, such as any artifacts and surrounding or protruding features, simply because they are ‘part of the scene.’ Thus, the Documentation Event allows for the same object to be documented several times, which may be used to account for any physical decay or movement of objects engineered by the excavation process itself. The clear advantage of having an infrastructure for visualizing 3D documentation is the ability to visualize not only any matrix of stratigraphic units or documentation events in their proper vertical sequence, but it also acts as a tool for documenting the excavation process itself, and how it impacts the archaeological features. Being such an affordable and time-efficient way of doing field recording, SfM provides far better conditions for documenting the process, in particular, the observations made in the intermediate stages between stratigraphic units and while excavating one context in preparation for the next. This way, observations which would usually not be recorded or considered too time-consuming to draw by hand, become part of the bulk photogrammetric evidence.

The online infrastructure facilitates data-entry in the field, and having both 2D GIS and 3D photogrammetric interactive visualization capabilities on the same platform delivers immediate accessibility in support of cross-disciplinary and collaborative research and knowledge exchange. An added benefit is the data accessibility, which allows for data reuse. In the case of the Archaeo framework, the augmented semantic value of having integrated textural and spatial components provides the means for far deeper queries based on archaeological classifications, compared to ordinary GIS attribute tables, and users are encouraged to use the online search functions for the purpose of exporting data to be reused and analysed in other contexts under an Open Data Commons Attribution License. A hitherto unexplored potential of the Archaeo framework is the combination of the segmentation of 3D models with the semantic web and its possible use of crowd sourcing. The 3DSA: Semantic Annotations for 3D Artifacts, for instance, does exactly that, and use crowd-sourced semantic annotations to streamline the cataloguing of 3D museum artifacts (Hunter and Gerber 2010; Yu et al. 2011). Having an online framework, which is focused on visualization and interaction, it is possible to take advantage of the contributions of citizen science. Not only will this aid in the scientific augmentation of legacy data, but assist professional archaeologists in working through an increasing amount of recorded visual data. As the scientific and digital revolutions change the basis for archaeological knowledge creation, the act of observation—and potentially re-interpretation—is moved from the physical trench to the online visualization.

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Bibliography


Archaeology Data Service. 2015. “Digital Antiquity Guides to Good Practice.” http://guides.archaeologydataservice.ac.uk/g2gp/LaserScan_3D.


Amsterdam: Pallas Publications.


