3D DIGITAL RECORDING: BASICS

Seta Štuhec (University of Ljubljana)

TERMS

3D model

A digital three-dimensional (3D) model is a digital representation of the 3D geometry of an object. The three geometrical dimensions are usually represented in a Cartesian coordinate system with three perpendicular axes: X, Y and Z (in most 3D software environments, the latter represents the depth). Such a virtual environment enables viewing of a 3D model from all possible directions, rotating the 3D model, zooming, creating cross-sections, measuring and other operations. The 3D surface geometry can be constructed and represented in several ways, the most common ones being Non-Uniform Rational Basis Spline (NURBS)-based, SubDivision surfaces (SubD), T-splines-based and polygon(al) meshes (also called mesh or polymesh) (Figs. 1-2).

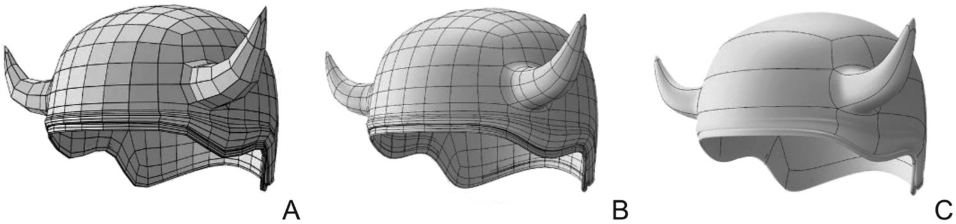

Figure 1. 3D model surface types: A: mesh-quads, B: mesh-quads, smoothed, C: NURBS. (Available at: https://andrewevs92.wordpress.com/2012/11/19/127/).

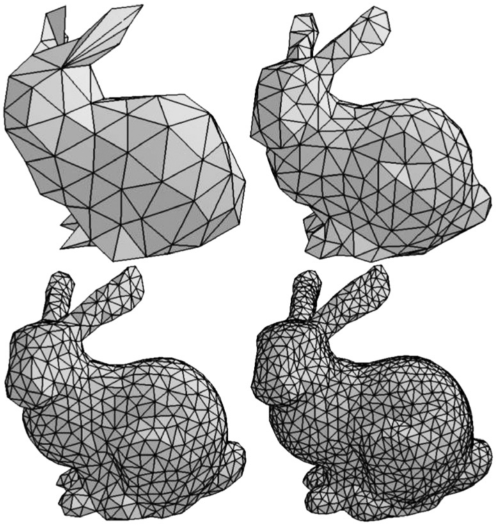

Figure 2. 3D mesh-triangles with different resolution (3D Modelling for programmers. Available at: https://cathyatseneca.gitbooks.io/3d-modelling-for-programmers/content /3ds_max_basics/3d_ representation.html.

The 3D polygon mesh model consists of linked polygon facets (also known as faces) that represent 3D surface of a specific form. The line segments that link the faces are called edges, and the point where the edges meet is called vertex (Tobler, Maierhofer 2006). The polygon models are most commonly constructed of triangular (tris) or quadrilateral (quads) polygons. Therefore, a single triangle consists of a triangular face, three edges and three vertices, whereas an additional vertex and an edge are needed for a quad. Polygons that consist of more vertices and edges are called *n*-gons, where *n* represents the number of vertices. Because such mesh-based representations are suitable for fitting noisy data (Ilic 2005), and their use is also flexible and efficient for various processing steps (such as simplifications, smoothing, etc.), meshes – in particular triangular meshes – are normally used to model surfaces that are acquired by 3D laser scanning and image-based 3D modelling. Additionally, polymeshes can also be constructed from scratch in several 3D modelling software packages used for 3D animations, video games, films and (re) constructions.

Important aspects of every 3D model are its colour and texture. The colour information for each face in a polygonal 3D model can be stored per vertex. This discrete colour information is afterward interpolated to represent the colour of the complete face. On the other hand, the texture is created by assigning a texture coordinate to every vertex and then projecting the 2D images onto the 3D geometry. Although polymeshes are ubiquitous in the 3D world, NURBS forms the standard mathematical model used by modern Computer-Aided Design (CAD) systems to model 3D curves and surfaces. NURBS can present complex surfaces that are completely smooth. As such, they have become the standard in industrial 3D modelling and reverse engineering industries (Danaher 2005, p. 156). Presenting an object such as a piece of ceramic vessel, with many small details, can, however, be very problematic with NURBS. This means that polygonal meshes are still preferred for the majority of cultural heritage objects.

3D modelling

When browsing through the literature, one finds many terms that refer to the creation of 3D models. Unfortunately, these terms are not used consistently and can cause confusion among researchers. Therefore, we are going to define the terminology of 3D model creation as it is used in the present book. The term ‘3D modelling’ is defined as a general term for the digital creation of a mathematical visualisation of an object in three dimensions (Vaughan 2012, p. 4) and does not imply how exactly the 3D model was created.

3D digital documenting/digitisation

‘3D digital documenting’ or ‘digitisation’ refers to the recording of a physical object in three geometrical dimensions. There are several techniques available that allow us to digitise existing objects. They can roughly be divided into two groups: active and passive techniques. Active techniques emit radiation onto an object in order to measure it. These techniques are normally referred to as 3D scanning. Following this definition, total station is also an active 3D recording instrument that could be used to create a 3D model of an object, but since it measures only one point at a time, it is too time-consuming to create high-resolution 3D models from the data. Passive techniques, on the other hand, do not emit any electromagnetic radiation. The most commonly used one is image-based 3D modelling that allows the construction of a 3D model from a set of overlapping images using the principles of photogrammetry and computer vision.

3D digital reconstruction

The term ‘3D reconstruction’ is often confused with ‘3D digitisation’, a confusion which most likely originates from the technical perspective. In the fields of photogrammetry and computer vision, reconstruction refers to the creation of light rays and their intersection with the physical object at the moment of capturing the image. In this sense, 3D reconstruction means re-creation of an object (in a digital way) using the imagery at hand. Notwithstanding this, the term ‘reconstruction’ is well-established within the cultural heritage field and refers to the virtual re-creation of a complete object or scene in order to show how it looked when it was originally created (ICOMOS 2013). Therefore, 3D digital reconstruction, as described in this book, refers to 3D virtual modelling of objects or parts of objects that do not (or no longer) exist. Such 3D models can be constructed from scratch in a 3D software environment, or can use data created by 3D digitisation and other techniques (geophysical survey, etc.) as a basis for further reconstruction.

A BRIEF HISTORY OF 3D DIGITAL RECORDING IN ARCHAEOLOGY

3D recording is not a new phenomenon in archaeological documentation. Since the ‘birth’ of photogrammetry in the middle of the 19th century, its principles were first used by aerial archaeologists in the 1920s to map larger areas (Fryer 2001). Later, from the 1960s onwards, archaeologists started to use photogrammetry to document archaeological excavations (Whittlesely 1966), mostly using low-altitude aerial images acquired from the top of poles and ladders. Photogrammetric processing at that time was based on analogue stereo images that were observed through a stereoscope to get the notion of the third dimension. Only after the so-called digital revolution in the 1990s, digital photogrammetry gradually took over and some techniques slowly merged with the research field of computer vision (Štular, Štuhec 2015). The development of the latter is to be situated in the 1970s and originates in the field of robotics and artificial intelligence whose task, among others, was to give a computer the same vision and understanding of a scene as in humans. At first, the task did not seem too challenging but, in the attempts at solving it, a new research field emerged (Szeliski 2011).

Although the discipline of computer vision currently covers a broader area than the sole extraction of 3D geometrical information, it has always been an important part of it. Gradually, certain computer vision techniques – which were always tailored toward speed – started to be combined with photogrammetric concepts and algorithms, for which accuracy has always been the main aim, that is – to extract reliable image-based 3D data rapidly (Cooper, Robson 2001). Nonetheless, it was not until the late 2000s that comprehensive, intuitive and cost-effective software packages and online services became available. Because of these software characteristics, image-based modelling quickly became a part of the standard archaeological 3D documentation workflow and has, in the course of this decade, superseded the 3D scanning techniques that were actually the first to hit 3D digitisation market.

3D scanners were, in fact, known already in the late 1960s, but 3D laser and structured light scanners as we know them today appeared later, in the 1980s (Štular, Štuhec 2015). Several private companies offered their 3D scanning services for the benefit of archaeology in the 1990s, but archaeologists themselves only started to use this method in the mid-2000s (Koller et al. 2009; Doneus, Neubauer 2006) when the equipment became easier to afford and use. However, at present, majority of 3D scanners can still not be considered cost-effective in most archaeological situations and are, therefore, as mentioned before, gradually superseded by image-based 3D modelling. Obviously, both techniques have advantages and flaws, and the superiority of one technique over the other is mostly related to the type of archaeological remains one intends to digitise. Although cost-effectiveness is not the only factor to be considered, it certainly plays a very important role when choosing a 3D documentation technique.

The first papers on the use of 3D in archaeology appeared at the Computer Application and Quantitative Methods in Archaeology (CAA) conference already in 1974 when L. Biek published his first in a series of several papers on LERNIE, the interactive and visual system that was to be used to record and analyse archaeological remains. His contribution contained photogrammetric approaches, animation, ‘video’ documentation, etc. (Biek 1974, 1976, 1978; Biek et al. 1981; Biek 1985, 1986). Soon after, active 3D digitisation techniques began to be used in archaeological documentation. One of the first examples is the 3D digitisation of a medieval moated site Mathrafal in Welshpool, Wales using the total station (Arnold et al. 1989). However, it was not until 1991 that 3D techniques, in general, received more attention, and the whole field of archaeological 3D applications got its own umbrella term. In his paper on photogrammetric digitisation of the Roman temple in Bath, England, P. Reilly coined the term “Virtual Archaeology” and thus laid the foundations for a whole new discipline (Reilly 1991). The early virtual archaeology applications of the 1990s covered 3D documentation as well as the use of 3D reconstructions for museological purposes. Some of these studies were compiled in the book

"Virtual Archaeology. Re-creating ancient worlds" (Forte, Siliotti 1997). Soon after, 3D models started to be used as a research tool (albeit to a very moderate extent, see below). Among the first of such efforts was the attempt to create a system of automatic pottery classification (Menard, Sablatnig 1996).

One of the first larger projects completely dedicated to the use of 3D in archaeology was called 3D MURALE. The project was aimed at the creation of a tool for recording, inspecting, reconstructing and visualising all kinds of archaeological remains (Cosmas et al. 2001). In the 2000s, several projects were carried out with a similar goal. Probably the most successful were the project EPOCH[1] and its successor, 3D-COFORM[2]. In 2005, in the framework of the EPOCH project, a software package MeshLab[3] for 3D data processing and analysis was created. A year later, the launch of the online image-based 3D modelling service ARC3D[4] marked more-or-less the beginning of the so-called digital image-based 3D modelling revolution in archaeology (although the same authors already published several archaeological publications at the end of the 1990s, i.e. Pollefeys et al. 1998, 2000, 2001). Afterward, several other programs and online services were established, such as Microsoft Photosynth and Bundler, followed up by Autodesk 123D Catch, Eos Systems PhotoModeller Scanner, Visual SfM and Agisoft PhotoScan, to name a few. This technological development caused an immense and sudden increase in the usage of 3D digitisation in archaeology. The previous, rather small group of people that was dealing with virtual archaeology suddenly grew into an extensive community.

Since 1974, the previously mentioned annual CAA conferences became the first platform where people could discuss the topics related to virtual archaeology (although, back then, virtual archaeology was not called that name). Other important conferences that, over time, started including contributions on 3D modelling in archaeology have been, for instance, the annual Digital Heritage International Congress (DH), the International Society for Photogrammetry and Remote Sensing (ISPRS) commission V conferences, the Scientific Computing and Cultural Heritage conferences, the EUROGRAPHICS Workshops on Graphics and Cultural Heritage and the biennial CIPA Heritage Documentation Symposia. Papers and ongoing projects presented at these conferences reveal a broad usage of the created 3D models today.

ADVANTAGES AND APPLICATIONS OF 3D MODEL

Various technologies enable the acquisition of geometrical as well as textural data of an object. Final result of such digitisation process is a digital, geometrical 3D model that is not only a representation of the object, but which should also be considered the object's digital surrogate. This does not mean that a 3D model can ever be a substitute for the physical object. However, ideally, the digital copy provides a comprehensive documentation, while it can also be used to examine the object in the ways different/supplementary to the ones possible when working with the physical object. However, for a 3D model to

---

[1] http://epoch-net.org/site/.

[2] http://www.3d-coform.eu/.

[3] http://meshlab.sourceforge.net/.

[4] http://www.arc3d.be/.

be treated as the virtual copy of an object, it is important to pay attention to the accuracy, spatial resolution and the precision of the digitisation. All three aspects depend on the particular method of data capturing as well as all the data post-processing procedures. Therefore, such provenance metadata are necessary in order to enable other users to properly assess a 3D model and verify its suitability for the intended purpose. In this way, a 3D model is not an interpretation on its own (as is, for example, a drawing), but it is a tool that can be used to showcase and analyse the object, simulate past activities, and gather information that enables a better understanding of the object. The combination of these activities makes it possible to better interpret the object.

The most obvious advantage of a digital 3D model, compared to the traditional archaeological documentation methods such as photography and drawing, lies in the fact that a 3D model is not static, but it can be manipulated in various ways. It can be viewed from all directions, zoomed in or out, the lighting conditions as well as texturing can be changed over and over again. These features enable us to grasp very small, very large or very heavy objects, buildings or areas. Furthermore, the geometry can be inspected without texture and in optimal lighting conditions. Certain algorithms also emphasise the digital model's geometry and can make it even easier to perceive. It is also possible to automatically detect distinct geometrical features (such as edges) and make a semi-automated 2D drawing from the 3D model. The various analytical possibilities, such as measuring and cross-sectioning, greatly add to the described benefits. Measurements extracted from a 3D model can, in many cases, be more accurate than those taken from the physical object, or its drawing or a photograph.

Even though various technologies are currently capable of reliably digitising the 3D geometry of a surface, there are still many open issues related to digital 3D objects. These concern the overall digital data management of 3D models, and there are also more specific issues associated with the long-term data preservation. Furthermore, there exists a large variety of approaches to digitising the geometry of a surface in 3D and not all of those techniques are suitable for every 3D digitisation job. For example, many 3D digitisation approaches struggle with shiny, glossy or transparent archaeological artefacts, so specific solutions have to be found in those cases. However, the choice of a particular technology generally depends on the time and finances available within the project.

In addition, there is also a lack of suitable software packages that allow for an all- encompassing, archaeologically-relevant analysis of the 3D data. Most of the tools support only a subset of the aforementioned (analytical) techniques. As an example, tools that allow measuring and sectioning might lack decent visualisation capabilities, while 3D environments that might be focused on displaying large datasets often do not support georeferencing in real-world coordinate reference systems. Finally, most archaeological workflows (e.g. excavation documentation), as well as publications, are bound to the 2D or 2.5D derivates of 3D models, which means that the full potential of 3D models has not yet been exploited (Štuhec 2012; Verhoeven in press).

Taking all their characteristics into account, digital 3D models can, therefore, be used to document, present, share and analyse archaeological objects, buildings or areas. Through the use of internet database systems, it is possible to share the models with a wider scientific and lay public. Objects and features that would otherwise be inaccessible (such as artefacts in museum depots, very fragile objects, archaeological remains physically difficult to reach, stratigraphic contexts that were destroyed during the excavation process, etc.), could be viewed from anywhere in the world. Such databases can also join 3D models of objects that are kept away from each other, but belong to the same period, area or interest group. There have been several projects aiming at creating a database that would allow researchers to view and/or inspect archaeological remains with common characteristics. The *Carnuntum Database* (www.carnuntum-db.at), for example, includes 3D models of objects found in the Roman city of *Carnuntum* in Austria (Humer et al. 2010). The Virtual Zooarchaeology of the Arctic Project (VZAP) is a virtual, interactive, osteological reference collection for the study of northern vertebrates hosted on http://vzap.iri.isu.edu/. Another 3D model database is hosted by the project Digitizing Early Farming Cultures (DEFC)[5], which includes the most representative shards from the F. Schachermeyr's Neolithic pottery collection originating from Thessaly, Greece. The 3D models uploaded online are not isolated, but are instead interconnected with the rest of the database containing information on the Neolithic sites and finds in Greece and Western Anatolia (Štuhec et al. 2016). Several other 3D databases are trying to enrich the 3D models by connecting them to other types of data. MayaArch3D is an example of such an interactive platform that also includes several different analytical tools (Billen et al. 2013). Apart from these relatively local projects, there has also been an initiative for a Europe-wide collection of 3D models. This initiative was called the CARARE project[6] and was carried out from 2010 until 2013 in the framework of the *Europeana* (D'Andrea, Fernie 2013).

A collection of 3D models can be presented online in the form of a virtual museum (e.g. Virtual Museum Iraq, http://www.virtualmuseumiraq.cnr.it/homeENG.htm); traditional museums and other educational institutions are also taking advantage of 3D technologies (Engel 2011; Hess, Robson 2012). By using 3D reconstructions and animation they offer a better visualisation of what 'might have been and might have happened'. In addition, museums are nowadays employing different interactive systems and augmented reality to bring the past closer to the visitors (Hookk et al. 2015; Verykokou et al. 2014). Also, the video games-format is becoming more and more popular for its potential in communicating educational content (Mortara et al. 2014; Kontogianni, Georgopoulos 2015; Cirulis et al. 2015). Last but not least, museums often resort to 3D digitising and reproduction techniques to create replicas. Such replicas can be used as a substitute for the real objects when these are undergoing conservation, restoration, or any other treatment, or when a museum would like visitors to be able to touch and inspect the objects themselves.

3D replicas are not only useful in museums, but also for scientific research, especially when very fragile objects or very large archaeological remains must be handled. The latter can be 3D printed in a reduced size, while very heavy objects can be replicated in lighter materials. It is also possible to document an object *in situ* and later work on the replica. Repeated *in situ* 3D documentation also enables monitoring of weather and other external influences (Vetrivel et al. 2015).

Nowadays, the most widely used virtual archaeology application of 3D objects is still only for simple documentation purposes. 3D models are used to document landscapes (Masini et al. 2011; Neubauer et al. 2012; Doneus et al. 2008; Verhoeven 2011), archaeological excavations (De Padova, Maria Doriana 2015; Doneus et al. 2011; De Reu et al. 2014;

---

[5] http://defc.digital-humanities.at/3Dmodels/.

[6] http://carare.eu/.

Barbaro et al. 2014; Dellepiane et al. 2013), as well as artefacts (Opgenhaffen, Revello Lami 2015; Richardson, Smilansky 2013; Štular, Štuhec 2015). The generated 3D models are only seldom used for actual archaeological analysis and interpretation, which is most likely due to the lack of user-friendly analytical tools (see above) and the lack of knowledge of the prospects of 3D technologies. However, in recent years there have been several attempts to use 3D models as a tool in archaeological research. Several studies tried to classify pottery or lithic tools based on the geometric characteristics of the 3D models (Kolomenkin et al. 2011; Grosman 2013; Athanassopoulos, Shelton 2015; Muller, Clarkson 2014) and some used pattern recognition algorithms to compare 3D models of artefacts in order to recognize similar threads that may lead to correct typological classification, or to establish new ones (Burrer 2013; Carrasco-Ochoa et al. 2015; Teddy et al. 2015). A rather popular usage of 3D models is, also, the surface inspection which was, for example, carried out on the high-resolution 3D models of Stonehenge (Abbott, Anderson-Whymark 2012). A closer look at the digital surface is often also beneficial for the inspection of rock art (Zeppelzauer et al. 2015) or the interpretative mapping of earthworks (Verhoeven in press).

For some time now, 3D models are also being integrated and used with other techniques and tools, for example, in geographical information systems (GIS). GIS enables the construction of whole cities (Baratin et al. 2015), or reversing the excavation process by visualizing the time component as the fourth dimension (Klinkenberg 2014; De Padova, Maria Doriana 2015). 3D models of individual artefacts can also be positioned in GIS at the exact spot where they were found during the excavation. Additionally, much effort has been put into the semantic description of 3D models. Especially *building information modelling* (BIM) aims at the creation of a semantic library of buildings and their elements, which allows researchers to better understand the construction, function and biography of a building (Cheng et al. 2015; Fai et al. 2011; Fregonese et al. 2015; Volk et al. 2014). Although it seems that 3D models are being used in various ways all over the world, there is a lingering notion that more could be done. Within the increasing cooperation between archaeologists and technicians, new tools and comprehensive software packages should be developed that would allow archaeologists to analyse, exploit and question their 3D models in an easier and a more meaningful way.