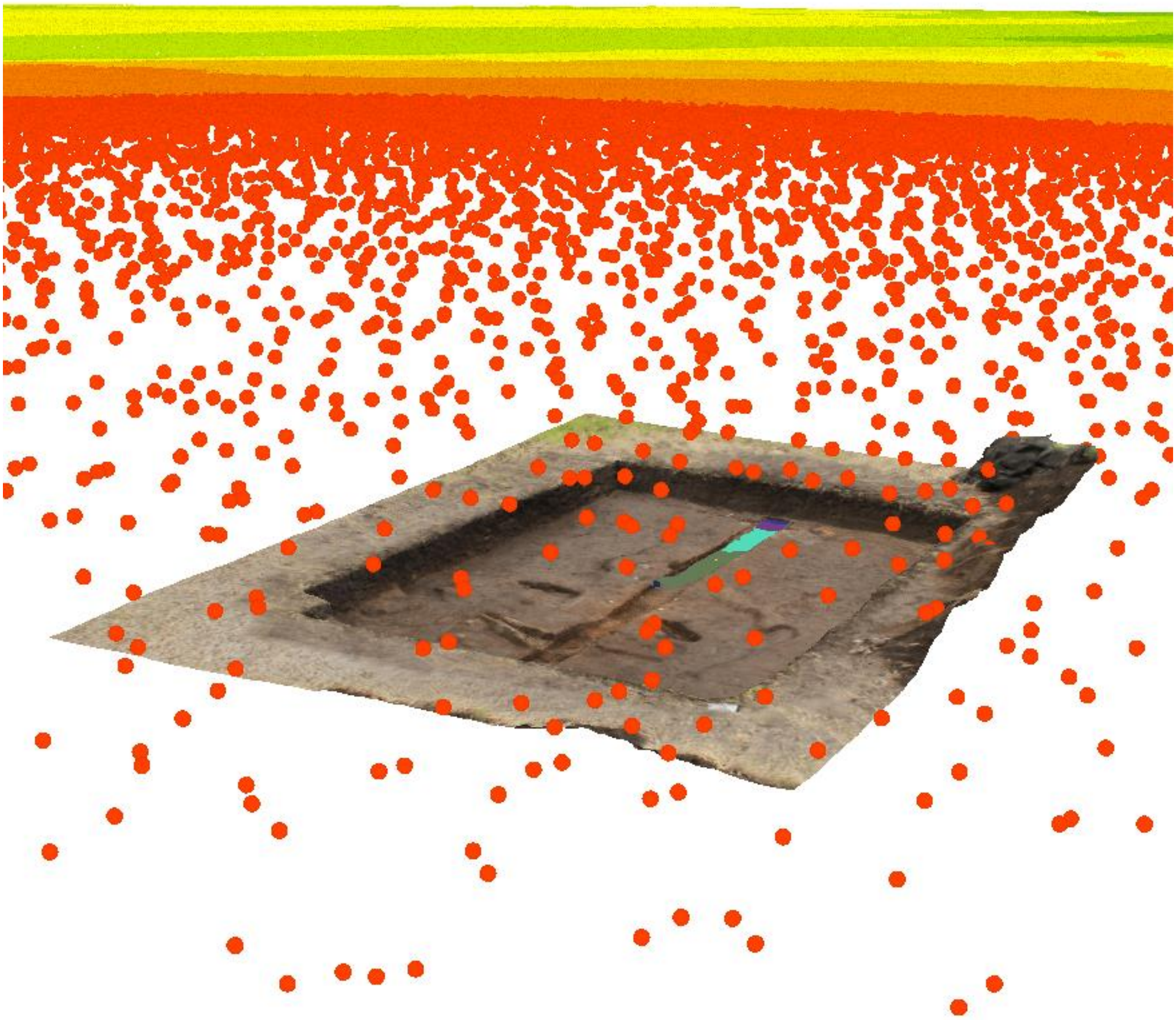
Exploring the use of 3D GIS as an analytical tool in archaeological excavation practice



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Abstract

Several digital technologies are now available to record and document archaeological excavations. A large number of studies have been published concerning the use of laser scanning, image based 3D modelling and GIS. By integrating different typologies of 3D data from Uppåkra, an Iron Age central place in southern Sweden, this thesis focuses on the development and evaluation of how 3D Geographic Information Systems (3D GIS) affect archaeological practice. In specific a Digital Terrain Model (DTM) was created for the site and the surrounding landscape. A UAV (drone) was used to document the excavation area in higher resolution, and image based 3D modelling was used to record the ongoing excavation on a single-context level. These different typologies of data were subsequently imported in a 3D GIS system (ArcScene) in order to conduct various types of spatial analysis (e.g. hillshade and slope analysis) as well as to create 3D drawings of the excavated contexts, using the textured 3D models as a geometrical reference. The ability to virtually revisit previous stages of the excavation and the use of tablet PC's for documentation and discussion *at the trowel's edge* increased reflexivity on the excavation and stimulated on-site interpretation by the excavation team. The model based drawing approach furthermore improved the drawing resolution compared to traditional documentation using a total station, especially for complicated contexts. This approach allowed connecting different typologies of data in the same virtual space, 1) increasing the possibility of researchers and scholars to gain a complete overview of all the information available, as well as 2) exponentially increasing the possibilities to perform new analysis. The ability to interact and navigate with all the data in 3D improved the impact of the data and comes closer to simulating the real world. Though some challenges still have to be faced, such as inaccurate georeferencing and unrealistic colour projection, the method was found to significantly improve the documentation quality by creating a multi-scale 3D documentation platform. By further developing this method, it can help us to improve the standards of archaeological excavation documentation.

Keywords: digital archaeology; 3D models; 3D/4D GIS; photogrammetry; LIDAR; laser scanning; excavation methodology; excavation documentation; archaeological drawing methods; reflexivity; landscape archaeology

Cover page: LIDAR point cloud combined with a 3D model of one of the Uppåkra 2015 excavation trenches and 3D context drawings, visualized in ArcScene. Image by Sjoerd van Riel.

Table of Contents

List of Figures

1 - Introduction - Research questions and methods

Archaeological fieldwork practice is a destructive process. Once the remains are uncovered and documented, the physical evidence is removed in order to progress with the investigation. The possibility of using technology to document in three dimensions (hereafter 3D) the stratigraphic sequence (length, width and depth) detected by archaeologists during the field investigation process, opens new important scenarios for what concerns archaeological practice and field interpretation, increasing the possibilities to visualize what Harris described as fourth dimension: time (1989, p.83).

One of the tasks of the archaeologists is to record these dimensions as accurate as possible, since the practice of excavating is in itself a destructive process. Barker describes the practice of field archaeology as an unrepeatable experiment (1993, p.13). In order to digitally record the archaeological remains so that they can be studied in the three dimensions and by other scholars, the 3D data has to be organized and managed as a dataset which can be used to diachronically simulating the investigation process (Callieri et al., 2011; Dellepiane et al., 2013). The documentation has to capture as many aspects of the real world as possible, since archaeological methods keep being developed and new questions to the material will be asked in the future. The standards of documentation for today's research might not be sufficient to answer tomorrow's questions, so archaeologists have to strive to improve the quality of their recording and documentation at all times. Since the last few decades, archaeologicalist have several new digital tools to their disposal which can contribute to an improvement of documentation methods. In order to do this, a solid methodological and theoretical frame has to be developed. Digital developments in archaeology need the creation of theoretical support (Zubrow, 2006, p.9).

Many studies have explored the potentials of digital methods in archaeology. However they have been limited by factors such as time-consuming (Dell'Unto, 2014, p.153) or the lack of a 3D visualisation and analysis platform (Dell'Unto, 2014, p.156). Moreover, these studies often use the 3D methods still to create a final output which is bi-dimensional (De Reu, 2014). However, the rapid development of technologies and 3D software packages allow us today to take these experiments a step further. This thesis aims to explore and discuss the potentials and limitations of 3D recording and modelling[1] of archaeological excavations, by discussing how these digital techniques can change the process of excavation and interpretation in both theory and practice. After the presentation and discussion of several digital techniques and their use within archaeology as well as theoretical implications that these techniques have, I will integrate the conclusions that I drew into a discussion concerning an experiment developed in the frame of the excavation site of Uppåkra, an Iron Age central place located in southern Sweden.

In the frame of a field investigation activity, developed by the Department of Archaeology and Ancient History, Lund University, an experiment concerning the 3D digital recording of the ongoing excavation was conducted in order to evaluate the potential of 3D Geographic Information

[1] During the course of this thesis I use the terms 3D *recording, modelling* and *documenting*. 3D *recording* refers to the data acquisition. 3D *modelling* refers to the use of this data in order to create a model, i.e. a mathematical representation of a 3D surface of an object. 3D *documenting* lastly refers to the broader concept of documenting archaeological remains in 3D, and can thus include both 3D recording and 3D modelling.

Systems (GIS) in support of field practice. The methodology developed and described in the frame of this thesis as well as the implications that his approach had on the field investigation and interpretation process have been evaluated and discussed in the final chapters in a discussion regarding the use of 3D recording techniques in archaeological excavations.

In summary, the questions that this thesis aims to answer are the following. 1) What is the state-of-the-art concerning 3D recording of archaeological excavations? 2) What theoretical implications do these techniques have? and 3) How can these techniques and theoretical backgrounds be successfully combined and integrated in order to create a fluent, accurate and theoretically supported workflow for real-time 3D documentation of all archaeological contexts on excavations? The latter will be discussed with a case study from the excavation in Uppåkra, Sweden.

1.1 - Research History

This section aims to provide with a short introduction on the research history in the field of digital 3D recording. Archaeology, as well as many other disciplines, is going through a 'digital revolution', but before the introduction of digital recording instruments, analog recording methods had been the standard for many decades. In this thesis I will not provide an extensive history of analog recording techniques, but rather refer to some works by other authors that deal with this subject in great detail (e.g. Barker 1993; Roskams 2001; Jensen 2012). What follows is a short introduction concerning several digital techniques that have been developed throughout the years, most of which are still in use. For a more extensive description and technical details of 3/4D GIS, laser scanning and photogrammetry I refer to chapter two, which deals with the current state-of-the-art in 3D recording technology.

Since the early 1980's, computers have been used to record and analyse excavation data. Geographical Information Systems (GIS) came in use to relate different typologies of data and further analyse them in for example a predictive model (Barker, 1993, p.158). In the years following, GIS have revolutionized the way archaeologists conduct spatial analyses and caused a highly specialized field of archaeology that deals with the practical as well as theoretical implications of GIS (Allen, Green and Zubrow, 1990; Gaffney and van Leusen, 1995; Kvamme 1999; Lock 2001; Connoly and Lake, 2006; McCoy and Ladefoged, 2009; Llobera, 2012). However it is necessary to highlight that Geographic Information Systems function as data management platform and their use and development in archaeology strictly depends on the possibility of having access to new and different typologies of data.

By using an Electronic Distance Meter (EDM) and an electronic theodolite, the location of individual artefacts could be digitally recorded in 3D as early as the 1980's as well (Barker, 1993, p.187). The introduction of these two tools in archaeology led to an increased accuracy in the 3D recording of points from ± 5 cm to ± 5 mm. The new technique was also faster and easier compared to manual drawing, and moreover reduced cumulative systematic errors due to measuring from a wrong basepoint. In fact the introduction of these techniques was found to be so useful that instead of one or a few points, outlines of entire objects were measured in 3D and then digitized in the computer (Dibble, 1987, pp. 250-251).

By the later 1980's, GIS was used to visualize sites (e.g. only Roman or Early Iron Age sites) with their locations plotted on a 3D Digital Terrain Model (DTM - figure 1), and the potential for this technique to be used in the 3D stratigraphical analysis of excavations was recognized. In fact, Trevor Harris was already mentioning the possibilities for dividing archaeological layers according to their temporal stratigraphy, and combining this data with an archaeological database inside a GIS (Harris, 1987, p.168). An early example of 3D stratigraphic modelling can be found in Reilly (1990).

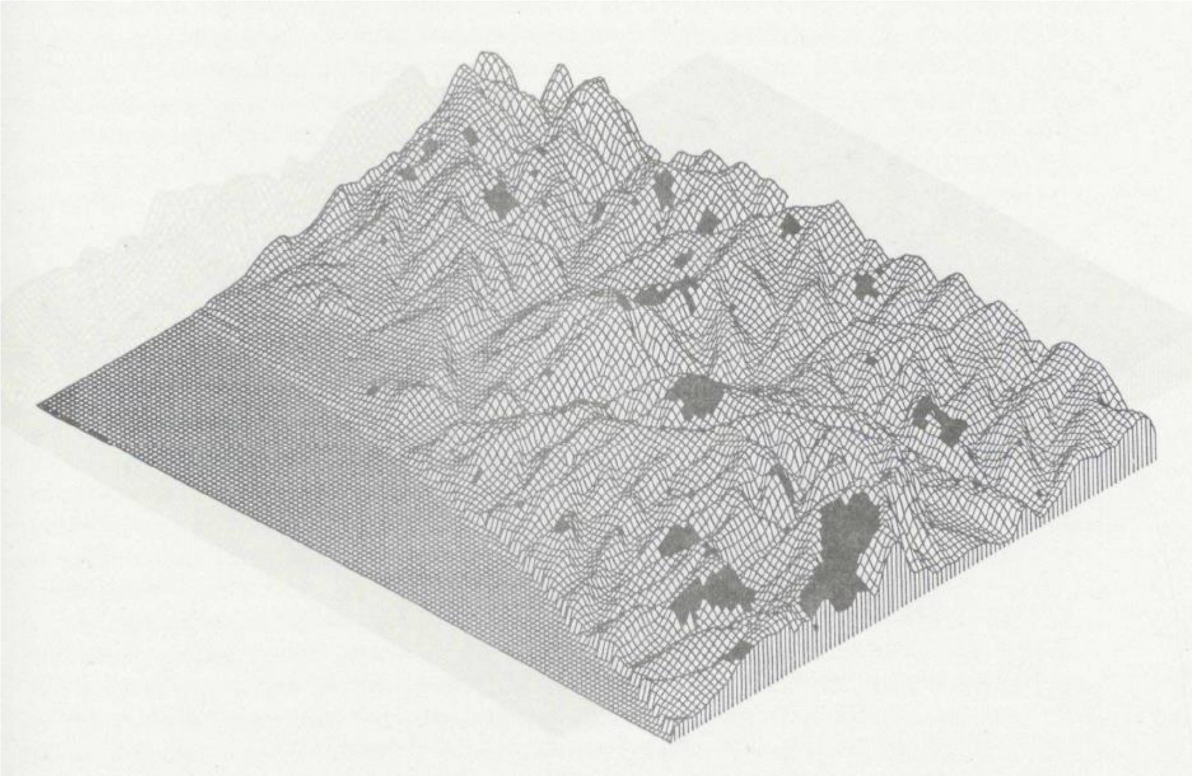


Figure 1. Early example of 3D GIS showing a selection of sites visualized as dark patches projected on a Digital Terrain Model (DTM). Source: Harris, 1987, p.165.

The theodolite can be seen as the ancestor of the Total Station in archaeology, which became widely used in the 1990's (Rick, 1996). Over time, total stations have largely replaced optical theodolites. With the introduction of the Robotic Total Station (RTS) the instrument became even easier to use since the remote control option allowed for the operation of the instrument by a single person. Moreover, a radio linkage between a control pad and the main station allowed for much quicker acquisitions, which made the instrument suitable to map entire landscapes (Kvamme, Ernenwein and Markussen, 2006). Total station data has been used for CAD (Computer Aided/Assisted Design/Draughting/Drawing) drawings in 3D since the later 1980's (Lock, 2003, p.53). Where a total station could not be used or did not provide enough detail, a 3Space Tracker was developed which could provide an accuracy of less than 2 millimeters (Lock, 2003, p.107).

A next step in the digitization of 3D data in archaeology was the introduction of the GPS (Global Positioning System), which was developed in the late 1970's but was restricted in use of the more accurate data by the US Department of Defence until May 2000 (Connoly and Lake, 2006, p.63). A Differential GPS (DGPS) which calculates differential correction between the estimated and actual location of the receiver, has accuracy to the centimeter or better. A GPS is easier to handle and much faster than a total station. Moreover it reduces the dependence on existing maps or coordinates which a total station needs to locate itself (Barratt, Gaffney and Goodchild, 2000, p.133). Furthermore, contrary to a total station where data visualization is only possible after importing the data in a computer, the obtained data from a RTK (Real Time Kinematic) GPS can be visualized and analyzed immediately on a little screen that is connected to the survey pole or 'rover' (Roosevelt, 2014, p.32). A final advantage of using a GPS over a total station is that a GPS does not require intervisibility between the base and the rover, something which can be very limiting in the case of for example urban survey. However, a GPS also has some limitations, which are mainly connected to the possibility of connecting with the satellites for example in heavily built-up or vegetated areas (Connoly and Lake, 2006, pp. 63-64).

The techniques described so far, although increasingly accurate, fast and without doubt very useful in the recording of 3D data, require a great deal of time if the goal is to acquire not just points but entire sites or even landscapes. They also have some other limitations, such as the fact that they require the archaeologists to walk over the features that need to be recorded, which can be problematic in the case of for example a waterlogged site, organic material or other vulnerable surfaces (Doneus and Neubauer, 2005, p.2). A new technique that solved some of these problems and significantly increased the speed and ease of acquiring thousands of points with a very low labour intensity is laser scanning (see chapter 2.1). Laser scanners came on the market in the late 1990's. They are very suitable for the documentation of standing structures such as buildings or caves, which, due to the geometrical complexity, are very hard to document with a total station or GPS, and have been used a lot since the early 2000's to document archaeological sites (Doneus and Neubauer, 2005; Lambers et al., 2007), caves (Lerma et al., 2010) and most of all, architectural remains (Strumpfel et al., 2003; Dell'Unto et al., 2013a; Dell'Unto et al., 2013b; Dell'Unto et al., 2015).

Besides their terrestrial use, laser scanners have also revolutionized remote sensing in archaeology. Airborne Laser Scanning (ALS), also widely known as LIDAR (Light Detection And Ranging), has come in use in archaeology in the last decade. The earliest LIDAR systems were developed by NASA in the 1970's, but limitations positioning and georeferencing equipment, the high cost and limitations in software and hardware prevented the adoption of the technique for commercial survey projects until the late 1990's (Opitz and Cowley, 2013, p.15). The main application of LIDAR is the creation of Digital Surface Models (DSM) or Digital Terrain Models (DTM) from the dense point cloud that it produces. The revolutionary characteristic of LIDAR is that it provides archaeologists with the possibility to select and visualize different typologies of elements (such as vegetation, structures, etc.) at a landscape scale previously acquired and classified by the system, providing archaeologists with the opportunity to effectively 'see through' vegetation (Doneus et al., 2008; Chase et al., 2011). Furthermore, it has proven to be extremely suitable for the discovery of new sites or to provide new information about the extension of already known sites, such as Stonehenge (Bewley, Crutchley and Shell, 2005).

The last development in 3D recording techniques in archaeology that will be described in this section is photogrammetry (image based 3D reconstruction techniques - see chapter 2.3). Together with laser scanning, this technique has revolutionized the concept of 3D recording in archaeology, but has also caused some "*misunderstandings and ambiguities*" (Campana, 2014, p.8). The introduction of these techniques has led some scholars to argue that recording and documentation in archaeology were now fully objective (e.g. Anderson, 1982, p.200). But essentially they are still subjective and based on interpretation (Campana, 2014, p.8). This subject regarding the theoretical implications of digital 3D recording techniques will be discussed in detail in chapter three of this thesis.

Photogrammetry has been used for archaeology since the 1950's. Despite its huge potential as a fast and accurate method, a number of significant drawbacks such as high costs and high demand of specialized operators has been the reason why the technique has not been able to become a standard method for archaeological recording and documentation (Anderson, 1982, pp.201-204; Fussel, 1982, p.165). In the last few decades however, the technique has become very popular because of lowered costs of both cameras and post processing tools, and the introduction of digital photography (e.g. Gisiger et al., 1997, p.11).

A development that has been closely connected with aerial photography and photogrammetry is the use of UAVs (Unmanned Aerial Vehicles). Since Giacomo Boni used a balloon to take aerial pictures of the Forum Romanum in the late 19th century, archaeologists have recognized the potential of using aerial pictures for the creation of maps and orthophotos in order to analyse the data from a clear viewpoint (see Ceraudo, 2013 for an overview of the use of aerial photography in archaeology). Tools that have been used to place a camera on a high point above the scene range from pigeons, poles and towers to kites, balloons and rockets (see Verhoeven, 2009 for an overview of utilized technologies).

Aerial photographs can be extremely helpful to detect archaeological sites which are (partly) hidden beneath the surface. It makes use of not only visible archaeological features, but also archaeological traces which are an impression by the archaeological material on surrounding elements (humidity, vegetation, relief etc.) These traces can be classified in crop-marks, soil-marks, shadow sites and others (Ceraudo, 2013, pp.28-29). A recent application of aerial photos in archaeology is the creation of textured 3D- and digital terrain models, using the photogrammetric techniques. The acquisition method of choice in present day archaeology is most often a UAV (Unmanned Aerial Vehicle), since they offer several advantages over the traditional tools (see chapter 2.4). Especially in the last five years, UAVs have been increasingly used to map and analyze archaeological sites using aerial photography and photogrammetry (Remondino et al., 2011; Roosevelt, 2014; Smith et al., 2014; Fernández-Hernandez et al., 2015).

In the last few years, 3/4D GIS systems became available for use in archaeology (Esri, 2013). Whereas the data obtained in 3D until recently was mostly restricted to 2D (bi-dimensional) visualization within GIS, it is now possible to visualize the 3D data in a 3D spatial context. However, as is discussed by Stefano Campana (2014, p.11), archaeologists still have a habit of thinking in two dimensions, because we have been educated to reduce reality from three dimensions into two. 3D Models are often just used in the end of the process to make reconstructions. Instead we should create a process "*in which the 3D model no longer constitutes the end but rather the means of achieving better understanding through analysis and simulation*" (Campana, 2014, p.10). Throughout the last ten years, many case studies have been conducted in which the potential of 3D models derived from photogrammetry or laser scanning, or a combination of both, as (almost) real time data for analysis and documentation of excavations has been explored (Katsianis et al., 2008; Callieri et al., 2011; Doneus et al., 2011; Dellepiane et al., 2013; DeReu et al., 2013; Dell'Unto, 2014; DeReu et al., 2014). However, the models are still rarely used as an analytic tool on excavations, providing with a fully real time documentation of the stratigraphy and the archaeological contexts. As will be seen in the next chapter, the current state-of-the-art of technology allows us to use the models as a geometrical and visual background, which serves as an interpretational tool and can be used in combination with overlaying digital drawings of contexts and features. In current GIS systems such as ESRI's ArcScene (version 10.2.2), these drawn contexts in the form of 3D polygons can be linked to a database within the software which replaces a manual context sheet, providing all the information required in traditional context sheets (Archaeological Site Manual, 1994). The next step is to combine different 3D recording techniques in a multi-scale analysis, focusing on the landscape, the intra-site level and the stratigraphical and single context level. It is in this line that the case study in Uppåkra was conducted, and this method will be evaluated and discussed in the following chapters of this thesis.

2 - Materials and methods

This chapter aims to summarize the state-of-the-art regarding 3D recording, modelling and analysis technologies that are currently used in archaeology, and introduces the materials and methods that have been used for analysis in this thesis. The developments that have been described in chapter 1.1 have led to the state of technology that we are facing now. The best results will be obtained by integrating these different technologies. This chapter presents a selection of the technologies that can be used for recording and analyzing 3D data, and will focus on the methods that have most potential for archaeological practice and have proven their use in several case studies.

2.1 - Terrestrial Laser Scanning for 3D recording of archaeological stratigraphy

Laser scanning refers to a method where a surface is scanned by laser beams, followed by a measurement of the travelling distance of these beams. The output data is normally a dense point cloud that represents the scanned surface, from which information about the morphology of the object can be derived (Opitz, 2013, p.13). In archaeology, laser scanners are mainly used for three purposes: to record objects, to record structures on the ground or to record the landscape from above. These methods are referred to as terrestrial- (TLS) and airborne laser scanning (ALS). Although they clearly have different methods of data capturing, the basic technology of laser ranging that they use is the same. The methods and algorithms that are used for the post processing of the data are also generally the same (Vosselman and Maas, 2010, p.ix). For this reason, I will first provide a short technological description of general laser scanning techniques that are used in archaeology, and then focus on specific applications of both terrestrial- and airborne laser scanning.
Laser scanners can be divided in three categories, separated by the method they use to capture the data: time-of-flight (TOF - figure 2), Phase Shift and Triangulation. The time-of-flight method is most suitable for the mid- and long range of archaeological excavations and landscapes. The TOF method uses the known velocity of light waves in a given medium, and measures the time delay (also called time-of-flight) of light travelling from a source to a reflective target and back to a light detector (Vosselman and Maas, 2010, p.2). The light detector can record multiple returns, in case there are multiple objects (such as vegetation) in the way of the light wave. In airborne laser scanning, at least the first and last return is recorded. Most systems detect four to five different returns. Some terrestrial laser scanners are now also able to record different returns. Most commercial TOF laser scanners have a range uncertainty for a single pulse in the order of 5-10 mm (Vosselman and Maas, 2010, p.5). There are several different methods to capture the light returns, each with their own pros and cons. For more detailed information about them I refer to publications that deal with the technical characteristics of laser scanners in great detail (e.g. Vosselman and Maas, 2010).

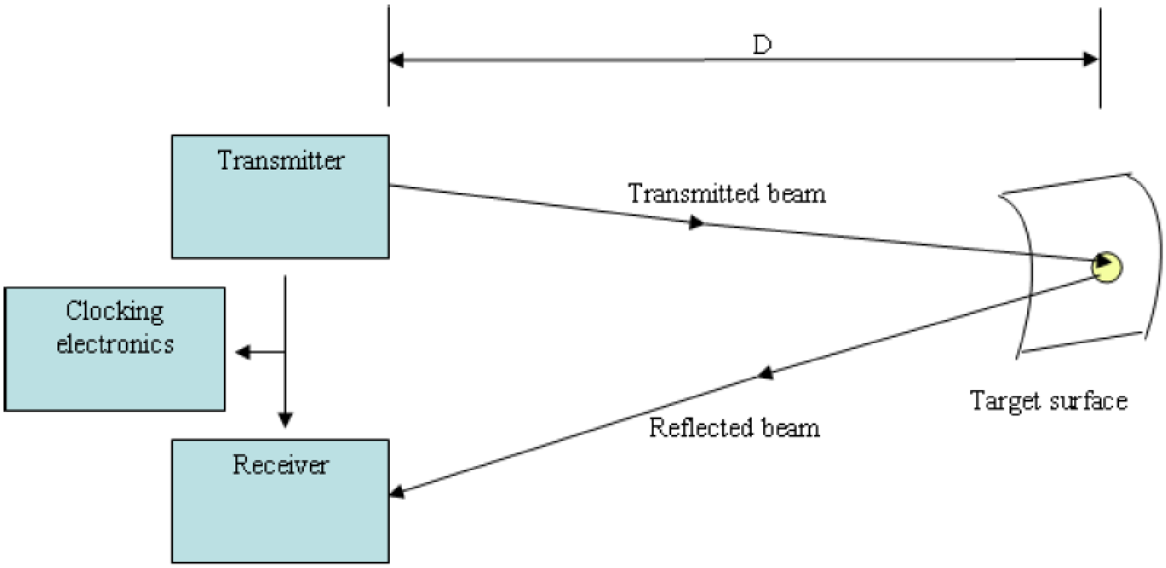


Figure 2. Time-of-Flight laser scanning principle. Source: van Genechten, 2008, p.22.

A second typology of instruments which measure the travelling time of the laser beam, but uses a different method to measure the distance of the object, is called Phase Shift (Vosselman and Maas, 2010, pp.5-8). In this method, a continuous laser beam is sent out from the scanner (contrary to TOF which sent out multiple short laser pulses), and the distance to the object is calculated by measuring the phase shift between the emitted and received laser beams (Opitz and Cowley, 2013, pp.13-14). Traditionally, TOF were more suitable for longer ranges, whereas Phase Shift dominated the shorter distances. During the last decade, experiments in archaeological recording using both TOF and Phase Shift scanners have shown very similar results (San José Alonso, 2011).

The third method of measuring that is used by a category of laser scanning devices is triangulation. This method is more suitable for surveys with a range of less than five meters and is thus mostly used for recording artefacts, and not for archaeological site or landscape survey. For this reason, I will not describe this method in this thesis but again refer to Vosselman and Maas (2010), who cover the triangulation method in great detail (pp. 8-11).

Laser scanners have revolutionized the accuracy with which we can now record 3D data in archaeology, and have been successfully used to document ongoing excavations context by context. However, experiments conducted by Doneus and Neubauer (2005) demonstrated that the use of these tools in support of archaeological practice was problematic in terms of time consumption (Doneus and Neubauer, 2005, p.3) and later articles showed how despite the exponential growth of technology this still represents a major problem (Forte et al., 2015). The major limitations stand in the long post processing time and the fact that the output data is not easy to manage. Furthermore, even though some laser scanners are equipped with a camera capable of recording colour information, due to the low resolution of the sensor the pictures are often not sufficient to be used for transferring the colour information to the models. For this reason, in order to map the colour information, it is often necessary to acquire an additional set of pictures by using a more resolute camera (Doneus and Neubauer, 2005, p.4). The case studies by Doneus and Neubauer show that despite the capability of the scanners to capture a large amount of 3D data in a relatively short time, they cannot yet be used as a single tool to document archaeological stratigraphy in 3D. One needs to take scans from several positions which need to be aligned and thus result in a lot of post processing work. The time spent for aligning the point clouds prevents the possibility of the models being used directly in the field as an analytic tool for the excavators. Even though in the last ten years laser scanners have become quicker and equipped with better cameras, the post processing time is still a major obstacle that stands in the way for the technique to be used for the documenting of archaeological stratigraphy (Forte et al., 2012).

2.2 - Airborne Laser Scanning for 3D recording of archaeological landscapes and sites

Airborne laser scanning (ALS, often referred to as LIDAR) consists of two basic components: a laser scanning systems which detects a point on the ground, and a GPS combined with an Inertial Measurement Unit (IMU) to measure the position of the scanning system (Vosselman and Maas, 2010, p.22). The scanner works with the same principles as terrestrial laser scanners (TLS). In most cases a TOF scanner is used because of its long range scanning capacity. Usually the data density that can be acquired is between 0.2 and 50 points/m^2. The GPS and IMU combination is able to reconstruct the flight path with an accuracy of 10 cm or less. The onboard measurement systems are complemented with a GPS station on the ground, which serves as a reference for differential GPS calculation (figure 3 - Vosselman and Maas, 2010, pp.22-23).

There are two kinds of LIDAR systems that are relevant to discuss in this thesis: discrete return and full wave form. Discrete return systems record a limited number of returns for which the intensity is greater than a set value. Full wave form systems record all the returns (Opitz and Cowley, 2013, p.15). Following this difference in return recording, it is clear that full wave form LIDAR has more potential in filtering out unwanted classifications such as low vegetation (Doneus et al., 2008; Lasaponara, Coluzzi and Masini, 2011). However, the success of the use of this type of LIDAR is depending on the method of classification, since an inappropriate classification will lead to the removal of archaeological features, or the creation of false information (see Opitz and Cowley, 2013, pp.20-23 for more information about different classification methods and their consequences for the dataset).

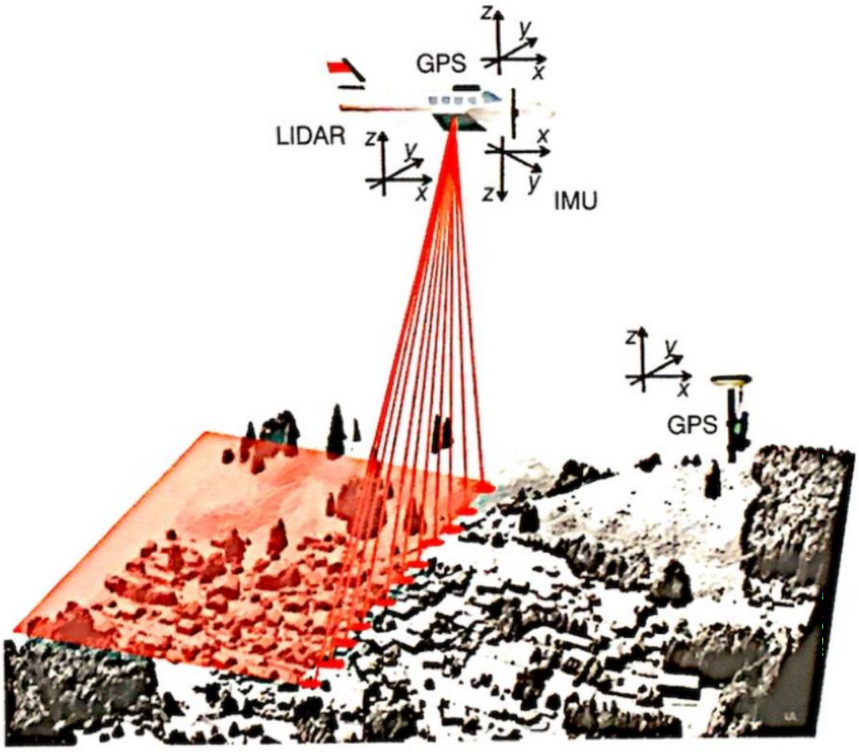


Figure 3. Airborne Laser Scanning (ALS) principle. Source: Vosselman and Maas, 2010, p.21.

2.3 - Image Based 3D Reconstructions and close range photogrammetry

Photogrammetry is a technique for obtaining geometric information from photographic images. Generally a minimum of two images of the same static scene or object from different points of view are needed to establish a geometric relationship between the images and the scene. A stereoscopic view and derivation of 3D data from the different relative positions of the object in the images allows the reconstruction of 3D surface geometry from the 2D images (Remondino, 2014, p.63). Photogrammetry in archaeology is used in different scales. We can make a distinction between satellite photogrammetry (distance to object ca. 200 km), aerial photogrammetry (ca. 300 m) and close range photogrammetry (< 300 m) (Luhmann, 2007, p.5). This thesis will focus on close range photogrammetry, since that is the category in which the recording of archaeological excavations on a single context level belongs (Luhmann et al., 2007, p.5).

There are several approaches and algorithms to reconstruct camera orientation and geometry from images. Currently one of the most used methods is based on the employment of Structure-from-Motion (SfM) algorithms. These algorithms belong to the computer vision research field and together with stereo-reconstruction techniques provide the opportunity to create accurate 3D models from images without prior information about the location of image acquisition, or about the camera parameters used to perform the acquisition (Verhoeven, 2011, p.67). In the frame of this thesis, Agisoft Photoscan 1.1.5 (http://www.agisoft.com/) was used. This software employs SfM algorithms for estimating the camera parameters (see chapter 2.5.2). With the SfM method, the 3D scene geometry and camera motion are reconstructed from a sequence of 2D images which are taken by a camera that moves around the scene. The Sfm algorithm detects common feature points in multiple images and uses them to reconstruct the movement of those points throughout the image sequence. With this information the locations of those points can be calculated and visualized as a 3D point cloud (Verhoeven, 2011, p.68 - figure 4).

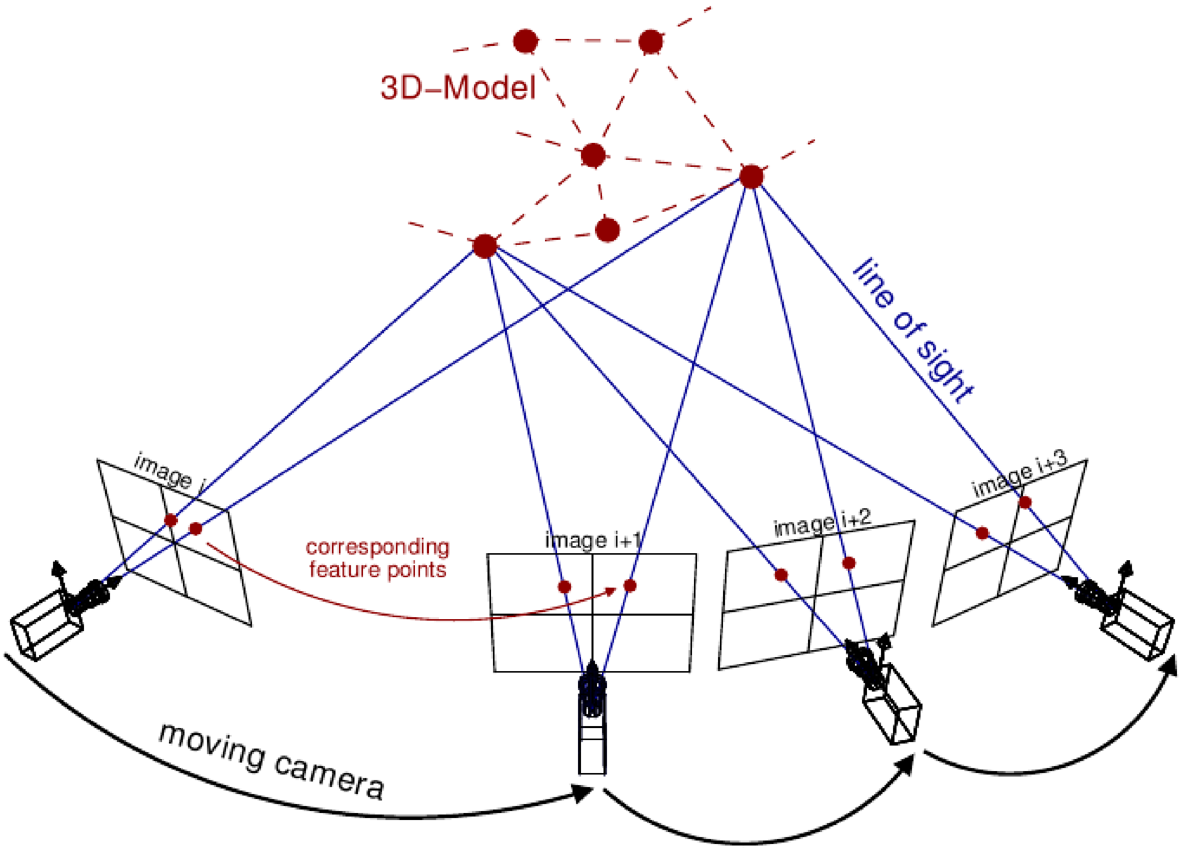


Figure 4. Structure from Motion (SfM) photogrammetric principle. Source: Theia-sfm.org (2016).

The image based approach offers several advantages over laser scanning. The equipment necessary to generate the 3D model (both hardware and software) are low cost. Images from an average priced DSLR (Digital Single Lens Reflex) camera are of much higher resolution and allow for better texture projection compared to images coming from a scanner's camera, and finally by using these techniques it is also possible to gather 3D resolute information using archived images of monuments or objects which are no longer available (Remondino, 2014, p.64; Gruen, Remondino and Zhang, 2004). However, a photogrammetric approach requires more expertise during the acquisition and post processing of the data. In order to reach the final output which is the same as the one coming from a laser scanner (a dense point cloud), instead of a fully automated process as used by laser scanning, image based 3D modelling employs a semi-automated process in which the operator has more influence on the final result. Due to new semi-automated procedures for the processing of images (Remondino, 2014, p.64) and the emergence of integrated commercial software packages that largely automate the post processing of the images, such as Photoscan, the process has become easier to control by the operator without losing the advantage of manually overseeing the complete modelling process. Moreover, the process of image based 3D reconstruction does not stop with the creation of a dense point cloud, contrary to laser scanning this is only one steps in the pipeline (figure 5).

Image based 3D reconstruction subsequently allows the operator to create a textured mesh, i.e. a finished 3D model.

2.4 - Unmanned Aerial Vehicles (UAVs)

A drone is the more common term for a range of Unmanned Aerial Vehicles (UAVs). UAVs offer several advantages over manned aircraft systems. This technology provides archaeologists with the opportunity to map areas which are impossible to reach, or to gather broader overviews of sites and landscape from a remote distance. Furthermore, UAVs can function in different weather conditions. More advantages include the lack of a highly trained human pilot and the accompanying economic expenses and lower cost of the equipment compared to most manned aircrafts (Eisenbeiss, 2009, p.3-4).

There are many different types of UAVs available. Examples are (heli)kites, helicopters, fixed wing devices, balloons and blimps. However, these devices all have certain drawbacks (Eisenbeiss, 2009, p.35).

In recent years, a large amount of radio- controlled (multi) copter platforms (UAVs) has been employed during mapping operations in the cultural heritage sector together with more traditional tools (De Reu et al., in press). These devices offer several advantages over traditional UAVs such as kites or balloons: they have a big range, are not dependent on wind, can be remotely controlled with very high accuracy and run on electricity and not for example helium. Moreover, they can be equipped with a wide range of sensors (e.g. thermal, infrared or LIDAR). However, there are also some drawbacks but they are mainly connected to logistics such as the need of permission to fly in certain areas. Due to the high demand from many different fields, the price of drones is going down rapidly and new models are released constantly with better cameras, lower weight and new features. The drone used for our study in Uppåkra, a Phantom 2 Vision+, is already out of production and succeeded by multiple new models with better cameras at the time of writing.

If the images that are acquired by the drone are to be used for image based 3D reconstruction techniques, some considerations need to be made regarding the flight planning. In order for the SfM algorithm to work successfully, an image overlap of 60-80% is advised (Verhoeven et al., 2013, p.43). With the most recent drones, an integrated camera system can be programmed to take a picture every few seconds, and the flight path can be predefined and automated (Eisenbeiss and Sauerbier, 2011, p.402). Mobile apps such as ‘Pix4D’ (Pix4D, 2016) provide predefined flight grids that are customized for specific drones. A gimbal is usually integrated in the drone for camera stabilization in the air. For more detailed information about flight planning strategies and UAV photogrammetry, see Eisenbeiss, 2009 & Eisenbeiss and Sauerbier, 2011.

For optimal usage of the 3D model in GIS, it is crucial for the model to be georeferenced. Georeferencing (or ground registration) refers to the allocation of spatial information to spatial data in order to define its correct location and rotation in relation to a specific coordinate system (Verhoeven et al., 2013, p.41). For the georeferencing of image based models, Ground Control Points (GCP’s) are usually placed in the scene and captured by the camera on the pictures. The location of the GCP’s is measured with a total station or GPS, and assigned (in Photoscan or other software) to the specific location in the picture which represents the GCP's. Photoscan needs at least three GCP's that are spatially well distributed (not too close to each other and distributed over the entire scene), but more GCP's are advised (Verhoeven et al., 2013, p.47).

2.5 - Software

This section will discuss and evaluate some of the standard software packages that are currently used for the acquisition, management and analysis of 3D data in archaeology. It is evident that the software presented here will develop rapidly. New releases will come out which will make the versions that are discussed in this thesis outdated and perhaps not usable anymore. However, I think it is important to have a brief look at the current possibilities (and limitations) that archaeologists are facing with the software that is available, since in the digital era software should be seen as an essential part of scientific methods, rather than just a tool.

2.5.1 - ESRI ArcGIS 10.2.2

ESRI (Environmental Systems Research Institute - http://www.esri.com) was founded in 1969 and is specialized in GIS software and geodatabase management. ESRI was the producer of ArcView, one of the early commercial GIS systems that was released in 1995. ArcView was replaced by ArcGIS in 2000. ArcGIS included a 3D analyst, which displayed a growing interest and provided with tools for management, analyses and visualization of 3D data. With the release of ArcScene in 2002, this 3D interest had grown to such a substantial amount that a separate application was created for it (Shephard, 2003; Esri, 2013; ArcScene, 2014). ArcScene is a 3D GIS which allows the user to interact and navigate with her/his 3D data. Contrary to ArcMap, which has a 3D analyst but still has a mainly bi-dimensional viewer; in ArcScene the user is able to perform any possible analysis in 3D.

ArcGIS' latest version (10.3.1) needs the recommended system requirements (desktop.arcgis.com, 2016): Windows 7 or later, Hyper-threading (HHT) or Multi-core processor, 2GB of RAM and NVIDIA, ATI, and Intel chipsets supported. For this thesis, ArcGIS version 10.2.2 was used. ArcGIS comes in three different versions: basic, standard and advanced. Information on pricing for an ArcGIS license is hard to find, which illustrates a possible problem with the software in the fact that it is aimed for big companies and not very user friendly when it comes to licensing and pricing for small and private companies. An ArcGIS standard license costs $3000 USD (€2760) per year. ESRI offers special licenses for students and educational institutions, but if one's budget is insufficient to pay a substantial amount per year for a GIS license, the solution can be sought in open-source GIS software such as GRASS (https://grass.osgeo.org/) or QGis (http://www.qgis.org/en/site/). However, ArcGIS is the only GIS system capable to manage and visualize 3D datasets.

2.5.2 - Agisoft Photoscan

Agisoft LLC (http://www.agisoft.com) was founded in 2006 and has its expertise in image processing algorithms and digital photogrammetry techniques. Its product, Photoscan, is one of the leading software packages in the field of digital photogrammetry and widely used for archaeological applications (Photoscan, 2015). There is other similar software, but Photoscan offers the most inclusive package of the photogrammetry process, from importing images to exporting textured models. Photoscan comes in two different versions, a 'standard´ and a 'professional'. The standard version provides with all the necessary tools to create a 3D model from images, organized in a ladder of steps from automatic camera calibration, automatic tie-point search and image alignment to the generation of sparse and dense point clouds, and finally the creation of a textured 3D model (figure 5). It is possible for the user to intervene at any stage and disable or mask certain parts of images that could disturb the process, such as translucent or glossy material. The professional edition includes all these features, and is enhanced with the possibilities of georeferencing, orthophoto generation, DEM (Digital Elevation Model) export and advanced area and volume measurements. For this thesis, Photoscan standard version 1.1.5 and professional version 1.1.6 were used, but by the time of writing Agisoft has already released version 1.2.3.

The recommended system requirements (Agisoft, 2016) are as follows: Windows XP or later (or MAC OS X Snow Leopard or later), Intel Core i7 processor, 12GB of RAM and a graphic card NVidia GeForce 8xxx series or later, or ATI Radeon HD 5xxx series or later. However, a better configuration will lead to increased processing speed of the images and improved navigation of the models, which can be an important factor in time limited archaeological practice such as excavations. Photoscan does not require an internet connection, which can be a very important factor in excavation practice as well.

A stand-alone license of the standard addition currently costs $179 USD (€163), whereas the professional version costs $3499 USD (€3186). However, Agisoft provides special licenses with reduced prices to university students and institutions, which accounts to a price of respectively $59 USD (€54) and $549 USD (€500) for the standard and professional versions. This means that archaeological departments connected to universities can easily afford multiple licenses for their research and education, which stimulates the rapid increase in the use of digital photogrammetry in archaeology. Non-education archaeological institutions will have to pay more for their license, but the standard version of Photoscan is still quite affordable and will provide with the opportunity to include a photogrammetric recording workflow in their projects, which can be georeferenced in external software.

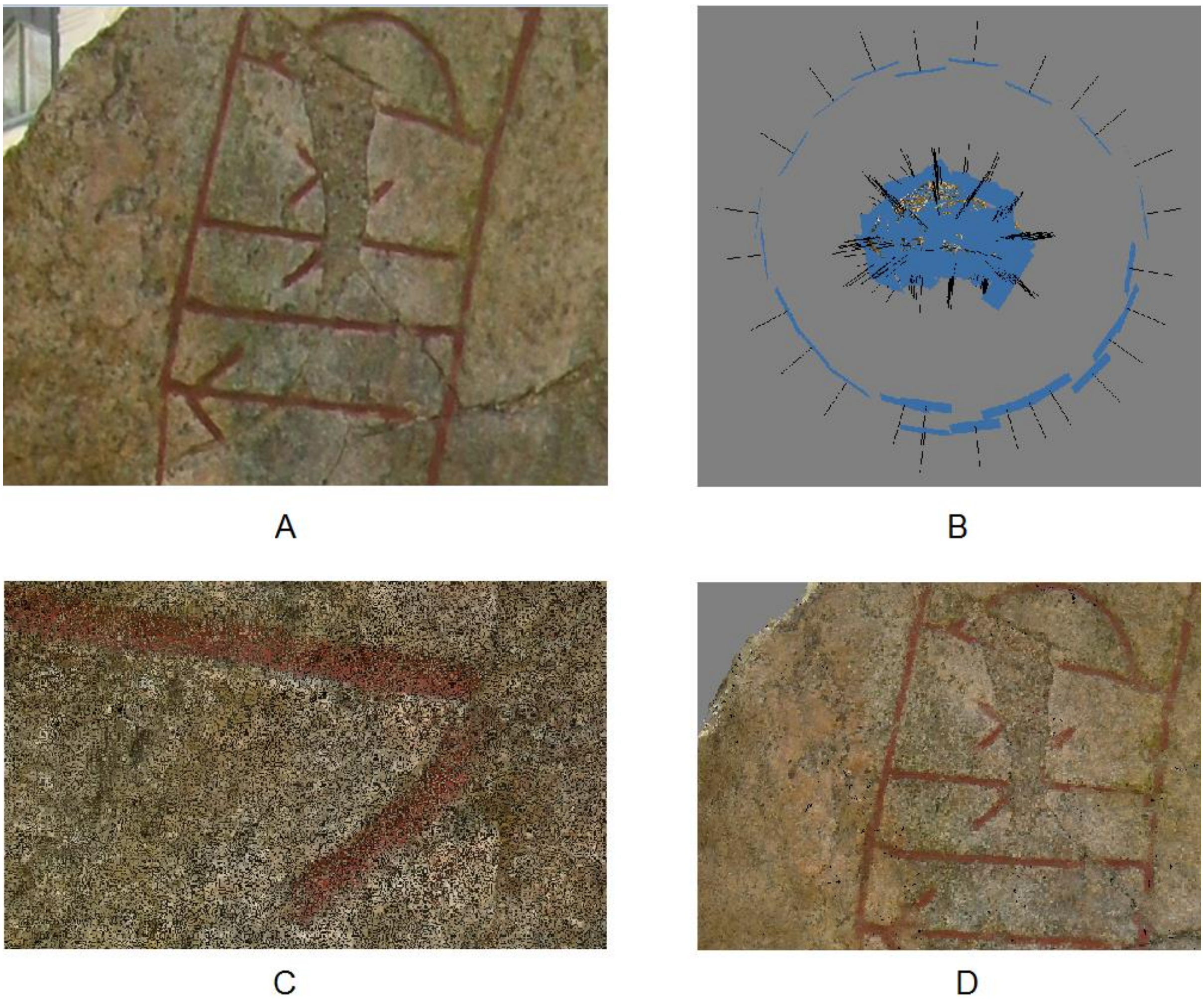


Figure 5. Different steps from 2D images to a 3D textured model of a runestone. A) One of the 198 original images used to create the model. B) Top view in Photoscan showing the reconstructed camera positions as blue panes. C) Dense point cloud showing detail of carved rune. D) Detail of textured model. Images and models by Sjoerd van Riel.

3 - Theoretical issues on the use of 3D recording in archaeology

The rise of a self-conscious archaeological theory debate can be traced back to the 1960's, when the so called new archaeology or processual archaeology emerged (e.g. Clarke, 1968; Binford, 1977). Theorizing and reflexivity was taken further by post processual archaeology from the 1980's onwards (Hodder, 1986; Shanks and Tilley, 1987; Hodder, 1989; Shanks and Tilley, 1992; Tilley, 1993; Hodder, 2001). GIS and digital technologies can hardly be placed within the limits of these paradigms. In fact, one point of view is that digital technologies are essentially just methodological; a set of tools that can be used to solve problems which are created by theoretical issues (Zubrow, 2006, p.11). However, another point of view is that digital technologies impact the current paradigm to such an extent that we can speak of a "*digital revolution*" (Zubrow, 2006, p.12) and influence the creation of new archaeological theory. This chapter aims to discuss these different points of view and the effect that new digital technologies have on archaeological theory. In particular, it will reflect on the implications of digital archaeology on landscape archaeology, and subsequently on the implications that digital techniques have on reflexivity and interpretation *at the trowel's edge.*

3.1 - The Digital Turn: implications of digital archaeology

The Digital Turn or Digital Revolution that archaeology is witnessing has several consequences for the current paradigm. The digital technologies offer us opportunities that we did not have before. Amongst others to manipulate and evaluate accurate measurements, to model and simulate real world processes and to create virtual worlds. Furthermore the technologies allow for the spread of all this information around the world with increasing speed, thus creating a "*digital village*" (Zubrow, 2006, p.12) in which the distance between archaeologists and their study areas, sites, artefacts and also colleagues is vanishing. Digital archaeology is filling the gap between processual 'scientific' and post processual 'interpretational' archaeology (Zubrow, 2010, p.2). Thus digital technologies should be seen as active agents that influence our thinking, rather than passive tools. There is a symbiotic relationship between the development of digital technologies and archaeological theory (Lock, 2003, p.1).

When we look back at the history of the introduction of several digital recording techniques, it has often been claimed that they were more objective compared to their predecessors (e.g. Anderson, 1982, p.200). The terms precision and accuracy are often used as a synonym for objectivity (Lock, 2003, p.4). It is argued that the more precise and accurate a recording technique, the more objective it is. But it is not taken into account that the process of the recording is still subjective and based on interpretation. Before the recording even takes place, it is subjectively decided what should be regarded as features, and which ones are worth recording. Secondly, the method of recording is decided. Since archaeological excavations are destructive by nature, it is the method of recording which determines how the feature will be preserved for the future (on paper, as a manual drawing or digitally as a series of points, line or photograph). The scale of recording is decided, which will affect the virtual preservation of the feature. According to most established excavation guidelines (e.g. the Museum of London Archaeological Site Manual - Westman, 1994), the method of find retrieving depends on a preliminary interpretation of the nature of the context. The method of recording is also directly influenced by the way that a context is preliminary interpreted and categorized, using different sheets for e.g. ‘deposits’ and ‘cuts’. According to Hodder (1999, pp.80-84), these interpretations derive from our theoretical pre-understanding of the archaeological record (figure 6).

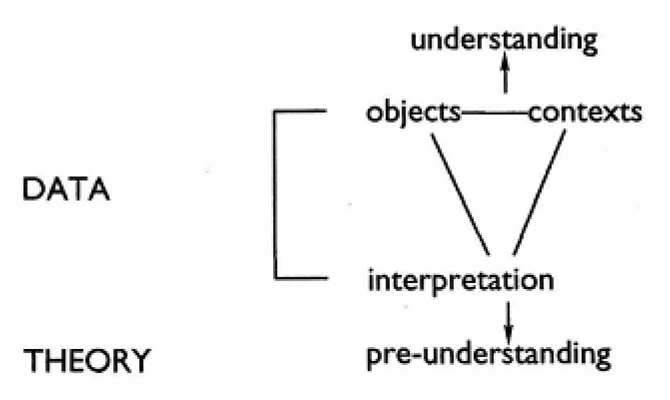


Figure 6. Relation between data and theory in archaeology, according to Hodder. Source: Hodder, 1999, p.84.

In this way, (digital) recording and the resulting models are part of the hermeneutic spiral, the process of interpretation. Figure 7 shows a visualization of the position of digital models within the hermeneutic spiral of archaeological interpretation. Their position derives from the data acquired out of the archaeological record in combination with the theoretical model that is used. In turn, these models are interpreted by the archaeologist and result in statements about the past (Lock, 2003, p.7).

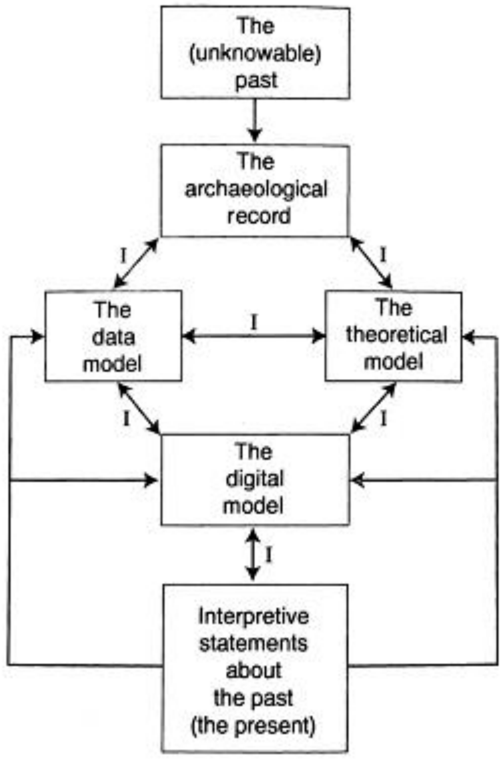


Figure 7. Visualization of the position that digital models can take within the hermeneutic spiral. Source: Lock, 2003, p.7

3.2 - Digital technologies and landscape archaeology theory

This section will discuss some theoretical developments within the study of landscape archaeology. Since archaeological sites are not isolated phenomena, their interpretation should be understood in a wider context. It is important to discuss first what comprises a landscape, and with the remains of what we are actually dealing with when we are excavating a site. After a possible definition of landscape and its components, I will discuss one of the current paradigms within post processual landscape archaeology; phenomenology. In particular, I will argue that digital archaeology has the potential to bring together different theoretical standpoints in landscape archaeology.

Landscape may be seen as consisting of a series of places, which are connected to each other by space. Space can be seen as a mere container of material objects, existing independently of these objects that fill it (Connoly and Lake, 2006, p.3). But it can also be seen as a "*positional quality of the world of material objects or events*" (Harvey, 1969, p.195) in which it is impossible for space to exist independently from the objects that are in it. In this view, everything that fills space is connected. The places are not cut off, but connected to the whole (Chapman, 2006, p.130). According to Tim Ingold (2000), places get meaning from those who spend time in them. Each of these places is special because of the unique combination of experiences, sights and sounds that take place in them. These sensual and mental experiences derive from the kind of activities in which the inhabitants of a place are engaged. This engagement with the world is what comprises the business of dwelling and what gives each place its unique significance (Ingold, 2000, p.192). By the array of related activities that are carried out by the people and animals that are dwelling in the landscape, something is created that can be called a *taskscape*. This taskscape is a social environment, where people tend to one another in the performance of their tasks (Ingold, 2000, p.196). One can regard the reconstruction of ancient taskscapes as one of the goals of archaeological excavations and analysis. Since the rise of post processual archaeology, scholars adopted the goal of reconstructing also the social environment of the taskscape, the agency of objects and the phenomenology of past people's tasks. The space of landscape is no longer seen as a 'container' in which human activities take place, decentered from agency and meaning. Rather, space is regarded as a medium in which human activity takes place. Space is involved in action (or tasks) and is socially produced and given meaning by particular societies and individuals (Tilley, 1994, p.10).

The use of sensory human experience to study past land- and taskscapes is what defines phenomenological studies. "*It* (phenomenology) *attempts to reveal the world as it is actually experienced directly by a subject as opposed to how we might theoretically assume it to be. The aim is not to explain the world but to describe that world as precisely as possible in the manner in which human beings experience it … coping with that attribute which is most distinctively human: subjectivity*" (Tilley and Bennett, 2004, p.1) This definition explains what phenomenology does but also reveals what could be recognized as one of its main problems: the subjectivity of humans in combination with "*revealing the world as it is experienced*". When an archaeologist is walking around a monument and perceiving it in a certain way, it is difficult to prove that a person who perceived the same monument hundreds of years ago had a similar experience. This problem is also recognized by Johnson (2012), who states that "*although phenomenology proposes a problematizing of human bodily experience, practitioners often tend towards a position of psychic human unity and away from an anthropological understanding of human experiences as being culturally different*" (p.277). In my opinion this is one of the biggest problems with phenomenology: that it is impossible to project our own experiences of a landscape on a prehistoric person, who lived in a totally different culture with a different *habitus*. There is no way of proving any experience that this prehistoric person might have had. Together with the problem of only experiencing contemporary landscapes because the prehistoric ones are lost, this is one of the most common critiques on phenomenological research: the fact that it cannot be verified (Fleming, 2006, p.268).

However, I think that digital technologies and in specific the use of virtual reality systems represent powerful simulation tools capable of providing archaeologists with information that can be used to apply a stronger control on phenomenological aspects of the interpretation. In past years GIS has been accused of being a processual tool. It has been denied the possibility to work together with a phenomenological approach, with the argument that "*it can only produce an abstract knowledge. It can't reproduce a sense of place acquired through being in place.*" (interview with C. Tilley, in: Bender, 1998, p.81). It has also been argued that the use of GIS has re-introduced the positivist approach of processual archaeology (Wheatly, 1993, p.133; Gaffney et al., 1996, p.132) But Tilley and others are mainly referring to the GIS tools available in the 1990s, when the software was indeed mainly used to produce bi-dimensional maps. After two decades of rapid development, I would argue that GIS and other digital methods are not a hindrance, but a tool that eventually can be used in support of phenomenological claims. Llobera (2012) discusses the use of GIS as a 'scaffolding model/method', with which he means a model to "*investigate concrete components or specific aspects of theory...constructed to explore how processes or concepts may play out within the specifics of a certain context. While no comprehensive interpretation is meant to emerge from their application, their construction can be seen as an attempt to shorten the gap that often exists between empirical information and narratives*" (pp.503-504). GIS can functions as a scaffolding method within the field of phenomenology, since it allows for the testing of at least two of the human senses that are used in phenomenological studies: visibility and sound.

The first human sense that can be effectively studies through GIS is visibility. Llobera (2003; 2012) introduced the concept of a *visualscape,* referring to the visual structuring of space. Visualscapes are considered to be a substantial source of many observations by archaeologists in the field (Llobera, 2012, p.501). They can be analyzed through a GIS by, amongst others, viewshed analysis. By using viewshed analyses, it is in fact possible to estimate which part of the landscape was visible from a certain point. Perhaps even more important, one can identify 'empty' places in the landscape which are in between, but within visible range of, different monuments and thus might have been significant places in the past but did not leave any physical remains (Chapman, 2006, p.136). A state-of-the-art example of 3D GIS-based visibility analysis to investigate the symbolic dimension embodied in standing structures and its paintings can be found in Landeschi et al. (2016), in which a 3D line-of-sight (LOS) analysis was employed in order to simulate past human perception of a Pompeian house. Virtual Reality (VR) can be used to test different scenarios of how the past landscape might have looked, thus overcoming the critique on phenomenology that it deals only with the modern landscape. One can simulate different archaeological scenarios such as different positions of the sun, and use immersive systems such as Oculus Rift (Oculus.com, 2016) to experience these scenarios, *almost* as if one was really there.

The second human sense that can be experimented within GIS is sound. One example of this is a study on the impact of church bells in early medieval towns. This has been done for the medieval city of Lund, where researchers have plotted medieval churches and processional routes and calculated the range of sound to explore in which parts of the city it was possible to hear the bells (Staaf, 1996). Thus, GIS has developed from a mainly bi-dimensional, 'processual' mapping tool into an interactive tool that can explore and reconstruct human interaction with the landscape, including at least two of the human senses (visibility and sound). There are several case studies that show a successful integration of virtual reality and phenomenology (e.g. Winterbottom and Long, 2006). The main advantages of the use of GIS and VR in support of phenomenological studies, is that they help overcome two of the major issues that I described earlier in this section. The first one is the problem of temporality. Where it is only possible to walk and experience the contemporary landscape in real life, GIS and VR help to reconstruct and test hypothetical past landscapes including vegetation, buildings etc. and experience those. The second problem with phenomenology that can now be overcome relates to the issue of verification. Using GIS and VR, experiments can be done over and over, under different or the same circumstances, and by different persons. This allows for referencing to more than the personal experience of an archaeologist, which could make phenomenology a bit more 'scientific' in the eyes of its critics.

3.3 - Reflexivity and interpretation *at the Trowel's Edge*

In the previous sections I have discussed some of the implications that digital technologies have on a wide range of landscape archaeological theory and practice, including the highly interpretational field of phenomenological archaeology. This section will focus on the single excavation scale and discuss the role of interpretation and theory on this level.

The digital recording techniques that have been described in this thesis have had a major impact on the field of archaeological practice. One aspect of this impact is the erosion of the traditional separation between data acquisition and data description (Connoly and Lake, 2006, p.37). Traditionally, a division existed between a-theoretical excavation practice and recording on the one hand, and interpretational and theoretical post-excavation work on the other (Beck and Beck, 2000, pp.173-174). The context sheets that make a distinction between description and interpretation as advocated by Barker (1977;1982;1993) and described by Hodder (1999), are still in use at excavations today. Carver (1989) argued that this practice of distinguishing between description and interpretation is particularly strong in Britain, where "*English excavators, particularly, believe that there ought to be a science of retrieving archaeological evidence which has nothing to do with the interpretations that are subsequently made*" (p.669). However, when the information acquired during post-excavation can also be available in the field, the barriers between excavation and post-excavation (and with it, between practice and theory) can be broken down (Beck and Beck, 2000, p.174). This is needed because theoretical interpretation is an integral part of archaeological practice. As Hodder (1999) shows, archaeological excavations are driven by theory from the beginning, rather than theory as a final process after the 'objective' empirical evidence is recorded (figure 6). Even the most practical actions in an archaeological excavation involve interpretation. Hodder gives the example of 'interpretation at the trowel's edge': "*As the hand and trowel move over the ground, decisions are made about which bumps, changes in texture, colours to ignore and which to follow. This is a practical bodily interpretation. It is influenced by one's interpretation of what is happening and by what one is finding. If an artifact flicks out, we interpret whether it came from this layer or that*" (p.92).

The occurrence of interpretation in the field is a prerequisite for a research-centered approach (Beck and Beck, 2000, p.176). Such an approach involves specific questions that are formulated before the excavation starts, and that are going to be 'asked' to the archaeological material. A question-centered approach has several advantages. The result of the work is more likely to be a coherent story, since the archaeologists know what they are collecting and why they are collecting it. But this approach can also be destructive, when the selectiveness results in ignoring the archaeological remains that are deemed irrelevant to the questions (Morris, 1997). In order to prevent such 'tunnel vision' and for the excavators to "*place their thoughts in context and make balanced judgements based on a greater understanding of the site as a whole*" (Beck and Beck, 2000, p.180), a reflexive methodology is required.

A definition of reflexivity according with Hodder is "*the examination of the effects of archaeological assumptions and actions on the various communities involved in an archaeological process, including other archaeologists and non-archaeological communities*" (Hodder, 2000, p.9). On the site of Çatalhöyük in Turkey, where Hodder is leading the Çatalhöyük Research Project, reflexivity is engendered by diary writing and filming, amongst others. The goal of these processes is to encourage the archaeologists to examine their own assumptions and provide contextual information on the excavation process which can be reviewed and evaluated by others (Hodder, 2000, p.9). In a recent article which is evaluating these and other reflexive methods in Çatalhöyük, it was shown that the digital techniques that have been developed in the last 15 years and applied in the Çatalhöyük Research Project facilitate several aspects of a reflexive approach. One example that is given is the use of tablets on the site which allow "*more information to be concentrated at the moment of excavation and interpretation in the trench*" (Berggren et al., 2015, p.437). In this way, the process of excavating is aimed to be made "*virtually reversible*" (Berggren et al., 2015, p.437). The use of digital tools has even allowed for "*reflexive re-interpretation*", where the use of digital 3D modelling made it possible to positively confirm skull retrieval at Çatalhöyük (Berggren et al., 2015, p.440-441). Furthermore, the project at Çatalhöyük showed that an intra-site 3D GIS improved the excavator's abilities to present and interpret archaeological data, and that the use of tablets in the field enhanced the reflexive method significantly (Berggren et al., 2015, p.442). In fact, the tablets were found to be a "*reflexive tool in their own right*", by providing the archaeologists with the possibility to produce a graphic archive that incorporated all the available data, including 50 year old georeferenced excavation plans of the area, allowing for more informed decisions and interpretations and thus improving the reflexive engagement of the excavators (Berggren et al., 2015, p.443).

In conclusion, I have argued that digital technologies bridge field data and theory with landscape theory. They help verifying viewpoints that are traditionally seen as extremely theoretical (e.g. phenomenology) and theorizing practices that are seen as a-theoretical (e.g. fieldwork practice). More importantly, this is done in the same virtual space of a GIS. In these multi-scale platforms archaeological data from a landscape level down to artefact level can be visualized, categorized and analyzed which stimulates a reflexive and theoretical approach.

4 - From theory to methods: the case study of Uppåkra

In this chapter, the 3D recording technologies and the theoretical viewpoints described above will be brought together and discussed in the light of an excavation that was conducted in the autumn of 2015 in Uppåkra, Sweden. This excavation was chosen as case-study for this thesis for several reasons. Firstly the author of this thesis has personal experience with excavating and digitally documenting the site. Secondly the site has an extensive history of experimenting with 3D recording, as will be discussed in chapter 4.1. These years of experience have led to the current method of 3D documentation that was used on site and discussed in chapter 4.2 and onwards. The third and final reason why Uppåkra is a suitable site for this study is because of its complicated stratigraphy (Larsson, 2003, p.10). This complexity provides a challenge to the digital methods that have been developed by Lund University, DARKLab (Digital Archaeology Laboratory), but strengthens the robustness of the method's workflow.

The site of Uppåkra is located approximately five kilometers south of Lund in southern Sweden (figure 8). It was first discovered in 1934, when excavations revealed cultural layers that were more than two meters thick (Vifot, 1936; Stjernquist, 1996) and has been the subject of extensive archaeological research from 1996 onwards, when the '*Uppåkra Research Project*' was initiated (Larsson, 2003).

Figure 8. Location of Uppåkra (red dot) in southern Sweden, some 60km east of Copenhagen (København). Pictures ©2016 Landsat, Data SIO, NOAA, U.S. Navy, GNA, GEBCO, Map data ©2016 GeoBasis-DE/BKG (©2009),Google. Source: maps.google.com, 2016.

In the period 1997-2000, almost 20.000 objects were found during large-scale metal detecting surveys. These objects suggested a settlement sequence from the late Pre-Roman Iron Age until the late Viking Age (Hårdh, 2000; 2003). A cluster of metal objects with high technological and chronological variety was found in the area just south of the church, which is the highest place in the landscape today. Excavations between 1999 and 2005 focused on this location, and revealed the remains of a distinctive cult house-like building in which more than a hundred gold-figure foils (Watt, 2004), a metal beaker (Hårdh, 2004) and a glass bowl (Stjernquist, 2004) were found (Larsson, 2007, pp.12-14). Figure 9 shows an overview of the Uppåkra landscape elevation, based on LIDAR data, together with the locations of the 2001-2004 excavation trenches and the location of the cult house. On this figure, it is clearly visible that the cult house was located on what is the highest point of the landscape today (visualized in white colours).

Since the late 1990's, several geophysical prospection methods have been applied to explore a large portion of the land around the cult house area, as the land was found to be very suitable for the testing of geophysical methods (Lorra, Kroll and Thomsen, 2001; Trinks et al., 2013). Since 2010, prospections have been carried out by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro).The goal of these prospection surveys has been to integrate spatiotemporal analysis and archaeological interpretation, thereby focussing on the wider landscape instead of just the site (Trinks et al., 2013, p.1). These prospection surveys have revealed a large number of anomalies indicating the remains of approximately 60 Iron Age buildings in the centre of the settlement, in the same area where the cult house has been found (figure 10 - Trinks et al., 2013, p.2).

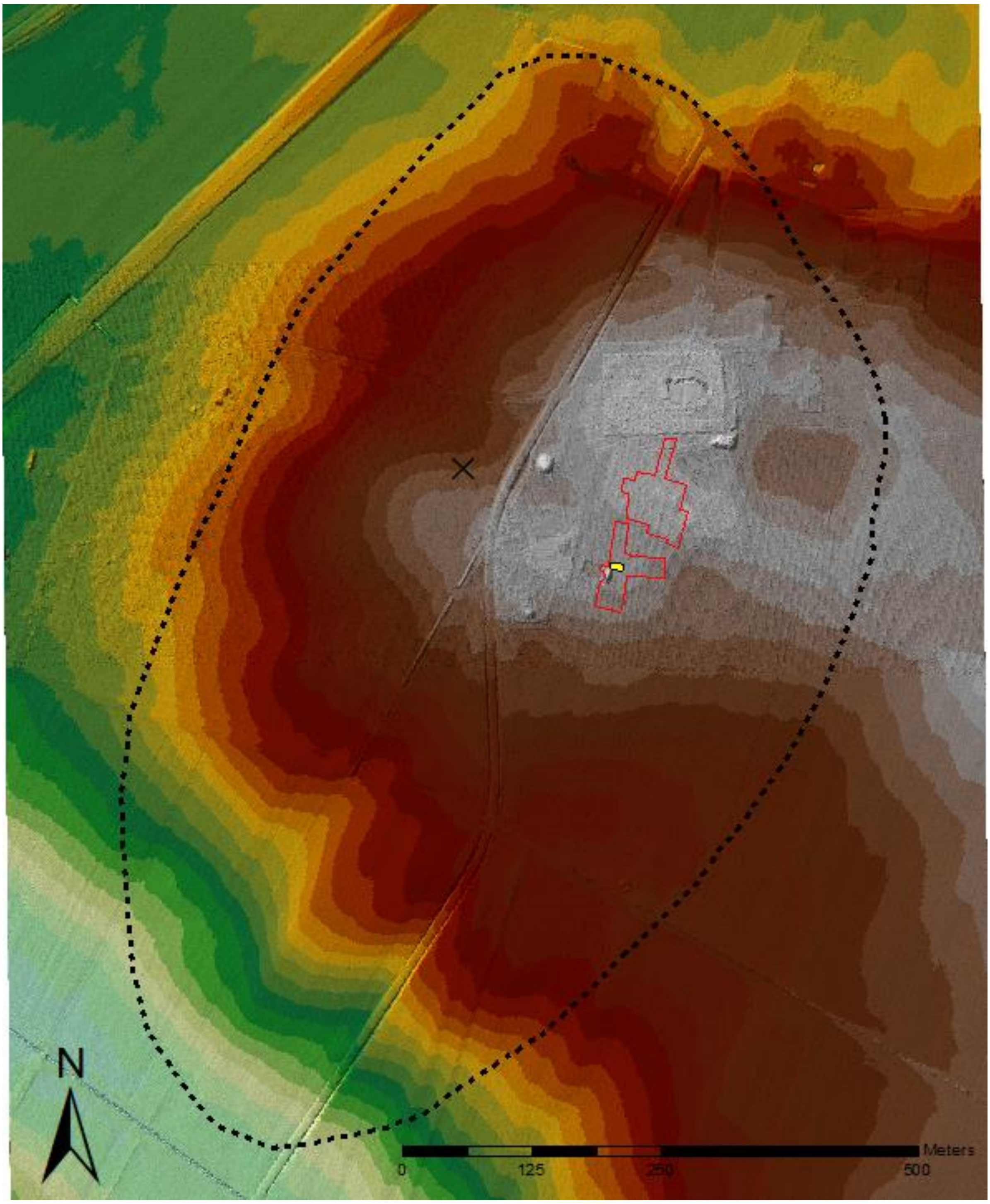


Figure 9. Map showing a Digital Terrain Model of the Uppåkra area. The assumed extent of the Iron Age settlement and the location of the 2015 excavation are marked in black and the 2001-2004 excavations in red. The location of the cult house is marked in yellow. LIDAR © Lantmäteriet I2014/00579. Site extension boundary after Sjernquist, 1998, p.4. Location of trenches and cult house after Larsson, 2007, p.14.
Map by Sjoerd van Riel.

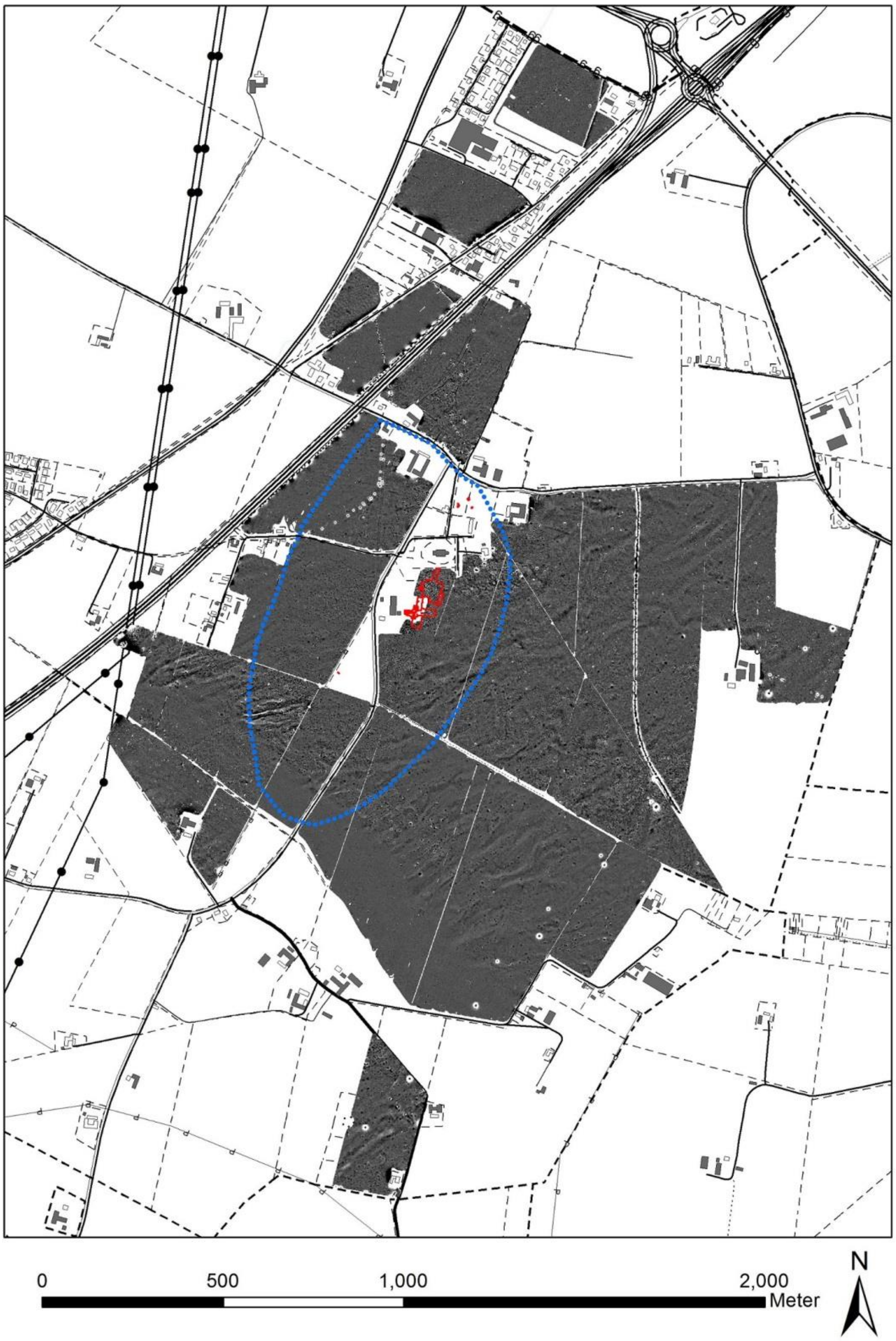


Figure 10. Map showing the extension of the magnetic archaeological prospection survey conducted by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology in 2010-2012. The assumed extent of the Iron Age settlement is marked in blue and the 2001-2004 excavations in red.
Courtesy of Immo Trinks, LBI ArchPro

In 2015 a new project called '*The Key to Uppåkra: digitizing a unique archaeological cultural heritage*' was created, which aims to create an integrated database containing the spatial and chronological data of Uppåkra that has been acquired over the years, and to visualize this data for further research and the public (ark.lu.se, 2015). The data generated in the frame of this project could be integrated with the 3D analyses that were conducted during the course of this thesis in order to create a multi-scale 3D GIS system containing all the spatial and attribute data of the Uppåkra excavations thus far, which could subsequently be used in order to perform analyses which were not possible before this integration, e.g. the combination of old and new excavation data in the same virtual space.

4.1 - Excavation, recording and documentation methods in Uppåkra

The excavation method in Uppåkra follows the *single context* method (Westman, 1994). All contexts, layers and other features are measured with a robotic total station (RTS) and photographed and drawn by hand when necessary. The method of find retrieval depends on a preliminary interpretation of the context in which the find is located (e.g. a potentially more interesting context will be water-sieved, but a context that is interpreted as a secondary deposit will not). In general, all finds are connected to the context in which they were found through a unique context number which is directly linked to the graphic documentation made by total station. During the excavation archaeologists and students are encouraged to keep field diaries, which should provide a more narrative and less coded documentation.

Since 2010, experiments with using 3D models to document and interpret on-going excavations have been conducted in Uppåkra via a collaboration between the Department of Archaeology and Ancient History of Lund University, Sweden and the Visual Computing Lab in Pisa, Italy (Callieri et al., 2011; Dellepiane et al., 2013; Dell'Unto, 2014, pp.152-153). The first tool that was tested for its suitability to record an ongoing excavation of an Iron Age longhouse was a ToF laser scanner. Although the device was extremely accurate and had a short acquisition time, the post processing took too long to use this instrument for the documentation of an ongoing excavation (Dell'Unto, 2014, p.153). In the frame of the same experiments, image based 3D reconstruction techniques were carried out. Due to the relatively easy acquisition process and fast post processing, the employment of such techniques proved to be more promising for further development of a 3D field documentation method. Due to the hardware and software limitations that occurred at that time, this approach was tested on a small portion of the ongoing excavation in order to provide archaeologists with 3D models which could be used to evaluate the excavation process and to take accurate measurements concerning the spatial relations among the different contexts and materials retrieved during the field investigation. However, these experiments were conducted separately from the regular excavation practice, by a special team. The results encouraged the researchers to discuss possible uses of this approach for the definition of formal guidelines for field archaeologists so that the method could be better integrated with the normal excavation workflow (Dell'Unto, 2014, p.153; Dellepiane et al., 2013, p.209).

In 2011, in occasion of a seminar excavation (Söderberg and Piltz Williams, 2012), an experiment was designed to evaluate the impact of the models on the process of excavating, with the following goals: *(1) to assess the sustainability of a documentation method based on the combination of 3D models and traditional data, (2) to evaluate the use of 3D models as geometrical references for documentation, and (3) to shed light on whether the use of different visualization* *tools increased comprehension of the stratigraphic sequence of the site within the time frame of the investigation* (Dell'Unto, 2014, p.153). The subject of this experiment was a late Neolithic grave which was detected the year before during the geophysical prospections (Trinks et al., 2013, p.4; Larsson et al., 2015). The grave was documented combining a total station for graphic interpretations by the excavators, with image based 3D modelling for better understanding of the excavated material (Dell'Unto, 2014, p.154). The models were produced daily and used by the excavators to discuss the stratigraphical sequence and to create visualizations which provided a deeper understanding of the contexts. Though able to reach most of their goals, the researchers acknowledged an important limitation of the method at the time, namely the impossibility of using a 3D visualization platform to visualize both the traditional documentation acquired by total station and the 3D models generated by image based 3D reconstruction techniques. This prevented a "complete visual description of the site's documentation" and caused the loss of a large part of the communication power of the 3D models (Dell'Unto, 2014, p.156). To solve this problem, the models were imported into ArcScene. A big advantage of this method was the possibility to connect attribute tables to the models, which allows for the direct connection of field records with the 3D models. However, there were still several challenges to be overcome such as the fact that at that time ArcScene was only able to import models which consisted of less than 34.000 polygons (Dell'Unto, 2014, p.157).

During the 2012 excavation season, 3D documentation using image based 3D reconstruction was carried out by students during the course of seminar excavations from Lund University's Department of Archaeology and Ancient History (Söderberg, Piltz Williams and Bolander, 2014, pp.14,26). In 2013 and 2014, image based 3D modelling was again used by students of Lund University (Apel and Piltz, in press). In specific, the 3D models of an Iron Age low-temperature oven (Apel and Piltz Williams, in press) were used in a study that explored the potential of the models as geometrical reference for 3D drawing in ArcScene (Kimball, 2014). This study found that archaeological drawings could be successfully accomplished in a 3D GIS, thereby successfully connecting the metadata (context numbers etc.) with the drawings through attribute tables in the GIS database. Furthermore, a chronological overview of the context could be provided, with the possibility of switching back and forth between different phases of the excavation (Kimball, 2014, p.63). Although the study showed very promising results and demonstrated the potential that 3D models have to be used for 3D context drawing, the author also recognized that the presented methodology could not be seen as a replacement of traditional documentation methods, but rather had to be used as complementary methods (Kimball, 2014, p.64). Furthermore, the study did not explore the possibilities of 3D drawing directly in the field, since the models were created previously and the drawing was only applied when the excavation was already over (Kimball, 2014, pp.29-30).

This thesis instead explores the possibilities for adapting these 3D context drawing methods in order to be used for real-time documenting of all archaeological contexts. In the following chapters, I will discuss the methods of 3D data acquisition during the excavation of 2015. I will focus on only one of the three excavation trenches, specifically the one that was located around the oven that had been excavated in the previous years and discussed in the thesis described above. The objective for the 2015 excavation in this area was to determine if there were any older ovens located underneath. In order to do this in an effective manner, it was decided to create a section which measured about 8 meters in east-west direction and 50 cm in north-south direction. At the end of the excavation, the section reached about 65 cm deep. Such a section is very suitable for a study such as this thesis, since it provides a deeply stratified 'micro-excavation' of a small area, which is a challenge for the single-context documentation methodology since it is hard to distinguish between different context in such a narrow but deep trench (see chapter 5.2.3).

4.2 - Methods of 3D data acquisition during the excavation of 2015

This thesis is based on the 3D recording activity and documentation conducted during the 2015 fieldwork season. In this section I will discuss the different methods of 3D data recording and documentation employed in support of the field documentation and analysis. First I will discuss the methods for 3D landscape recording (sections 4.2.1 and 4.2.2) and after that I will discuss the methods that have been used for the trench and context recording (sections 4.2.3 and 4.3).

4.2.1 - LIDAR

The LIDAR data used in the frame of this study was acquired and made available from the Swedish land survey service (lantmäteriet) with the license of Lund University (© Lantmäteriet I2014/00579). The full wave form scanning was commissioned by the Swedish government and carried out by lantmäteriet in April 2010. The point clouds are georeferenced in SWEREF 99 ™ (plane) and RH 2000 (height). The points are classified in four classes representing the ground, water, bridges and unclassified points (Lantmäteriet, 2015). The area of Uppåkra has fairly good conditions for ALS survey since there are little natural factors that can disturb the point cloud classification, such as heavy vegetation, steep terrain or water (Lantmäteriet, 2015, pp.11-17). This has resulted in a point cloud with an average point spacing (distance between the points) of 0.93m. Due to flight overlap, the point density in my study area differs in certain areas (figure 11). The point clouds coming from the different acquisition flights have also been slightly mismatched. As a result of this, a horizontal band will be seen in most DTMs of Uppåkra since they will be based on the same raw laser data (figures 9, 11, 13 and 14).

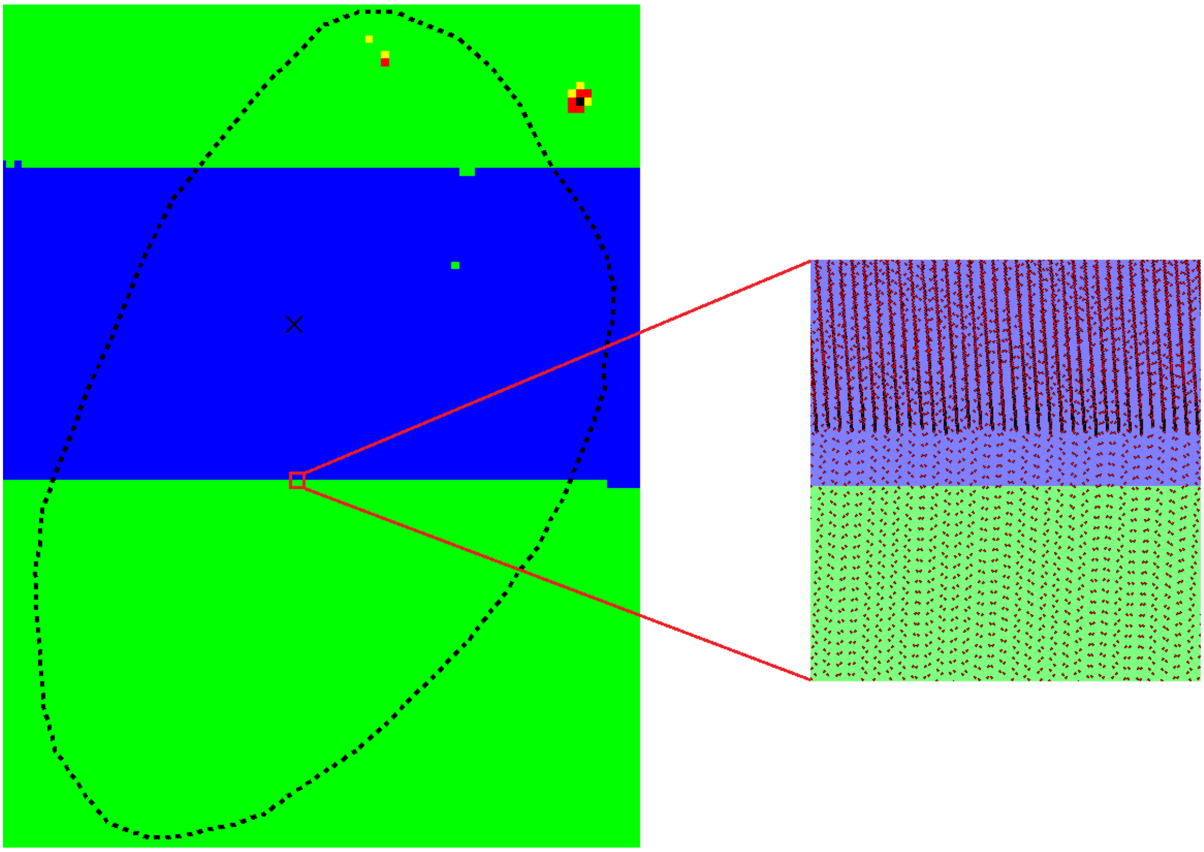


Figure 11. Map of the Uppåkra study area representing the flight coverage (blue colour represents > 1 point/m² and green colour > 0.5 points/m²). Estimated site extensions and 2015 trench location are visualized in black. LIDAR © Lantmäteriet I2014/00579. Images by Sjoerd van Riel.

The point spacing resolution of 0.93m means that the DTM that can be created with the data will be detailed enough to visualize changes in the morphology of the terrain and big features such as mounds. However, the DTM will not be able to reveal any kind of feature that is smaller than about one meter. This is a significant limitation if the goal is tracing archaeological features, since many of those (e.g. post holes, small waste pits or other smaller deposits) will be too small to be visible in the DTM. However, the LIDAR data is particularly useful for the creation of terrain models which highlight different aspects of the landscape in general, such as slope or aspect. For this reason, it can be extremely helpful to create a more detailed DTM from a point cloud that is generated with the use of photogrammetry from aerial photographs. The use of UAVs for this method has proved to provide much more detailed terrain models in comparison with models coming from LIDAR data, which can lead to the identification of more archaeological structures (De Reu et al., *in press*). The survey carried out in Uppåkra to test this method will be described in section 4.2.2 of this thesis.

From the LIDAR point cloud, a Triangulated Irregular Network (TIN) is created, which is a vector-based interpolation that results in a mesh of triangles which represent the surface morphology (figure 12 - see Connoly and Lake, 2006, pp.107-109 for detailed information about the creation of a TIN).

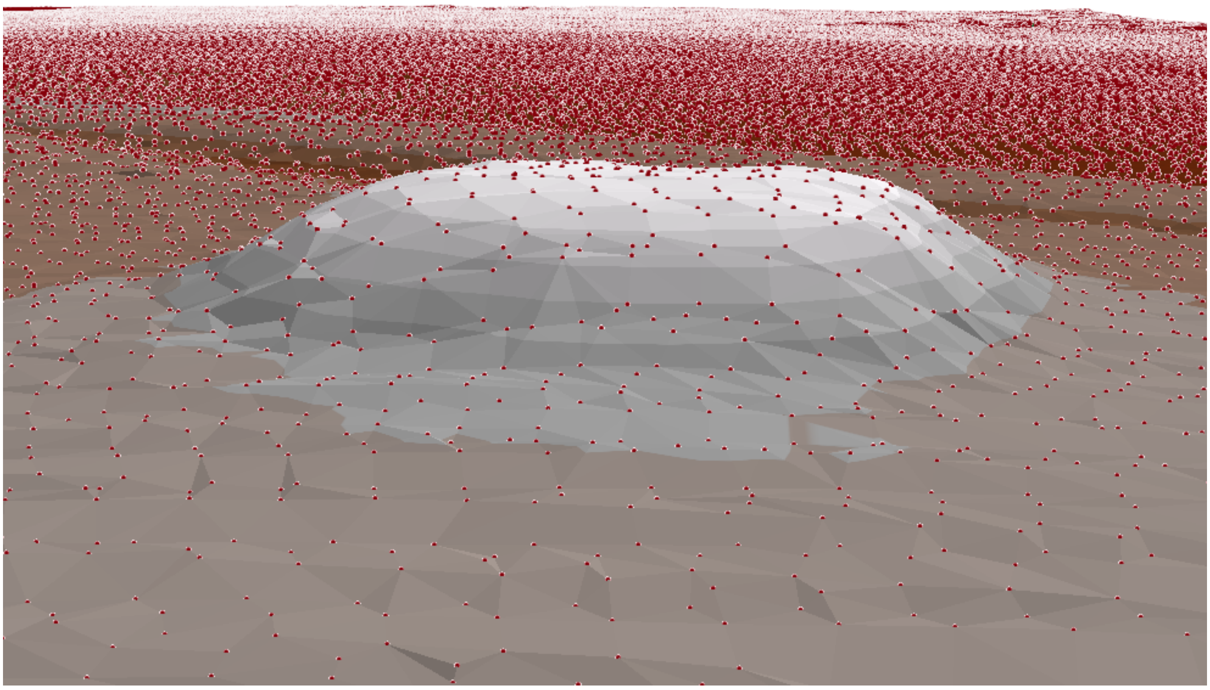


Figure 12. Lidar point cloud and TIN visualization of one of the Bronze- or Iron Age mounds in Uppåkra. LIDAR © Lantmäteriet I2014/00579. Image by Sjoerd van Riel.

TIN data structures are extremely useful but also have some limitations. One of them is that they lack mathematical potential. In order to compare surface morphology systematically, a TIN needs to be converted to a raster (Chapman, 2006, p.73). This can be done in several ways. In my case, the raster image was created in ArcGIS by interpolating raster cell values from the elevation of the input TIN at a specified sampling distance, in this case 10cm (Chapman, 2006, p.77). On the raster Digital Elevation Model (DEM), several surface analyses can be performed in order to detect archaeological features or to understand terrain formation in relation to archaeological distribution. In this case, a hillshade (figure 13A) and slope (figure 13B) analysis have been created.

Hillshading is used to display details of topographic change. Hillshading creates a shaded relief from the surface raster by considering the illumination source angle and shadows (Kokalj, Zakšek and Oštir, 2013, p.103). In my case, the default settings of ArcGIS with an altitude angle of light (measured from the horizon) of 45° and an azimuth angle of light (measured as a compass clockwise from the north) of 315° degrees were used. One of the major drawbacks of hillshade analysis results from the fact that linear features that are located parallel to the direction of the light source will not be visible (Kokalj, Zakšek and Oštir, 2013, p.104). To overcome this problem, the user can produce several hillshades with different azimuth (angle of light) values (figure 14). Slope analysis uses the combination of both gradient and aspect, in this case resulting in a raster map of which the cell values relate to the inclination of slope calculated in degrees. An advantage of slope analysis over hillshade analysis is that it is not affected by the orientation of the features. However, a slope analysis is less powerful for low relief landscapes (Challis, Forlin and Kincey, 2011, p.287).

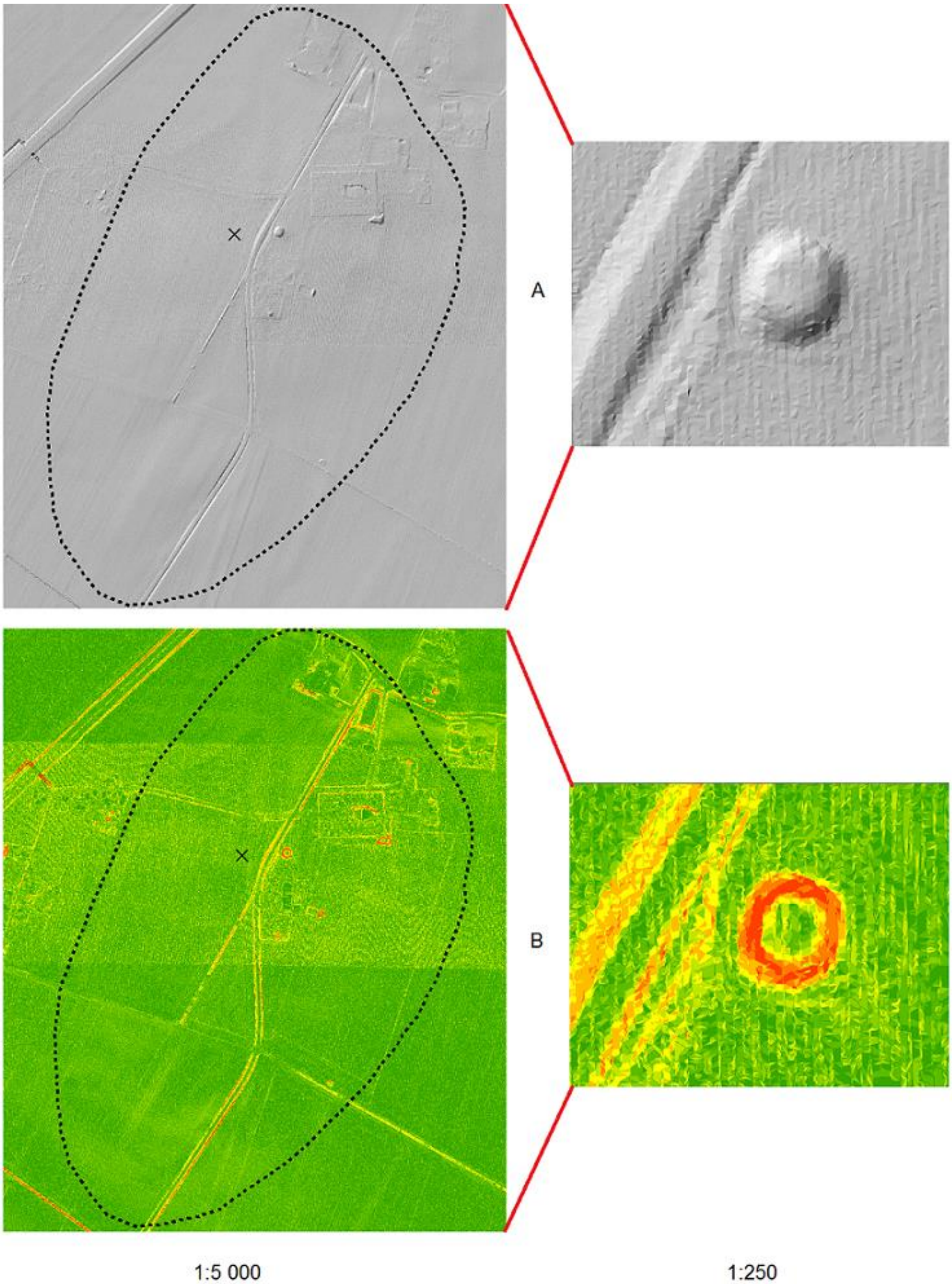
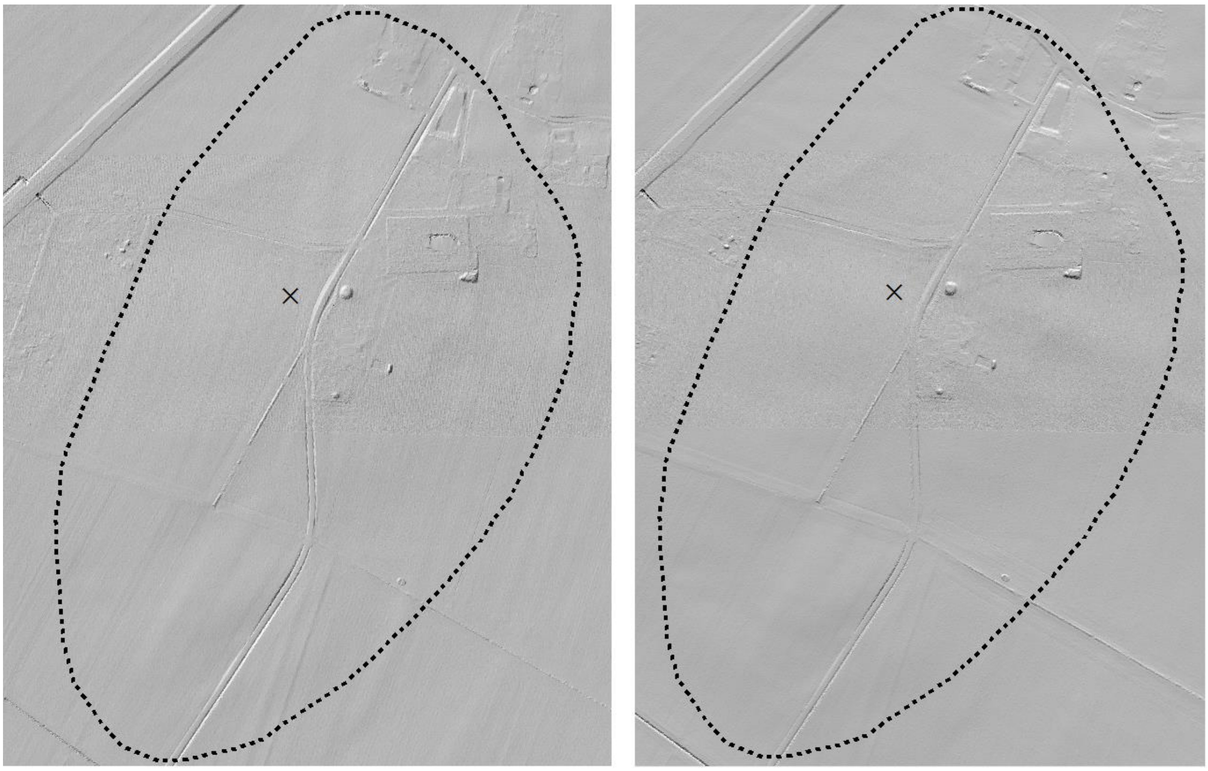


Figure 13. Raster DEM with a cell size of 10cm showing a hillshade (A) and slope (B) analysis of Uppåkra. Note the artificially created horizontal band due to difference in point density that is well visible in the slope analysis. Highlighted is one of the two remaining Bronze- or Iron Age mounds. Site extensions and 2015 trench location are visualized in black. LIDAR © Lantmäteriet I2014/00579. Images by Sjoerd van Riel.



A - 315° azimuth B - 360° azimuth

Figure 14. Different hillshade analyses with azimuth set on 315°(A) and 360°(B). Note the difference in potential for identifying structures that are oriented in north-south direction (A) or east-west direction (B). Estimated site extensions and 2015 trench location are visualized in black. LIDAR © Lantmäteriet I2014/00579. Images by Sjoerd van Riel.

The LIDAR data provided by lantmäteriet has not led to the identification of previously unknown features in Uppåkra. As a result of agricultural ploughing, possible micro topography resulting from archaeological features is not easy to identify. The relatively low resolution of the LIDAR available from Lantmäteriet (0.93m point spacing) further decreases the likelihood to detect smaller archaeological features. Instead, the LIDAR data for this study has been mostly contributory for a sense of 'site-awareness' on the landscape scale. With site-awareness I mean the archaeologists' experience of where the site is located in the landscape, and how different areas of the site are related to each other. Moreover, it is important to be aware of the location of a specific excavation within the site, in this case our 2015 campaign trench, for which the location is marked with a black cross in figures 9, 11, 13 and 14. Landscape archaeology should not be separated from excavating archaeology, since the position of the excavation in the landscape has significant influences on its characteristics. In chapter three I have argued that the use of digital technologies can help integrating landscape- and field archaeology. One example of this is the integration of LIDAR data into the GIS system and in direct spatial relation with the field recording in order to stress the relation between the contexts retrieved in the field and the surrounding site. If we take a look at the 2015 excavation trench location, several observations can be made. Firstly the trench is located just outside the highest area (the 'plateau') where the cult house has been found (figure 9). It is also located alongside the modern road which runs north-south alongside two mounds which date from the Bronze- or Iron Age (figures 9, 12, 13 and 14). In other words, the trench is not located in the most significant area of the site (the plateau with the cult house), but still quite close to it. The interpretation of this location is outside of the scope of this thesis, but it is important that observations of site location and positioning relative to other structures on the site are included in the excavation documentation in order to maintain a reflexive method.

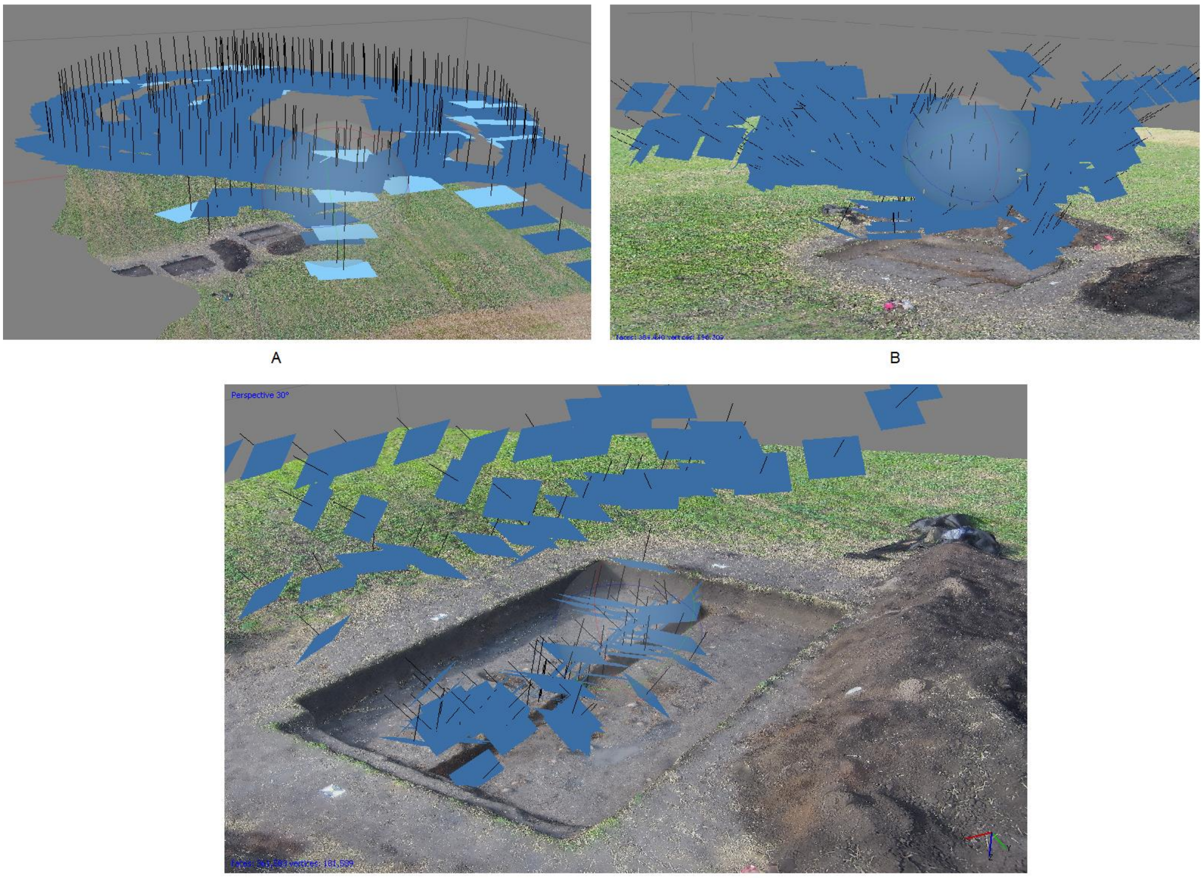
4.2.2 - UAV Image Acquisition

For the acquisition of aerial pictures, a Phantom 2 Vision+ drone was used (Dji.com, 2014). By the time of writing, this drone is already out of production and replaced by the Phantom 4. This illustrates the high demand for drones and because of that, a rapid development in technology. Drones will get cheaper and more powerful in the years to come, and we as archaeologists have to find a way to make use of this technology and develop a customized methodology that fits the archaeological practice and contributes to new methods, rather than just adapt the technology without theorizing its use.

The Phantom 2 is a quadcopter (four rotors) with a mounted 12 megapixel camera (figure 15). The camera's FOV (Field Of View) can be set between an angle of 110° and °85. The Phantom 2 was remotely controlled in manual flying mode since the acquisition campaign was not just focused on the landscape but also on the trench, and thus required a flexible flight pattern. For the acquisition of the landscape, the camera was turned in a 180° angle, aiming downwards. For the acquisition of the trench an angle between 90° and 135° was used, as can be seen on figure 15.

Figure 15. Phantom 2 Vision+ during the image acquisition campaign. Image courtesy by Giacomo Landeschi - Department of Archaeology and Ancient History, Lund University.

A total of 780 pictures were taken, divided over three different flights. Since the use of drones for both landscape and site analysis is still a developing field of study and experiments have to be conducted to test different methods, several flight methods were tested (all in manual mode) to see which would give the best results. It was decided to carry out three separate flights focusing on the landscape, an overview of the trench and a close-up of the section in the trench (figure 16).



A B C

Figure 16. Camera positions of the three different UAV flights, focussing on the landscape (A), an overview of the trench (B) and a close-up of the section in the trench (C). Pictures acquired by Nicolò Dell'Unto. 3D models by Sjoerd van Riel.

During the image based 3D reconstruction process, the images from the different acquisitions were combined in order to realize a 3D model which represented both the trench and the landscape. In this way, the 3D models generated by employing the pictures acquired by the drone allowed bridging the 3D model of the entire site (LIDAR) with the 3D models of the contexts retrieved and created during the excavation, providing a typology of information which is multiscalar and fills the gap that existed between close range photogrammetry/TLS and ALS. Figure 17 visualizes different 3D recording techniques categorized by object size and object complexity (or rather: recording complexity). It shows an inability to record in 3D objects which are between 100m and 2km in size with a recording resolution of more than 10.00 points (which is achieved with total station survey, e.g. extremely time consuming).

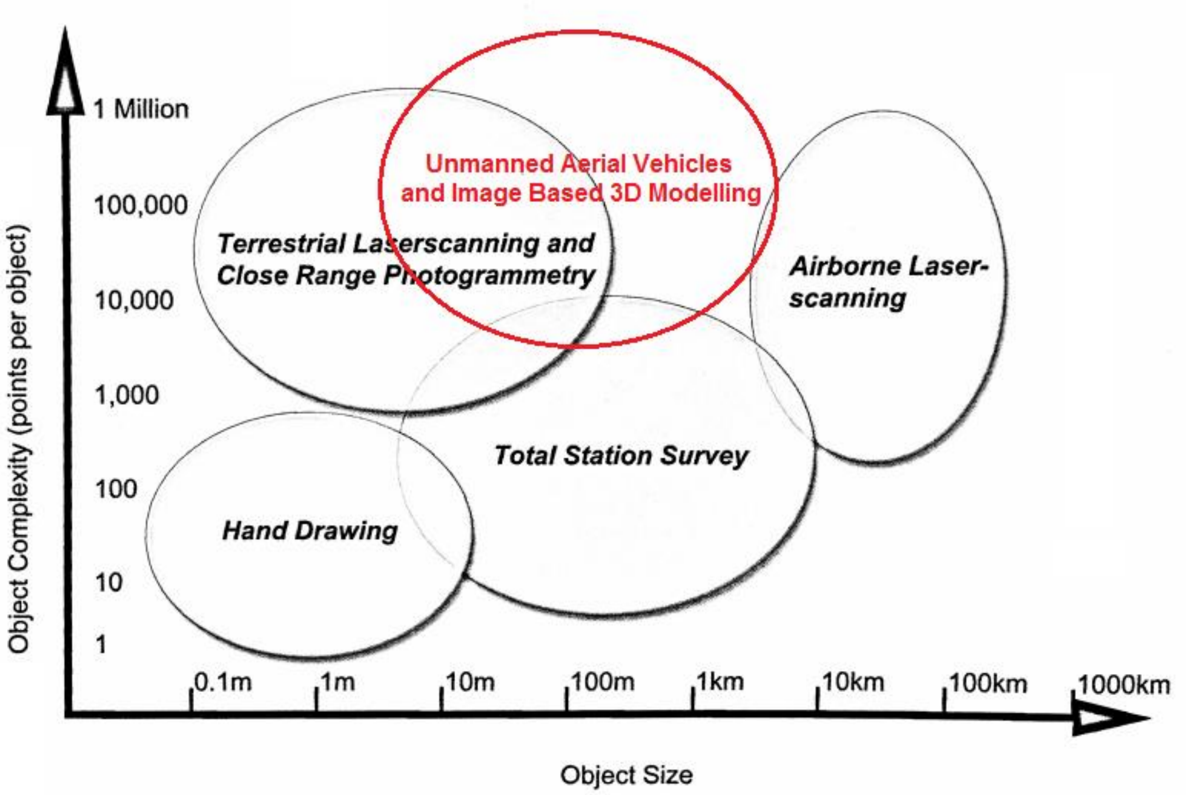


Figure 17. 3D Digital recording methods by object size and recording complexity. UAV survey can bridge the gap between TLS/close range photogrammetry, total station survey and ALS. Source original figure: Opitz, 2013 p.14. Additional edits in red by Sjoerd van Riel.

Using a combination of UAV and image based 3D modelling, it is possible to bridge this gap (red circle). UAVs can cover a range from a few meters up to more than a kilometer, and provide models which consist of several thousands and up to several millions of points. More importantly, the operator has direct control over the resolution of the model by changing the dense cloud settings in Photoscan. Moreover, contrary to laser scanning and total station survey the resolution of the model is not so much depending on the acquisition settings, but rather on the post processing. This means that data from the same acquisition can be used to create multiple models with different characteristics, depending on the needs of the archaeologists.

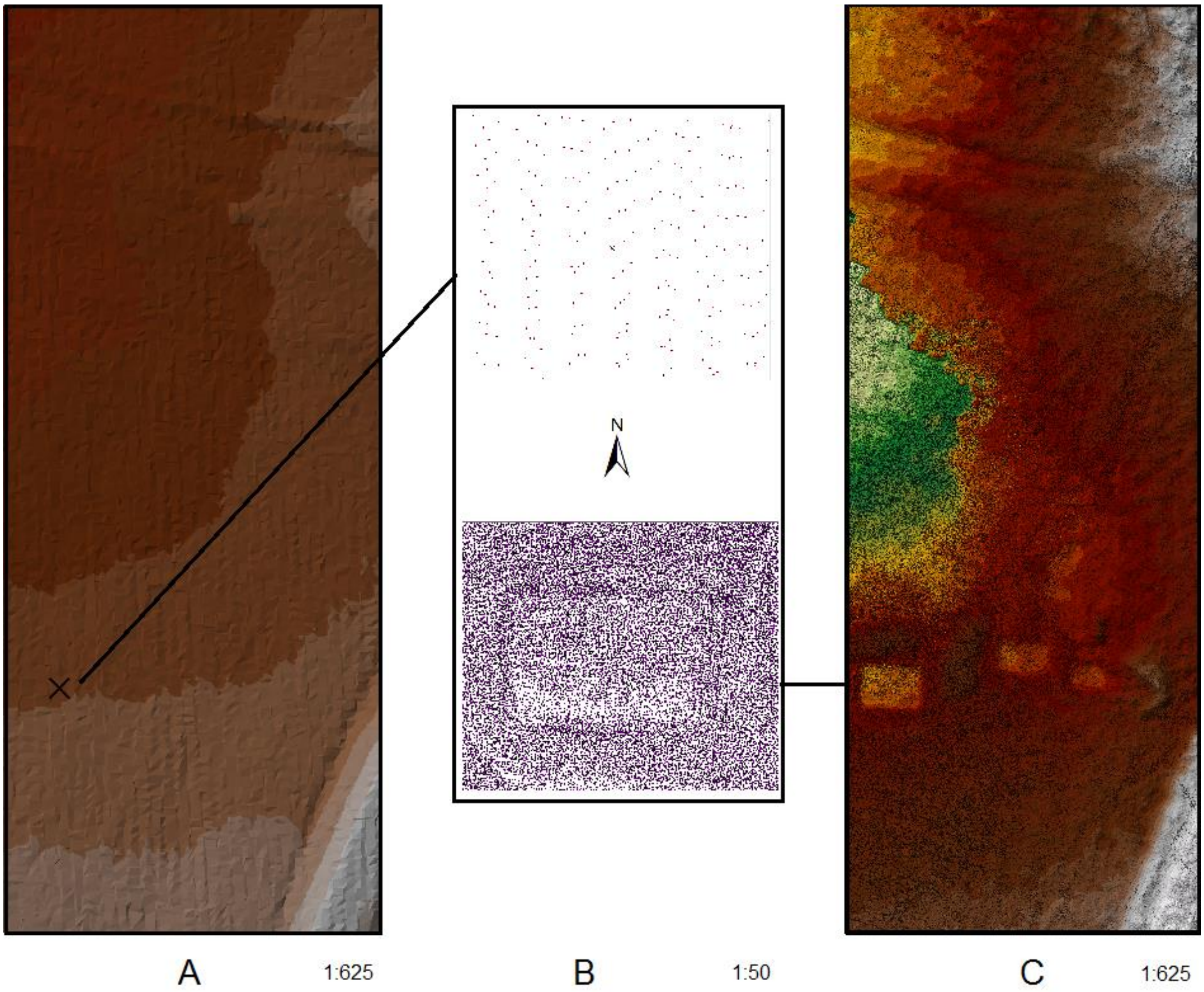


Figure 18. Comparison between the Digital Terrain Models (32 classes) coming from LIDAR (A) and UAV survey with image based 3D modelling (C). Highlighted is the point density on the location of the 2015 excavation trench (B). Image by Sjoerd van Riel.

The 3D models from the UAV survey for this study were processed in a way that resulted in a much higher resolution than the LIDAR data (figure 18). With a point density of less than 10 cm, it is possible to map out the morphology of the terrain in much higher detail (compare for example the modern road in the north of the surveyed area). Unfortunately the acquisition was originally focused on the excavation area and for this reason the datasets produced did not allow for extensive surface analysis such as hillshading. However, the combination of UAV survey and image based 3D modelling was found to be a useful method to bridge the existing gap between close range photogrammetry and LIDAR, and contributed to a more including and complete documentation of the wider excavation area.

4.2.3 - Robotic Total Station (RTS) and GPS

A Leica TCRP 1203+ R1000 (robotic) total station was used as the main instrument for the recording of individual finds and soil samples. The traditional documentation system in Sweden is designed for the use of this instrument to record all the spatial data, including layers and features retrieved on site as result of the excavation. This data is then imported into a GIS platform (Intrasis.com, 2016) specifically designed to host and manage archaeological records. Intrasis is a GIS platform developed by 'Arkeologerna' (http://arkeologerna.com/) at the National Historical Museums in Sweden, and customized to be used in archaeological investigation environments. Intrasis allows for the visualization of all the recorded data that is collected during several seasons of excavation. However, the options to conduct spatial analysis are limited compared to ArcGIS and the system does not allow 3D visualization (figure 19).

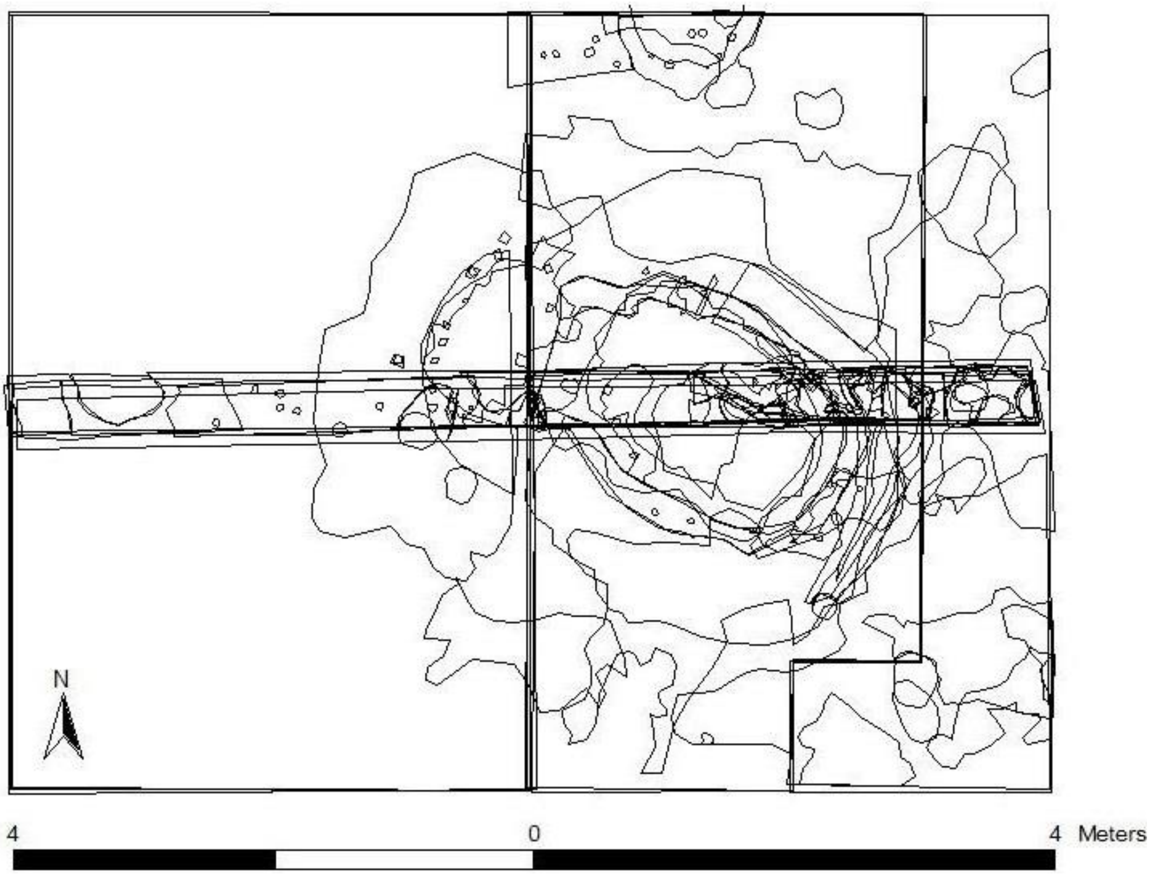


Figure 19. The excavation trench of seasons 2013-2015 visualized in Intrasis. Layers are visualized as black lines. Image courtesy by Birgitta Piltz-Williams.

In the light of the Field Archaeology course for Master students at Lund University, an Altus Real Time Kinematic (RTK) GPS was also used to measure and georeference the retrieved contexts. In specific, the main use of the GPS was the recording of the GCPs in order to georeference the 3D models. The GPS was chosen over the RTS for this task, because the GPS data proved to be more convenient for quick importation in ArcGIS due to a more straightforward georeferencing procedure. However, this negatively impacted the georeferencing accuracy of the 3D models, since the GPS is less accurate than the RTS. This problem will be more elaborately discussed in chapter 5.2.2.

4.3 - Image Based Modelling and 3D context drawing

The 3D models that were created during the excavation were not just serving as visualization or representation tools. Rather they are an integral part of the documentation process itself. Because the approach of image acquisition is determined by the documentation process and its different components, I will in this section first describe the data organization structure before discussing the image acquisition method itself.

The information that is required for the manual context sheets in Uppåkra has been included in the ArcGIS database by the DARKLab. The database was divided in three parts: a basemap consisting of additional information such as historical maps and satellite images, the topographic survey files such as GCPs and find locations, and the 3D models coming from image based modelling (figure 20).

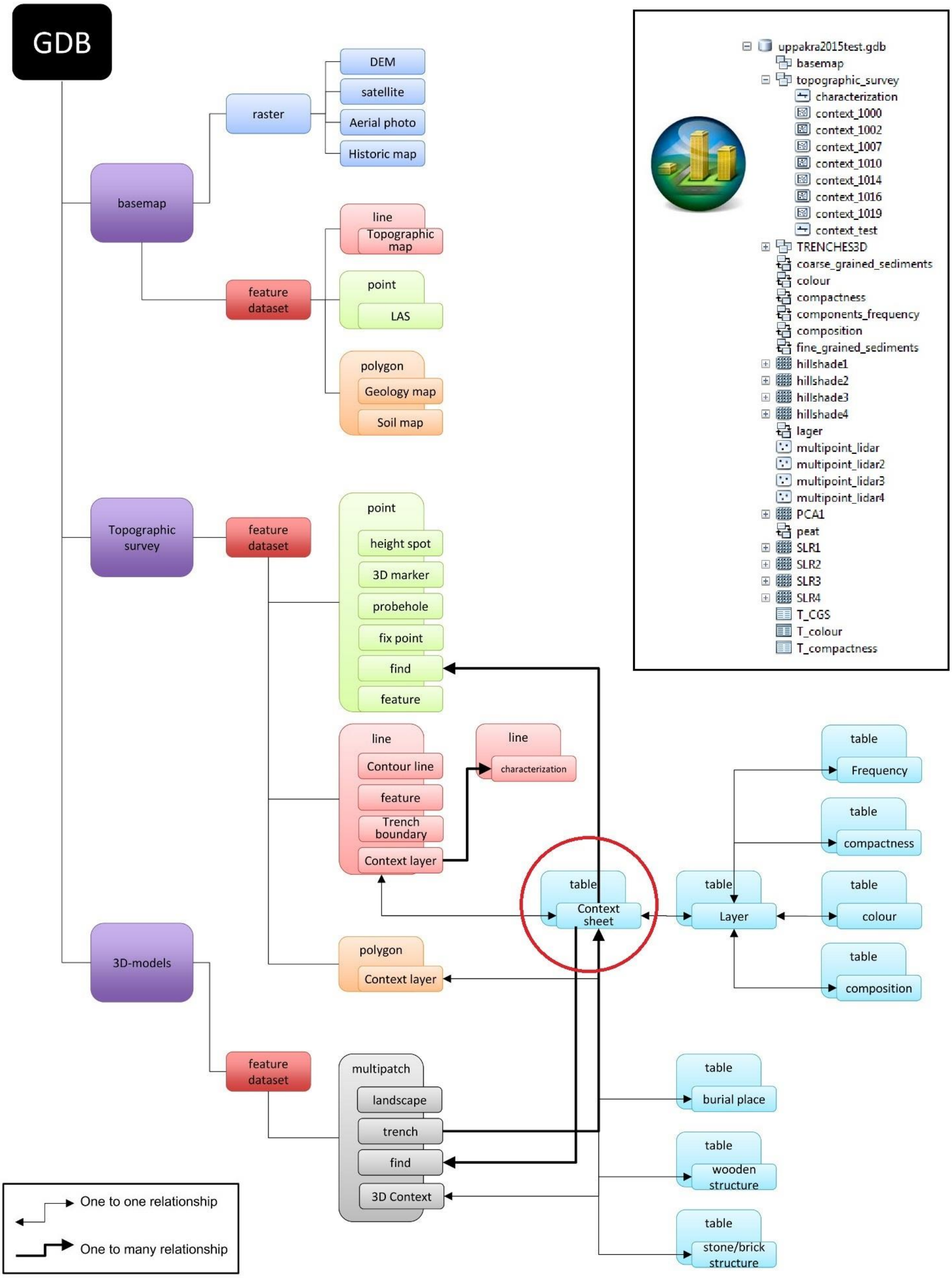


Figure 20. Uppåkra ArcGIS Geodatabase structure. Original image (Dell'Unto et al, submitted). Additional edits by Sjoerd van Riel.

The main goal of this work was to document all contexts by using 3D drawings in ArcScene, using the 3D models as result of image based reconstruction techniques as 3D geometrical reference. In other words, the contexts could only be drawn as soon as the 3D models were completed. To ensure a smooth workflow for this process, a standard approach had to be developed. A schematic visualization of this approach is shown in figure 21.

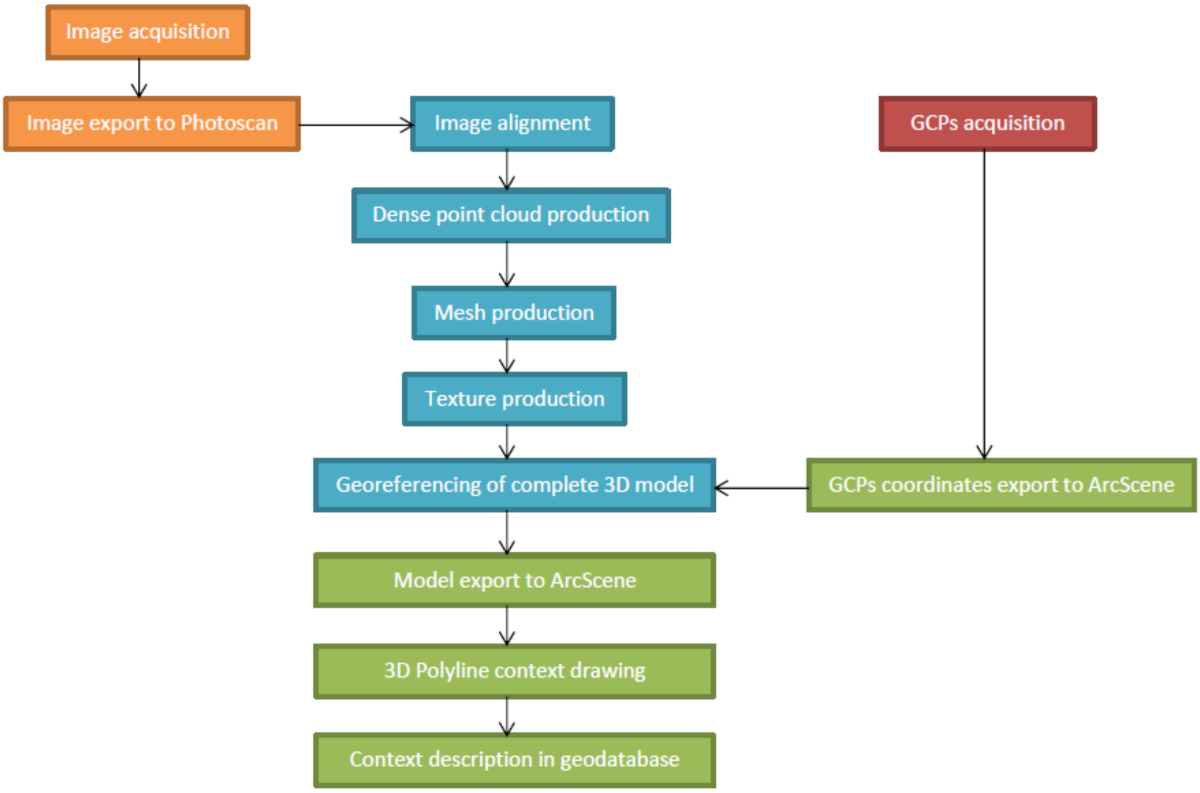


Figure 21. Workflow for the acquisition of georeferenced 3D models designed by the DARKLab and used for 3D context drawing in ArcScene. Diagram created by Sjoerd van Riel.

The process starts with the acquisition of the images (orange blocks in figure 21). The images were taken with a Canon EOS 550D DSLR (Digital Single Lens Reflex) camera (focal length 55mm, resolution 18 megapixels). Depending on the type of feature that was acquired, between 28 (for a detail of a section) and 180 (for the entire trench) images were taken. These were then exported to Photoscan (blue blocks in figure 21), where the images were aligned and a sparse point cloud was created. The sparse point cloud was then cleaned and processed to a dense point cloud. Subsequently the mesh was created, and finally the texture projected. The last step in Photoscan consisted of georeferencing the model. In order to do this, at least three GCPs are needed. For our models, four GCPs were measured with the GPS, from which the coordinates were exported to ArcScene (green blocks in figure 21). These coordinates were used to georeference the models in Photoscan Pro, after which the models were exported to ArcScene in order to be used for 3D context drawing. Depending on the amount of images and the chosen processing quality, the total time for this workflow was between 22 minutes (for a detail of a section) and one hour and 28 minutes (for the whole trench). The complete procedure was carried out on a laptop in the 'field office' of the site. In addition, a Microsoft Surface 3 tablet was used as a portable field computer. The ArcScene GIS data was synchronized with this tablet so that all the data could be analyzed directly in the field, at the trowel's edge. This allowed for context drawing on the tablet with the virtual trench as geometrical reference, and the real trench in front of the archaeologist providing essential information that cannot be modeled such as the grain size and dampness of the soil. This method allows for a highly reflexive approach, the implications of which will be discussed in chapter 5.1 of this thesis.

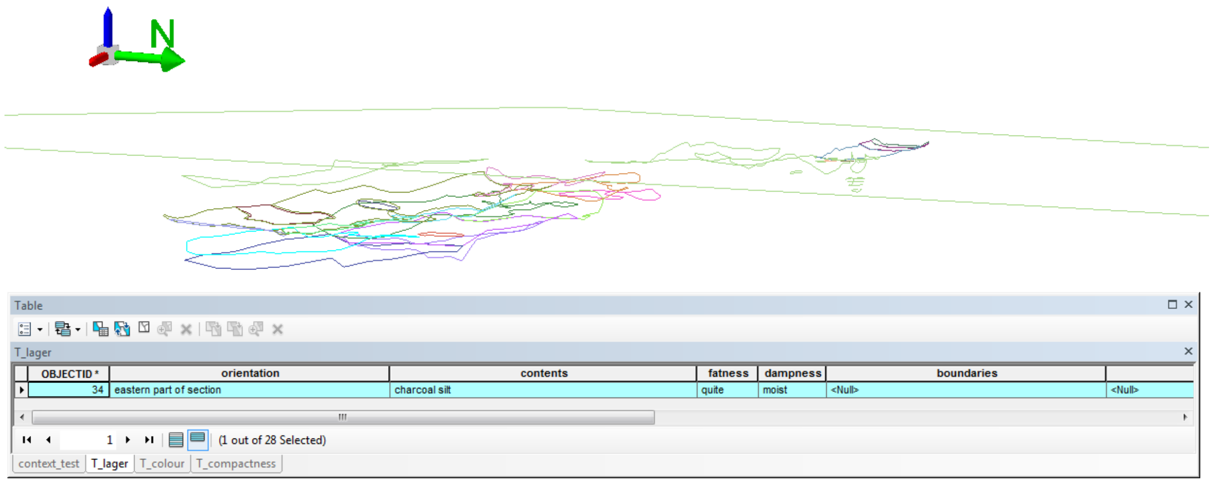


Figure 22. 3D Polylines representing several archaeological contexts in ArcScene, with additional information for each context provided in the database tables. Image by Sjoerd van Riel.

Each archaeological context was drawn as a closed 3D polyline. Once this line was created, additional information about the context was provided in the connected database tables, such as orientation, colour and contents (figure 22). As stated above, it is crucial that this documentation occurs at the trowel's edge since many of the necessary observations can only be made during direct physical interaction with the archaeological remains.

5 - Results and discussion

This chapter will discuss the influence of the 3D data recording and documentation methods on the excavation practice in Uppåkra. The discussion will include results in terms of accuracy, precision and resolution of the models and drawings, as well as theoretical influences of the methods. In section 5.1 I will discuss the impact of the method on the excavation and interpretation process. I will highlight the subjective nature of the methods and discuss the influence of the choices that were made on the results. In section 5.2 I will discuss the current limitations of the methods and problems that were encountered during the 3D documentation and analysis in Uppåkra.

5.1 The impact of the method on the excavation and interpretation process

"On-site interpretation requires an archive that can be easily analysed and quickly synthesised" (Beck and Beck, 2000, p.176).

In order to break down the barrier between methods and theory, and reach a research-centred approach, on-site interpretations have to be made. On-site interpretations in turn require a well-organized archive. Using a 3D GIS which includes georeferenced 3D models, drawings and context information, this archive is provided. Given the fact that the data is representing different stages of the excavation as well as different periods of use of the site, it is actually more appropriate to refer to the archive as a *4D GIS*. A suggested adjustment to the GIS database which enhances this 4D nature of the data in the form of a 'spectral signature' will be discussed in chapter 5.3.

Model based drawing is found to offer several improvements compared to traditional documentation in terms of reflexivity and inclusiveness. One of these is the further elimination of the archive division between spatial and attribute data (Beck and Beck, 2000, p.177). Traditionally a division existed between the spatial site data (plan and section drawings) and attribute data (context sheets). With the introduction of computer applications, this division was reduced. Total station drawings can be queried and the attribute data that is connected is only a mouse-click away in software such as IntraSIS. However, when a total station is used as 3D data recording device there is still a need to take separate photographs to record texture and colour information. Using image based 3D modelling instead, the workflow results in the integration of spatial and texture data. This example is illustrated by a comparison of figures 19 and 23. In IntraSIS, contexts are represented by merely a polyline. Additional texture- and colour information has to be retrieved out of photographs which are connected to the contexts through the database. Using model based drawing instead, the texture and colour is included by the very nature of the data acquisition method, which is image based. Barriers of different data classes can be taken down further by the inclusion of e.g. 3D models of significant individual finds (see chapter 5.3).
A second advantage of model based drawing is the higher level of precision when compared to total station drawings. Though very accurate (if handled carefully), total station drawings usually represent a very simplified version of the real feature. This is because surveyors tend to take too

few points out of time concerns or plain negligence. An example of this can be seen in figure 23, where three circular shaped features are shown as they are drawn using a total station (in red) and model based drawing (in green). Note that the red polylines which represent the outline of each feature are very irregular compared to the green ones. This is because the round features are represented by too few points (seven or eight). Since the lines are created by connecting the too small amount of points, the lines do not come out very smoothly. The model based drawings on the other hand are much smoother since they are not created by connecting several points, but instead by directly drawing a line.

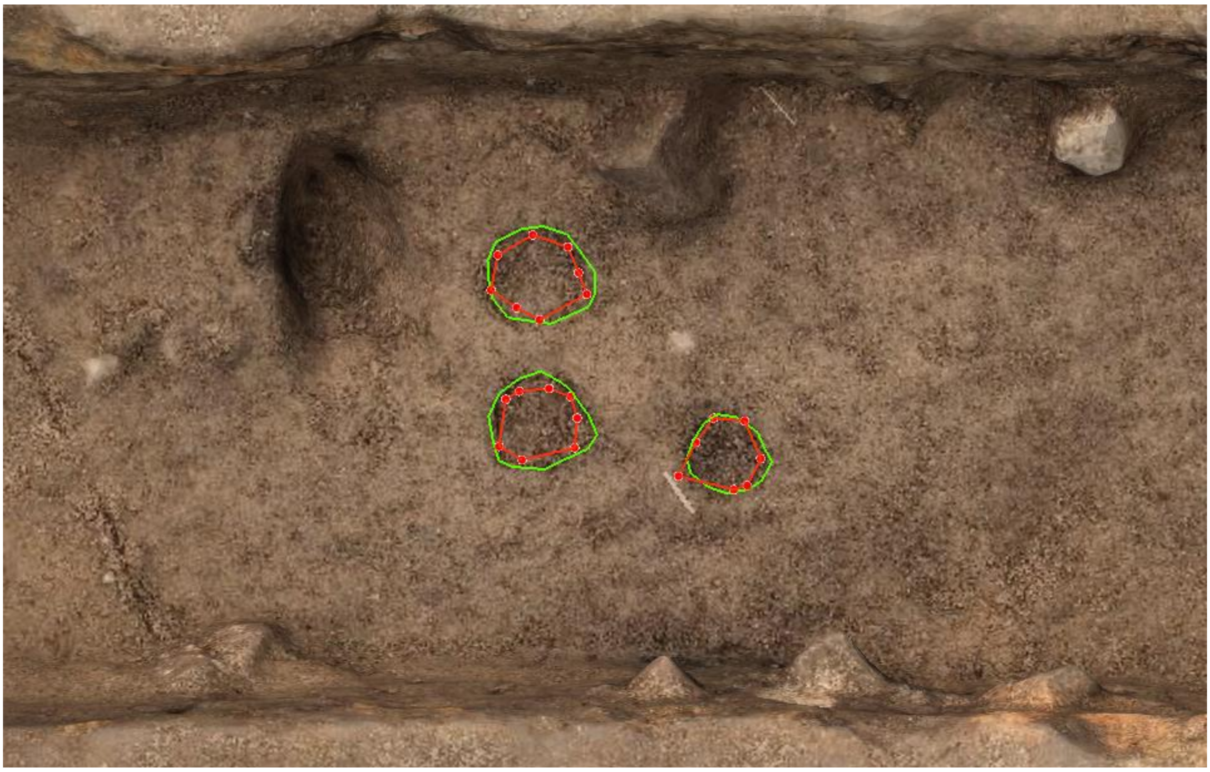


Figure 23. Three circular shaped features visualized in ArcScenes orthographic view. Two different methods of context drawing are visualized: total station drawing based on points (red) and model based drawing based on a polyline which is drawn with the 3D model as geometrical reference (green).
Model and drawings by Sjoerd van Riel.

Figure 23 also illustrates a third advantage of model based drawing over total station drawing, namely the fact that the drawing pipeline is more direct and transparent. The results of a total station drawing acquisition can only be visualized after the raw data has been exported to a computer and imported in a GIS such as IntraSIS. The usual practice is that the concerned features are removed in the meantime. This means that in case a mistake in the drawing is discovered, it is already too late to redo the drawing. This can result in imprecise drawings such as the circular feature on the right side in figure 23, where the lower left point is taken in the wrong position. With model based drawing on the other hand, the drawing is made directly on top of the 3D model which means that the outline of the feature can be followed at the trowel's edge. In this way, the method is capable of combining the best of traditional drawing (documenting at the trowel’s edge) and digital recording (producing data which includes geometrical description, colour information etc.).

After explaining some of the most important advantages of model based drawing over total station drawing, I will now discuss the method in the light of excavation logistics, especially the factor time. As discussed in chapter 4.3, the time for the entire pipeline from image acquisition until 3D context drawing varied between 22 minutes and one hour and 28 minutes. The biggest factors that influence the processing time for the models are the amount of images and the chosen processing settings. These factors in turn depend on the foreseen goal of the model, e.g. if the model is used as a general overview to represent the state of excavation, the geometrical quality of the model will be lower than when the model is to be used for detailed analysis of complicated archaeological features. To exemplify this, we can take a look at the graph presented in figure 24.

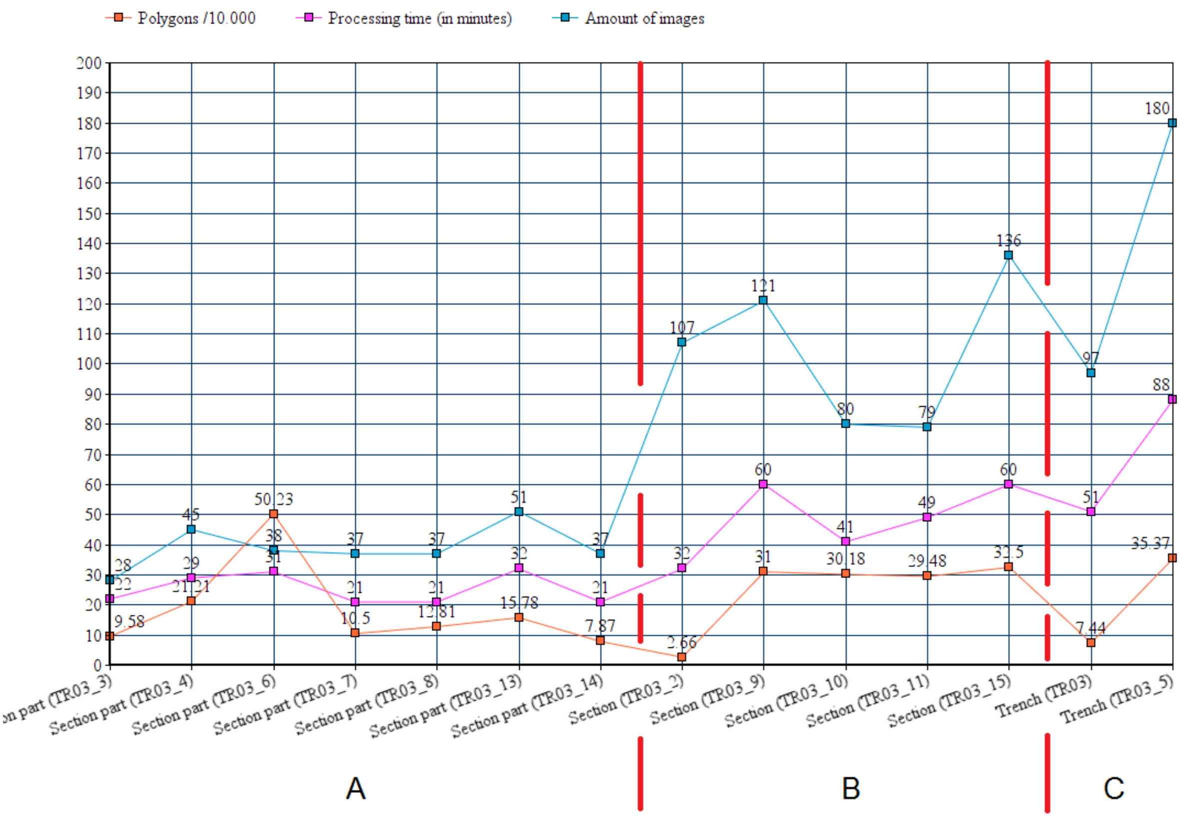


Figure 24. Graph showing the resolution (measured in amount of polygons divided by 10.000), processing time and amount of images for each 3D model. Created by Sjoerd van Riel.

The graph shows the relation between the amount of images, resolution and processing time for each model that has been created during the excavation. The processing time consists of the (partly estimated) total time spent on the acquisition of the images, model processing in Photoscan, georeferencing and exporting the model to ArcScene. On the X axis, the models have been categorized according to the type of feature(s) which they represent. Seven models consist of a part of the section (A). Five models consist of the complete section (B) and two models consist of the complete trench (C). Some general trends can be recognized from the graph. Firstly, the models that represent a bigger surface are naturally created from more images. This results from the fact that the SfM algorithm needs an overlap between the images, thus a bigger surface will

naturally require more images to create a 3D model. However, the graph also shows that the higher number of images does not necessarily result in a higher resolution of the model.
The models representing the entire trench (C) consist of respectively 74.400 and 353.700 polygons. The reason why those models consist of relatively few polygons is that they were created using the lowest quality processing settings for the dense cloud and mesh building. Model TR03_6 on the other hand which represents only a part of the section but is processed with medium settings consists of more than 500.000 polygons. However due to the small amount of images that were used to create the model (38), the processing time is still significantly lower than the low resolution models in category C. It is apparent from these examples that the processing time is really a result of the combination of the amount of images and the processing settings. For a more consistent investigation of the relation between the amount of images and specific processing parameters, an experiment should be conducted where all the models are run with the same settings on the same PC, and then repeat this procedure with different settings. Unfortunately such an experiment did not fit in the timeframe of this thesis, and moreover it would give more useful results for field practice if it would be conducted on the PC that is used on the field, which is less powerful than the one that was used for this thesis.

In order to evaluate what effects the processing parameters have on the resulting model, the images taken in the final stage of the section at the end of the excavation were processed in low and higher settings (figure 25). Even though the geometry is much more detailed in the higher quality model (25B and C), the models do not show many differences after the texture is projected (25D). The time it took to create the models was respectively 60 and 80 minutes for the low and higher quality model. A good practice could therefore be to process a model with lower settings in the field to be used for initial model based drawing, after which the model can be reprocessed if a more detailed geometry is required. The geometry resulting from the low quality processing parameters is sufficient to be used for initial context drawing, and therefore no more time should be spent on improving the geometry during the excavation, when time is costly. This example illustrates another advantage of using image based modelling, namely the flexibility and possibility to reprocess models for different objectives. However, to be able to do this it is crucial that the image acquisition campaign is carried out properly. It is good practice to take more images than deemed necessary since it does not take a lot of extra time but it can prove extremely useful during post processing.

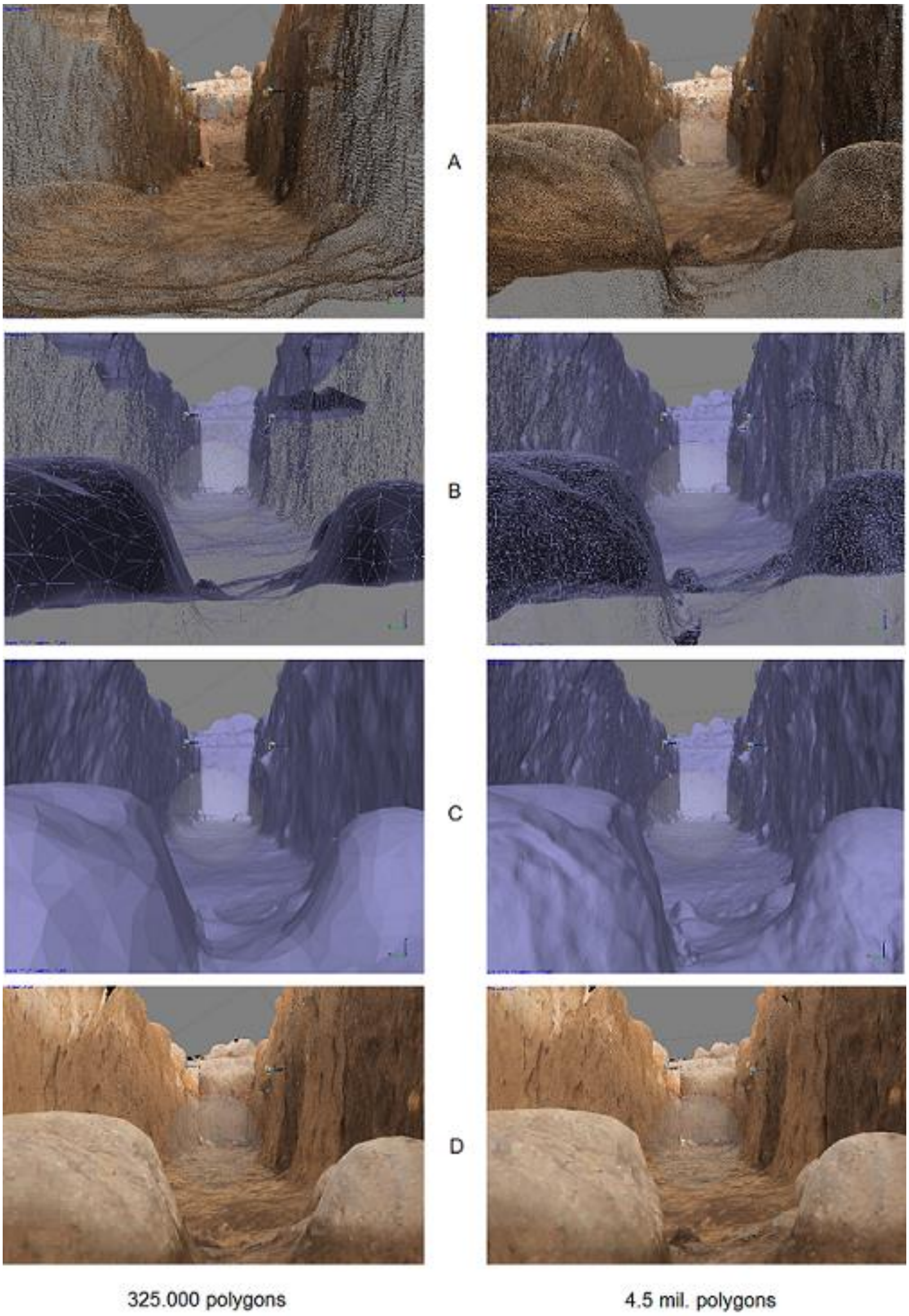


Figure 25. Comparison of dense cloud (A), wireframe mesh (B), solid mesh (C) and textured mesh (D) for a lower quality model (left) and a higher quality model (right) of the section. Created by Sjoerd van Riel.

From the above discussion can be concluded that the method has several implications on the practice of archaeological fieldwork. It requires a significantly different workflow from the one that is traditionally used with a total station as primary recording device (figure 21). If the method is to become common practice for field archaeologists, it requires a switch in the mindset of the archaeologists. Several miscommunications and misunderstandings happened because the image based 3D modelling and model based drawing method is not yet a standard procedure. Few archaeologists have knowledge of image based 3D modelling techniques or 3D drawing techniques in ArcScene. The bias which is created due to a lack of familiarity with the method is evident from the Uppåkra 2015 field report written by a group of master students which at that moment were not trained in the use of 3D recording and documenting techniques (Nemecek et al., unpublished student report). The authors refer to the method as "*an investigation of the use of digital archaeology in the field*" (Nemecek et al., unpublished student report, p.10) and to the practice as "*photos for 3D imagery were taken*" (Nemecek et al., unpublished student report, p.11). The models are referred to solely as "*visually strong tools for the documentation*" (Nemecek et al., unpublished, p.21). The analytical potential of the method is not mentioned. This illustrates a discrepancy between archaeologists who have not (yet) been trained in the use of 3D recording and documentation techniques and those who are employing it. In order to overcome this, the workflow will need to be better implemented in the common practice of archaeological field work. This means that several stages of the excavation need to be approached in a different way. Firstly, when it is decided that the current state of excavation should be documented, contrary to total station documentation it is very important that the trench is cleaned. Since the contexts will be recorded with texture and colour information, everything that is irrelevant (trowels, buckets etc.) has to be removed or else it will be visible and disturb the documentation. It is good practice to also scrape the top surface of the trench since the soil will be in the most natural condition when it is fresh and has not been exposed to the sun or rain for hours. Indeed, these rules are corresponding with the common rules for standard photographing in field archaeology (Roskams, 2001). Secondly, the recording and drawing process itself takes a lot longer compared to total station documentation. As can be seen in figure 24, it took at least 22 minutes until a model was ready for drawing. Then the context drawing itself would take another 15 minutes or so, depending on the amount of contexts and their complexity. Total station recording of these contexts on the other hand would have taken only several minutes. Though I argue that that the advantages of model based drawing (such as the higher resolution of the drawings, the integration of drawings, colour and texture information and less post processing work if the excavation is over) outweigh this disadvantage, it has to be anticipated that it will take more time to record and document before a feature can be excavated compared with total station documentation.

Apart from some more practical advantages that the method provided, it was also found to significantly increase reflexivity on the excavation. Even though there is no formal documentation of interpretation and subjectivity to the same extent as in the Çatalhöyük project, reflexives and discussion amongst the excavators can take place without these formalized guidelines, if the right conditions are created. The crucial part is to allow time for reflection and regard these moments as a natural part of the fieldwork (Berggren, 2001, p.21). In the Uppåkra excavations, such reflexive moments could be created with the use of the tablet PC's. By having the entire site database including historical maps, terrain models and the complete excavation documentation together on the same portable device, discussion and interpretation could be moved from the office to the field (and not vice versa). By having a sequence of 3D models and associated drawings (figure 26) which represent different stages of the excavation, the team could virtually go back to a previous stage of excavating in order to discuss and interpret contexts and features directly in the field. During this experiment it was also possible to benefit from the 3D models of previous excavation seasons, imported and visualized in the system in spatial relation with the information retrieved on site in 2015. My notion that digital technologies enhance reflexivity in the excavation process by allowing different types of information being concentrated at the trowel's edge and making the excavation process virtually reversible is supported by the experiences of the Çatalhöyük Research Project (Berggren et al., 2015, p.437).

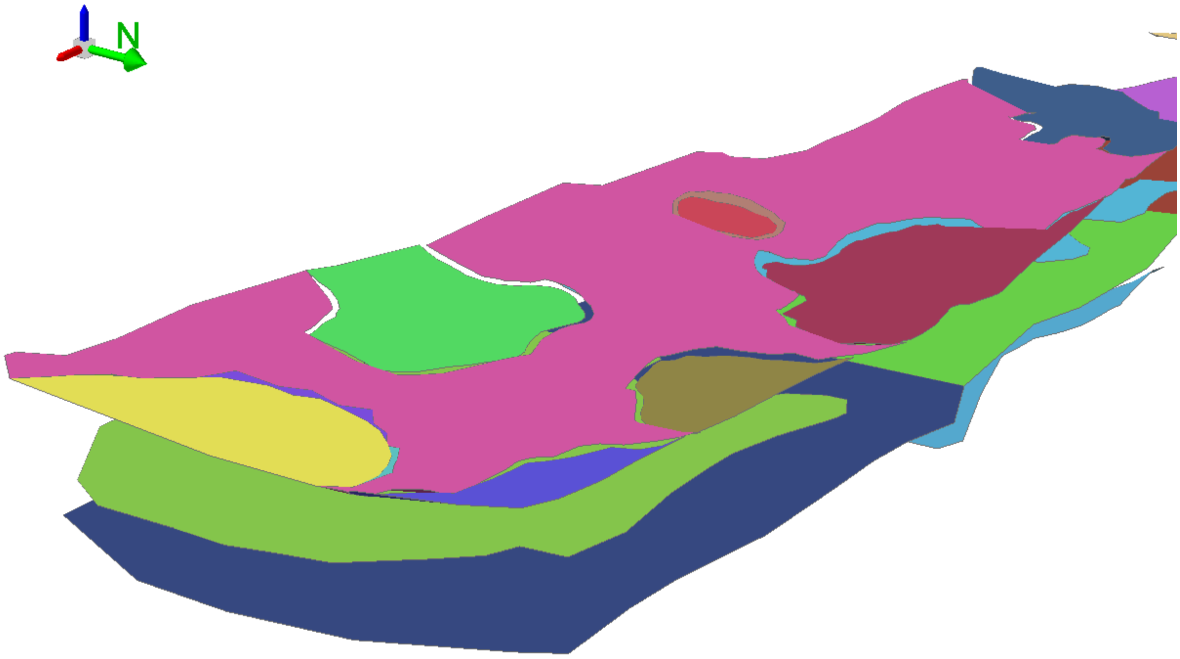


Figure 26. Visualization in ArcScene of several horizontal interfaces of contexts with which the user can interact in 3D. Drawings by Giacomo Landeschi and Sjoerd van Riel. Image by Sjoerd van Riel.

There are still some improvements that could be made regarding the use of tablets in the Uppåkra excavations. Most challenges are related to practical issues such as the inability to use the tablets properly in very sunny or rainy conditions. However, this problem can easily be overcome by using a covering case which protects the device from rain and removes the reflection of the sun on the surface of the tablet. A more substantial problem that I encountered in the Uppåkra project was the fact that we only had one tablet to use. This meant that it was almost always in use in order to draw contexts and feed information to the database, instead of being used for discussion and reflection. A proposed solution could be to use one tablet for context drawings and filling in the database, and have another tablet which is used for reflexive and narrative/interpretative purposes. Even though the excavators in Uppåkra are encouraged to keep a field diary, these are often disappearing into private archives and not shared with the archaeological community. Perhaps one tablet could be functioning as a 'digital diary', where the archaeologists insert a field diary at the end of each day. If this tablet is synchronized with the 'drawing tablet' on each day, it encourages the archaeologists to directly connect their interpretations and diaries with the documented contexts. These 'daily sketches' can then be included in the more formal documentation of the site, as they have been found to be a helpful record of the interpretation process as well as the work progress (Berggren et al., 2015, p.437).

5.2 - Problems and limitations

The novelty of the method and lack of standardized methodology causes for several challenges which still need to be overcome. The problems that I encountered can be divided in three different categories: colour representation, georeferencing and positioning of the models and visualization limitations. The following sections will discuss each of these problems in detail.

5.2.1 - Problems regarding colour information

In archaeological excavations, colour is often used in support of interpretation. It is a fundamental part of the recording, often with its own section on a context sheet (Barker, 1993, p.164; Westman, 1994, pp.30-31; Roskams, 2001, pp.175-176). In most situations, colour is recorded describing the tone ('dark'), hue ('greyish') and dominant colour ('brown') (Roskams, 2001, p.175). Recording colour information on photographs can be a problematic issue. Colour of soil looks different in different situations. If the weather is sunny, colours will show up more bright and shiny than in a cloudy situation. Soil changes colour when it is exposed, a dried out feature can look very different compared to when it was fresh. As discussed in the previous section, it is therefore important to clean the surface just before a photographic acquisition is made. All contexts should be recorded as if they were just exposed. To create further homogeneity, contexts should be recorded as much as possible during the same weather circumstances. Photographic recording is best done in cloudy weather, so that the sun cannot dry out the soil or cast shadows over the context. Finally, the 'white balance' should be set on the camera before each acquisition, in order to remove unrealistic colour casts as much as possible. Despite taking some of these precautions, we still experienced problems with colour projection on the 3D models in Uppåkra. As can be seen on figure 27, two different models created on different days but displaying the same section show very different results.

Figure 27. Two 3D models of the same section showing different colour information. Models and image by Sjoerd van Riel.

The difference in colour likely occurs at least partly due to different weather conditions. Probably it was sunny when the model on the right was created and cloudy when the model on the left was created. In order to better understand the reasons for this problem, it is necessary to have more information about the weather conditions on the specific moments when the models were created. However, this information is not available at the moment. This illustrates the importance of keeping a field diary with the weather conditions for each day. Another solution could be to add a column in the attribute table in which the weather conditions during the acquisition campaign can be described.

A possible solution to overcome problems regarding colour information on photographs is the use of RAW format images. RAW images must be developed using additional software such as Photoshop or GIMP. The user can edit (colour) information of the photograph in a controlled environment, after which the images can be converted into a more useable format such as JPG (Kimball, 2014, p.62). In this way the archaeologist has control over the image editing process, instead of letting the camera altering some image properties automatically as is the case with the JPG format (Kimball, 2014, p.62).

However, there are some disadvantages in using this method in archaeological excavation. The main reason why RAW images cannot be used for 3D modelling in the time-frame of an excavation is that Photoscan is not able to process RAW format pictures. In order for the images to be used for image based 3D modelling, they need to be converted in a format such as TIFF or JPG. This operation does not fit in the time-frame of archaeological excavation practice and would make the use of this technique not sustainable. A possible solution would be to acquire the images in both formats (JPG and RAW, most DSLR cameras allow for the simultaneous capture of JPG and RAW format images), and then using the JPG images for immediate creation of 3D models and the RAW images for processing models during post excavation activities. This method would utilize the advantages of both JPG (speed and user-friendliness) and RAW (possibility to edit the colour information) format images without impacting the image acquisition workflow (Kimball, 2014, p.62).

5.2.2 - Problems regarding positioning of the models

When taking a closer look at figure 27, another problem catches the eye. At the place where the two models meet, the wall of the section seems to jump in a few centimeters. In reality the walls of the section were straight. This means that the models can have a discrepancy of several centimeters, and since the contexts are drawn with the models as geometrical reference these will be inaccurate on the level of several centimeters as well. This is an unacceptable error level when the models are meant to be used for analysis and interpretation rather than just visualization tools. It is therefore important to understand where this inaccuracy comes from, and how to improve the accuracy of the models.

Photoscan automatically calculates the georeferencing error level in the metric order of centimeters. The error in the models that were produced for this thesis varied between 5mm and 20mm with an average error of 13mm. The error level in Photoscan does not explain the discrepancy of the models as shown in figure 27. The discrepancy arises not from inaccuracy in the model geometry, but rather from the inaccuracy of the GPS measurements through which the models are georeferenced and scaled (figure 28).

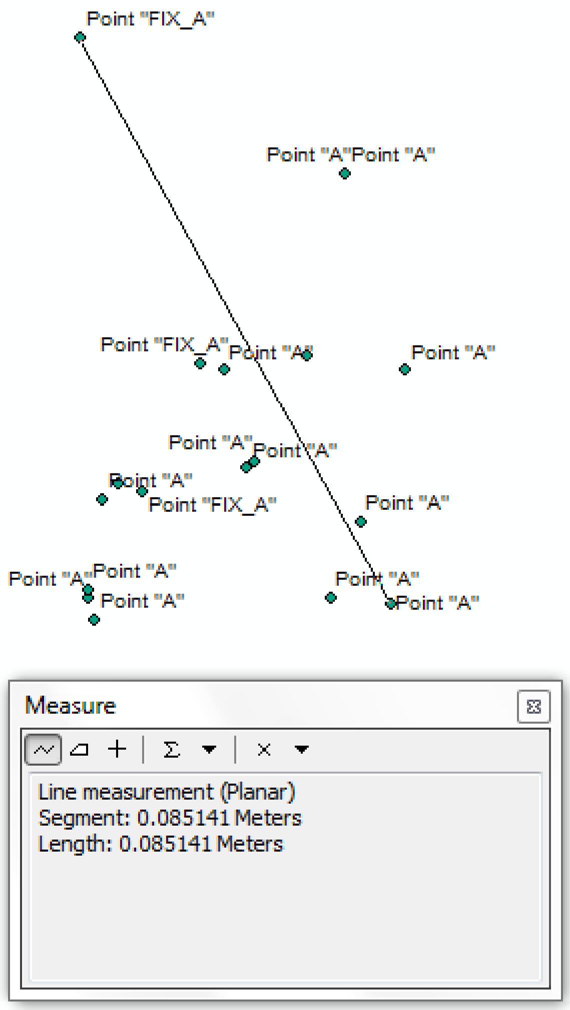


Figure 28. Cluster of 18 points acquired with the GPS which represent the same Ground Control Point (GCP A). A line measurement in ArcMap shows that the measurements have an error of as much as 8.5 cm. Image by Sjoerd van Riel.

Figure 28 shows a cluster of points which represent a single ground control point in the field (GCP A). In order to evaluate and correct the GPS inaccuracy, a set of four fixed ground control points was set up in Uppåkra. These points were recorded each day after the GPS base station was set up. Since the points were not moved during the excavation, the GPS points which represent the ground control points should be located in the same position for each day. But due to the inaccuracy of the GPS the points shift a little bit, which causes the distribution of the points to be quite widespread. Due to the fact that the ground control points that have been used to georeference the 3D models of the trench and contexts were also measured on a daily basis, a similar error distribution can be expected for the georeferencing of the 3D models, which causes mismatches between different models as can be seen in figure 27.

A possible solution to solve this problem could be to have fixed ground control points for the georeferencing of the models and measure them only once at the beginning of the excavation. These points should then be used for the remaining part of the excavation to georeference future models. In this way, the accumulating error of a slight mismatch on each day will be avoided. However, this method will require that the ground control points stay in place for the whole excavation, and moreover have to be visible in each acquisition round. This means that they have to be placed close enough to the features that are going to be recorded to appear in the 3D model, but they cannot be in the way of the excavating process. To meet these requirements will be easier in some excavation circumstances than others, depending on the characteristics of the excavation method and features. A second possible solution could be to use a total station instead of a GPS for the recording of the ground control points, since a total station has a higher accuracy compared to a GPS. However, a total station has other disadvantages which have been discussed earlier in this thesis, such as longer post processing time and the impossibility for direct visualization of the obtained data. The optimal approach will therefore be depending on the priorities of the archaeologists and the tools available. However, it is important to recognize the consequences that different tools and methods will have on the documentation.

5.2.3 - Problems regarding documentation methods and visualization

Besides colour projection and inaccuracy issues, the third problem that I encountered relates to the lack of visualization and symbology options in the documentation principles. This problem is part of a bigger issue in field archaeology, namely the impossibility to document the full extent of the excavated area. Because this problem relates directly to the challenges in 3D documentation and presentation of the data I will discuss shortly the various methods are commonly used to excavate and document archaeological sites.

Traditionally, the documentation consists of the recording of plans and sections. Plans record the length and width of an archaeological interface. Sections record their thickness. Plans are the records of single interfaces and do not show a sequence, whereas sections represent the time dimension of a site (Harris, 1989, p.83). Three types of plans can be distinguished: multi-context single-level, multi-context phase and single-context (Roskams, 2001, p.137). A single-level ('top') plan is a drawing done at a designated time, consisting of all the features that are visible in the trench at that time. A phase-plan is a multi-context drawing created when the exposed stratigraphy is considered to belong to the same time period. A single-context plan lastly is, as the name suggests, a plan of one context which is exposed to its full extent (Roskams, 2001, pp.137-141). Sections can also be divided in three types, distinguished not by their output but rather by their purpose. The first type is used to record the stratigraphic sequence, often of the trench walls. The second type is used to provide information about the internal stratigraphy of a single deposit, say different filling phases of a posthole. The third and last type is used to shed light on specific stratigraphic problems on a site (Roskams, 2001, pp.143-144). The motivation to create a section through the trench in Uppåkra belongs in the third category. Since the excavations follow the single-context method of planning and excavating, it is crucial to understand the boundaries of individual contexts in order to record them in a single plan. The section was established since we had troubles doing this and wanted to obtain more information about the vertical relation between different contexts, amongst others whether or not there was another structure located underneath the oven which was excavated during the 2013-2014 excavations.

A combination of both plan and section recording has long been the standard in archaeological documentation, since they complement each other.
According to Harris (1989), "*Plans give the length and width of a site, if you will, and sections record its depth: these three dimensions are woven together by the stratigraphic sequence, which represents the fourth dimension, time, on archaeological sites."* (p.83). Harris was discussing 4D on archaeological sites as early as the 1980s. However, until recently the documentation was confined to *bi-dimensional* plan- and section drawings or photographs. Figure 29 illustrates the standard drawing procedure of plan- and section drawings. A portion of the section in Uppåkra containing eight possible postholes[2] is used as an example (29A). Figure 29B shows the postholes as they would be drawn in a manual or digital single-level or phase-plan, respectively section. Figure 29 C and D shows what a combination of these two types of drawing would result in. These drawings are hypothetical and created by the author; they are not part of the official site documentation.

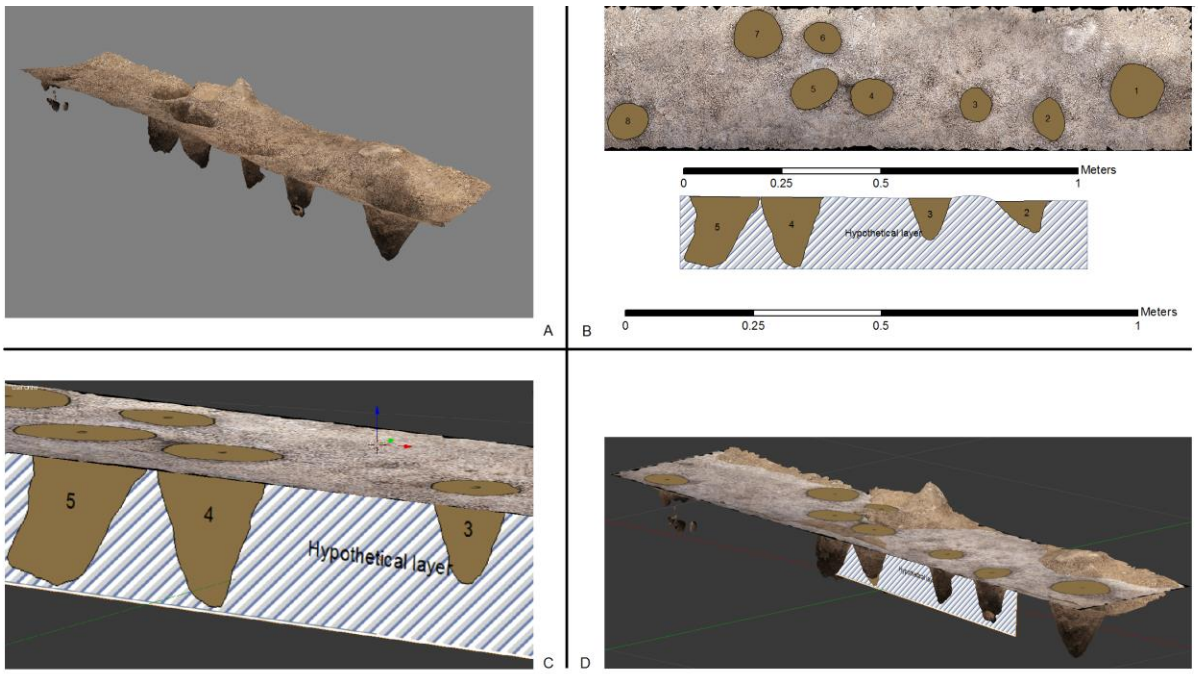


Figure 29. Illustrating the concept of plan- and section drawings (B) in archaeological excavations. A combination of plan- and section will give the contours of the upper interface and the depth of the feature (C and D). Images by Sjoerd van Riel.

Since the features were in the real situation excavated and documented according to the single-context method, the section drawing is purely hypothetical because there has never been a section in the real situation. Hence the white/blue 'hypothetical layer'.

The method of plan- and section documenting has several limitations. The first one relates to incompleteness of the contexts in the plan. Due to the fact that layers are overlapping each other, only a part of the layers' surface will be exposed at a time. A plan drawing would thus only partially record any units of stratification which partly lie under other deposits (Harris, 1989, p.89).

[2] At the moment of writing it is unsure whether the features are interpreted as postholes, animal burrows or something else. In this discussion they will be referred to as postholes.

By sectioning each context some of the underlying layers can be recognized, but their upper interface will still be undocumented. A second limitation derives from the fact that only a 'slice' of the vertical extent of the context will be recorded. In the hypothetical example presented in figure 29, the postholes are sectioned in east-west direction. In this way the vertical angle is only recorded in east-west direction, therefore information about the angling in north-south direction is lost. This problem can be partly overcome by sectioning a feature in quadrants, but it will still be impossible to reconstruct the total volume of a feature with this method.

The above described problems were reasons for the development of the single-context method (Harris 1979;1989). In this method, ideally every unit of stratification is recorded in both plan and section together with a set of coordinates and a number of elevations on a pre-printed context sheet. The context is then removed in its entirety, and the same procedure will be repeated for the next context (Harris, 1989, p.95). The individual records of single-contexts can then be used to create composite plans. Critique on this method includes the arguments that it denies the possibility for on-site interpretation since every unit is presented to be floating free of any of its associates (Roskams, 2001, p.141) and that it holds the incorrect assumption that all contexts are clear-cut and easily distinguishable (Barker, 1993, p.169). Moreover it is claimed that the quality of drawing drops when the site is split into unconnected units (Barker, 1993, p.169; Roskams, 2001, p.140). A good practice could be to document single-context where possible, and a composite drawing where necessary.

The above discussion is relevant for this thesis because a new method of documenting a site, in this case based on image based 3D modelling and 3D context drawing in ArcGIS, reopens the debate concerning what should be documented and how. As discussed before, the timing of 3D acquisition is subjective and depends on the theoretical strategy of recording. Figure 30 illustrates the result of different documentation methods if they would be followed using image based 3D modelling.

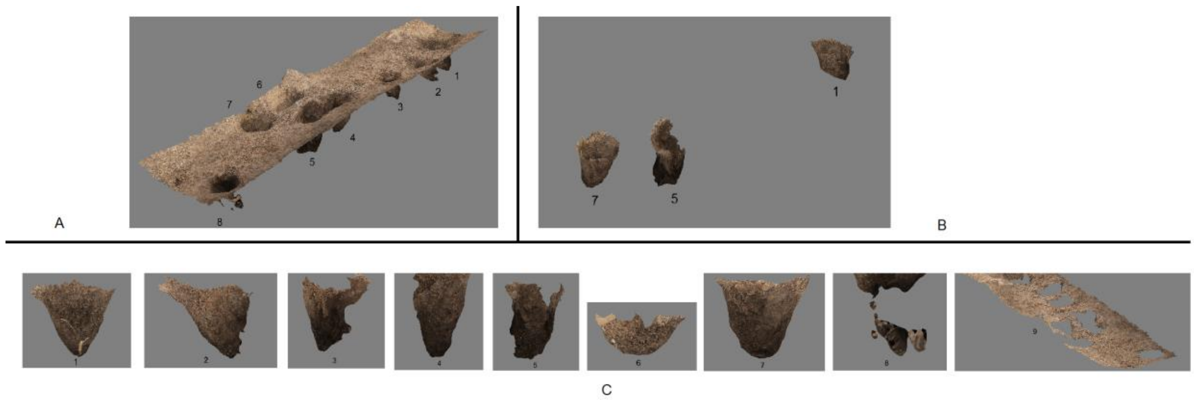


Figure 30. Illustrating the result that different documentations principles would give if they would be applied on 3D recording. Visualized are single-level planning (A), phase-planning (B) and single-context planning (C). Images by Sjoerd van Riel.

The illustration shows the same cluster of postholes that were used to illustrate the result of plan- and section drawings (figure 29). The traditional method of single-level planning would mean that acquisitions are done of big surfaces which are exposed at the same time during the excavation (30A). This means that a surface is recorded which was probably never exposed during the lifetime of the site. Certain stratigraphic units would be laid down at earlier periods than others, but this would not be visible from the plan (Harris, 1989, p.86). Phase-planning would mean that only those contexts are acquired that are thought to belong to the same archaeological time period (30B). Unlike the arbitrary single-level plan, from the phase-plan it would immediately be apparent to the observer that postholes one, five and seven are thought to belong to the same phase.[3] Clearly the value of this type of visualization depends on the validity of the phasing interpretation. As discussed above, it is impossible to recognize all units of stratification in this manner, since some deposits will be sealed by others which makes them invisible from the top (Roskams, 2001, p.140). Single-context planning finally would mean that acquisitions capture only one context at a time (30C). I have already discussed some of the traditional arguments against this method above, such as the suggested isolation of contexts and the lack of on-site interpretation.

During the excavation in Uppåkra, the method presented in figure 30A was used. 3D models were created on moments when a major surface had been found, instead of creating 3D models for single phases or contexts. However, the excavation followed the single-context method, and a context sheet as well as graphic documentation was produced for every individual context. Thus one could argue that a discrepancy exists between the documentation method followed by the excavation team (single-context), and the one that is implemented in digital documentation practice (single-level). This is mostly a consequence of a shift in recording and documenting tools that are utilized. In practice it is much easier to acquire a single-level of a trench in a set of images and create a 3D model of this in Photoscan than it is to create separate 3D models for each individual context.

The model based drawing approach offers some opportunities that were not available with 2D total station drawings. One of these is the possibility to generate volumes which could be used for artefact density mapping of specific contexts. Using a total station, volumes can be partly reconstructed by measuring the upper and lower interface of a context such as a posthole. However, often only the upper interface is recorded and information about the vertical extension of the context is only described on a context sheet. The resulting documentation from this method is illustrated in figure 31. In the best scenario, both the upper and lower interface of a context is documented with the total station, which would result in two lines representing these interfaces. In figure 31A the hypothetical results of documenting upper (in brown) and lower (in red) interfaces with this method are illustrated. Figures 31B and C show one method, in this case using a spiral, of how the volume of the postholes can be documented using model based drawing. As previously discussed, the lack of standardization due to the novelty of 3D documentation in archaeology results in the fact that drawing conventions as they exist for manual drawing (e.g. Westman, 1994), do not exist for 3D drawing yet. This means that experiments need to be conducted to find suitable ways of visualization for different types of contexts. The spiral representation for postholes has the advantage of showing the depth and angling of the posthole in 3D, but also has some limitations such as the lack of mathematical potential, e.g. volume calculation. Another pitfall for this method of drawing can be observed in figure 31D. This posthole has been acquired with too few images, which caused problems for the SfM algorithm to reconstruct the geometry for the bottom part of the posthole. Hence the deepest part of the posthole is recreated as loose chunks of geometry which are not connected to the rest of the model and thus cannot be used for 3D drawing, since the 3D polyline in ArcScene needs the geometry of the model as geometrical

[3] The assumption that postholes one, five and seven are contemporary is hypothetical. I do not have information about the actual interpretation of these features.

reference. This problem illustrates the importance of a good image acquisition campaign, since the use of poor images has consequences for the quality of the documentation and the context will likely will be gone when the mistake is discovered.

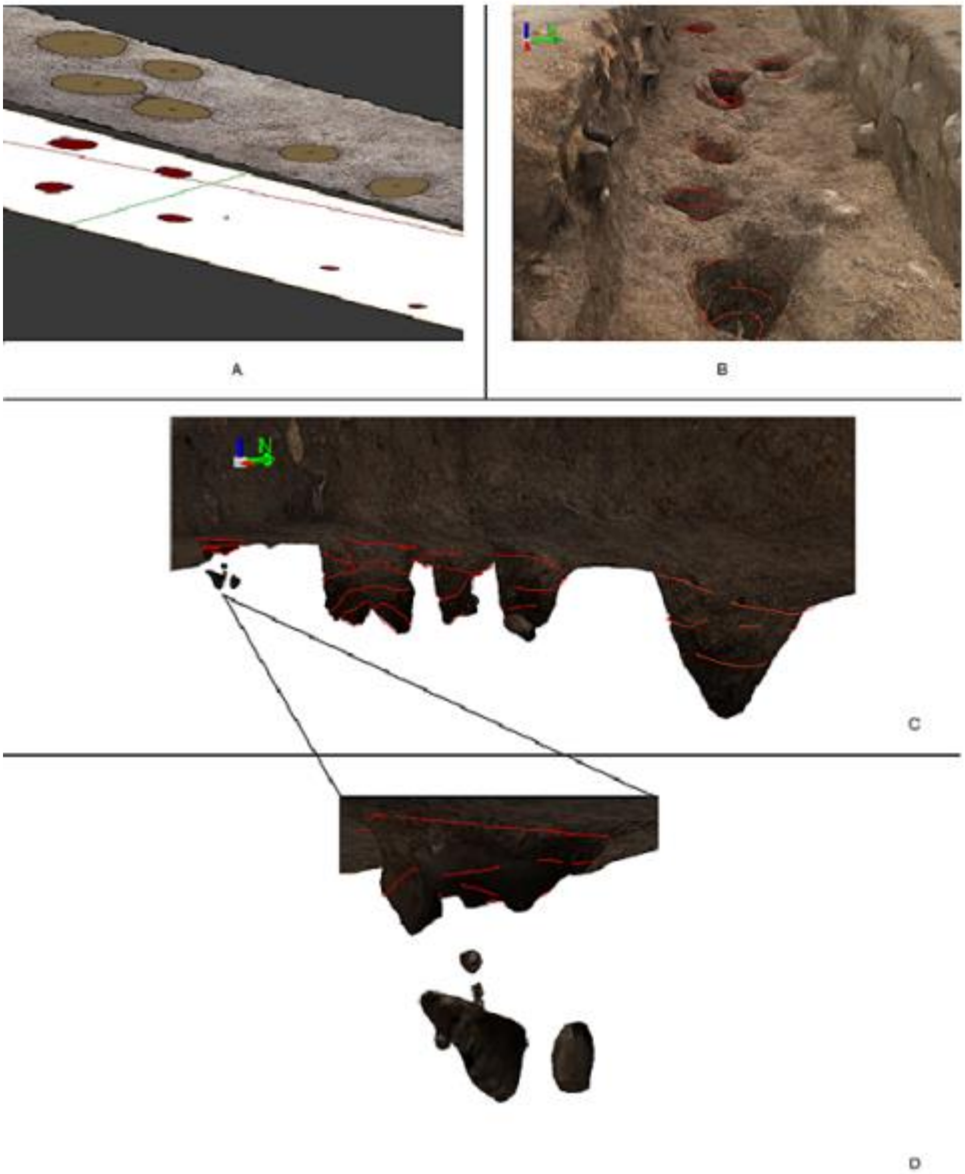


Figure 31. Illustration comparing the digital documentation of postholes in single-context excavation using total station (A) and model based drawing (B-C) as well as visualizing the consequences of a poor image acquisition session (D). Created by Sjoerd van Riel

5.3 - Suggestions for further research

As discussed in the previous section there are still several problems to overcome, such as insufficient colour projection and georeferencing accuracy. Future research should focus on fixing these problems in order to create new methods that can be successfully used to record and document archaeological excavations in 3D. Next to working on repairing these flaws, future research should also aim to develop new features which will enrich the final documentation.

A first example of this is to include a preliminary dating record in the geodatabase context tables, in order to add an archaeological chronological dimension which can help interpreting the site. This could potentially lead to the identification of '*spectral signatures*', i.e. period specific deposition patterns (Beck and Beck, 2000, p.177). Naturally, the success of this procedure would be depending on the availability of finds with high potential for on-site dating, such as pottery or coins. Alternatively, experiments could be conducted using a relative dating sequence, such as to visualize all the contexts which are interpreted to be pre- or post- another context, date, or whatever the archaeologists choose as a reference. By including this traditionally post-excavation phasing work partially in the excavation documenting process, the supposed division between 'a-theoretical' excavation practice and recording on the one hand and interpretational/theoretical post-excavation work on the other hand can be deconstructed further. This will improve interpretation and reflexivity during the recording and documentation process.

A second suggestion for future improvements is to include 3D models of significant individual finds in the documentation database. One way of doing this could be to leave significant finds *in-situ* and include them in the image based modelling acquisition. This would have the advantage that all the information about the exact position and location where the find has been retrieved is kept, but it would also mean that the artefact will be only partly visible, since it will be partly buried or covered by deposits. Another way of doing this would be to retrieve the artefact and document its context as usual, and then create a 3D model of the entire object in the lab. This model can then be imported in ArcScene and connected to its original position in the corresponding model of the trench, so that the artefact can be studied in detail and in connection to its original context. This method prevents the segregation of artefacts into their specialized groups, which would result in fragmentation of the data and lack of discourse between various specialist sub-groups (Beck and Beck, 2000, p.177).

6 - Conclusion

Digital technology has changed the way of how archaeological sites are recorded and documented. The recent development of 3D visualization GIS software and low-cost 3D modelling software which creates high-quality 3D models from 'ordinary' digital images has revolutionized the Digital Turn by allowing archaeologists to use 3D models not just for visualization, but also for analysis. Moreover the use of 3D models for analysis is not limited to artefact or building analyses, but extends to documenting and analyzing entire archaeological sites.

The goal of this thesis has been to explore the potential of several methods of 3D data acquisition, post-processing and analysis in the frame of an ongoing excavation in Uppåkra, southern Sweden. After providing a short historical background on the subject of digital archaeological documentation practice in chapter one, I have discussed several digital recording and documentation methods as well as their associated software programs in chapter two. Specifically, LIDAR data was used to conduct analysis on the landscape in which the site is located. In support of a more detailed landscape analysis of the immediate surroundings of the excavation area, a UAV (Unmanned Aerial Vehicle) was used to provide a Digital Terrain Model (DTM) with a resolution that was significantly higher than the DTM created with the LIDAR data. The UAV model was used to cover a scale which neither close range photogrammetry nor LIDAR was covering, thereby closing the gap between several 3D recording methods and creating a multi-scalar 3D dataset. For the recording of the trench and its contexts, image based reconstruction techniques were used to create resolute 3D models in Photoscan, which were georeferenced with a RTK GPS and imported into a 3D GIS (ArcScene). This resulted in a multi-scale 3D dataset ranging from the landscape to the single-context level, organized spatially and diachronically in the same visualization platform.

This thesis has also set out to discuss the theoretical implications of these 3D methods and digital methods in general within archaeological excavation practice, which was presented in chapter three. It was argued that digital recording is a subjective process which is based on interpretations which are in turn based on a theoretical pre-understanding. These different steps of subjectivity and interpretation result in a 3D database which should not be seen as more objective compared to traditional documentation, but rather as the result of a series of choices which were made by the excavators. In order to make this subjectivity transparent and open for discussion, it is important that a reflexive documentation method is maintained, where the obtained digital data is easily accessible and where space for interpretation is integrated in the excavation process, rather than something that is saved for post-excavation work. Moreover, a multi-scale approach where theory and data from landscape and intra-site perspectives are included will further enhance such a reflexive method. I have argued that the use of digital technologies significantly improves the process of reflexivity and that it is able to bridge the gap between certain aspects of landscape archaeology and field practice. 3D GIS systems are capable of integrating data from landscape to single-context scale in the same virtual environment. Tablet PC's can be taken out in the field so that all this data is accessible for the excavators in order to analyze a trench in its wider context.

In chapter four I have provided the results of the various recording techniques, from the landscape level with LIDAR technology down to the single-context level with image based 3D modelling technology. The result of these analyses together with the theoretical discussion have then been taken together in a discussion concerning the impact of 3D recording and documentation technologies in archaeological practice, which is presented in chapter five.

I have argued that the described method has several advantages over traditional recording and documentation methods. Firstly, model based drawings are more precise than total station drawings. Secondly, the method overcomes the traditional separation of vector (in this case points and lines) and raster (in this case images) data. Thirdly, the method is more able to visualize and analyze the obtained data in 3D or 4D, rather than visualizing and analyzing 3D data in a bi-dimensional environment such as IntraSIS or ArcMap. Fourthly, the method allows virtually revisiting some stages of the excavation and analyzing features which have been excavated on different days in relation to each other. Finally, the method is more inclusive of several typologies of data coming from different acquisition methods or times, which enhances a reflexive recording and documentation method.

However, some drawbacks and flaws have also been discussed in chapter five. Firstly, there are problems with the colour projection on the 3D models which results in misleading information. Secondly, the cumulative inaccuracy of the GPS measurements has led to inaccurate georeferencing of the 3D models, which makes some of the strong points of the method such as the possibility to virtually deconstruct the excavation process and revisit some of the excavation stages less effective. The third problem is not so much an issue with the method itself but rather the consequence of introducing a new recording and documentation method which demands a different approach from the archaeologists in the field. It takes time to change the way of thinking for archaeologists who have been trained in certain methods of documenting an excavation, as was shown for example from the student field report which is discussed in chapter four.

Given the fact that in my opinion the advantages of the discussed method outweigh the disadvantages, and that solving most of the problems which I have discussed is just a matter of time and more experimentation, I argue that the methods presented in this thesis can bring the recording and documentation methods that are used in archaeology a step forward. It should not be seen as a replacement of traditional documentation, since it is still in development and therefore still facing many challenges. But if future studies focus on further improving the use of 3D recording and documentation techniques and 3D GIS systems in support of archaeological practice and solving the problems that have been highlighted in this thesis, big steps forward can be taken in the field of archaeological excavation documentation in the years to come.

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