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Structure from Motion for Systematic Single Surface Documentation of Archaeological Excavations

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Abstract: Requiring archaeological standard equipment (measurement unit and camera) only, Structure from Motion approaches offer an affordable, easy to use and accurate documentation method for stratigraphic excavations. Photo-realistic three-dimensional models generated with this method can be looked upon as virtual replicas of stratification units and thereby allow a comprehensible documentation of archaeological remains, making the models an excellent basis for interpretation purposes. However, on most excavations, Structure from Motion is still not applied in a frequent and systematic way.

During excavations within the exceptionally well preserved Copper Age settlement Meidling im Thale/Kleiner Anzingerberg/ in Lower Austria, Structure from Motion and Multi View Stereo has been used intensively for single surface documentation. The commercial software Agisoft PhotoScan was deployed for a fully automated calculation of intrinsic and extrinsic camera calibration parameters, for the creation of three dimensional point clouds and for the generation of photorealistic surface models. The models generated were transferred to a GIS environment providing the means for visualisation and data management. By arranging and displaying the models according to their stratigraphic position, a four dimensional virtual reality was created, through which the user can move interactively. Thus, as a method of digital preservation, Structure from Motion creates an objective and traceable documentation of archaeological remains.

For accurate results, special attention has to be paid to the process of data acquisition: high image quality and good light conditions are as mandatory as a high stereo coverage of the images. To optimize the latter, ground based aerial photography was introduced at the site of Kleiner Anzingerberg. A photo crane and a telescopic pole served as camera platforms for the generation of overview and serial vertical shots. Images taken that way improve accuracy and point density as well as the computing time required to build the models.

Keywords: Structure from Motion – documentation – visualisation – pole aerial photography – stratigraphy

Introduction

The ever-expanding use of digital documentation methods introduced over the course of the last 15 years has led to revolutionary advances concerning recording techniques for archaeological excavations. The introduction of total stations and differential GPS were core requirements for the establishment of an accurate and efficient workflow for the documentation of three-dimensional surfaces (see BARCELÓ et al. 2003). Subsequently, the use of terrestrial laser scanners increased the quality of surface models considerably (DONEUS et al. 2005).

However, due to their high cost, they aren't used extensively on excavations. Instead, low cost image based modeling approaches have more and more often been applied to archaeology during the last years (see DONEUS et al. 2011). Advances in the field of photogrammetry and computer vision as well as the improved processing power of modern computers have made image based modeling available to a wider community (VERHOEVEN et al. 2012, p. 8). So far, Structure from Motion (SfM) and Multi View Stereo (MVS: often running along under the umbrella term of SfM) have been used mainly for large-scale terrain modeling (e.g. BOGACKI et al. 2010) and for the documentation of individual objects (e.g. KOUTSOUDIS et al. 2009). There have been only few attempts to introduce SfM as a standardized recording technique for archaeological excavations (e.g. WEßLING et al. 2013 and DE REU et al. 2013). The aim of this study is to show how image based modeling can be utilized systematically within the workflow of documentation and interpretation of an archaeological excavation carried out using stratigraphic methods.

Single Surface Documentation

The documentation of the unique stratigraphy of the area excavated is an essential part of archaeological excavations. This is done by uncovering the individual stratigraphic units in the reversed order of their deposition (HARRIS 1979, p. 111). This way the excavated stratigraphic units are inevitably destroyed. Therefore, the physical and spatial properties of each surface – which can be considered to relate to an act or process – have to be recorded. The documentation of both the top surface and the bottom surface of every deposit allows a virtual reconstruction of the volume of the excavated deposits (DONEUS et al. 2004, pp. 113).

Case Study: Kleiner Anzingerberg

Modern excavations within the exceptionally well preserved Copper Age settlement Kleiner Anzingerberg / Meidling im Thale (Lower Austria) have been going on since 1999. The site is assigned to the Jevišovice Culture and dates to around 3000 cal BC. (KRENN-LEEB 2010)

The current investigations in trench 5 (6 to 8 meters) have revealed an extensive sequence of extraordinarily fine layers, indicating numerous activities and different phases of the settlement (fig. 1). In terms of choosing and designing proper documentation methods, the complexity and the density of the layers represented a challenging situation.

The aim of the case study was to create a comprehensible and easy-to-understand documentation of the archaeological evidence hidden in the ground. This was done by implementing 3D modeling into the fieldwork. Basic hardware needed for computer-assisted image-based modeling (that is, a total station – Leica TCR 407 Power – and a digital SLR camera – Nikon D5000, 18-55 mm Nikkor lens, sensor size 23.6 × 15.8 mm, pixel size 5.5 µm) was already available at Kleiner Anzingerberg even before the first experiments with SfM were conducted onsite at the end of the campaign in 2011 (KRENN-LEEB et al. 2012, pp. 23).

Fig. 1 – Rectified photograph of trench 5, Kleiner Anzingerberg. The vertical image was created using a photo crane.

Based on these first experiences, a systematic SfM documentation was implemented into the excavation workflow on Kleiner Anzingerberg in 2012 and has been used in 2013 as well. To put it in a nutshell: SfM based recording became part of the documentation and interpretation routine at Kleiner Anzingerberg.

Workflow

Typically, digital documentation of stratigraphic excavations in Austria is done by taking measurements of the features outlines and topographies (i.e. height points), sometimes complemented with the generation of rectified and georeferenced photographs (see ANSORGE 2005). As – in terms of quality and confirmability – this approach was not deemed sufficient for the study site of Kleiner Anzingerberg, another straightforward workflow was developed for the application of image based modeling, resulting in a more accurate, but still relatively cost efficient 3D documentation.

The overall workflow for digital documentation can be assigned to three steps (fig. 2):

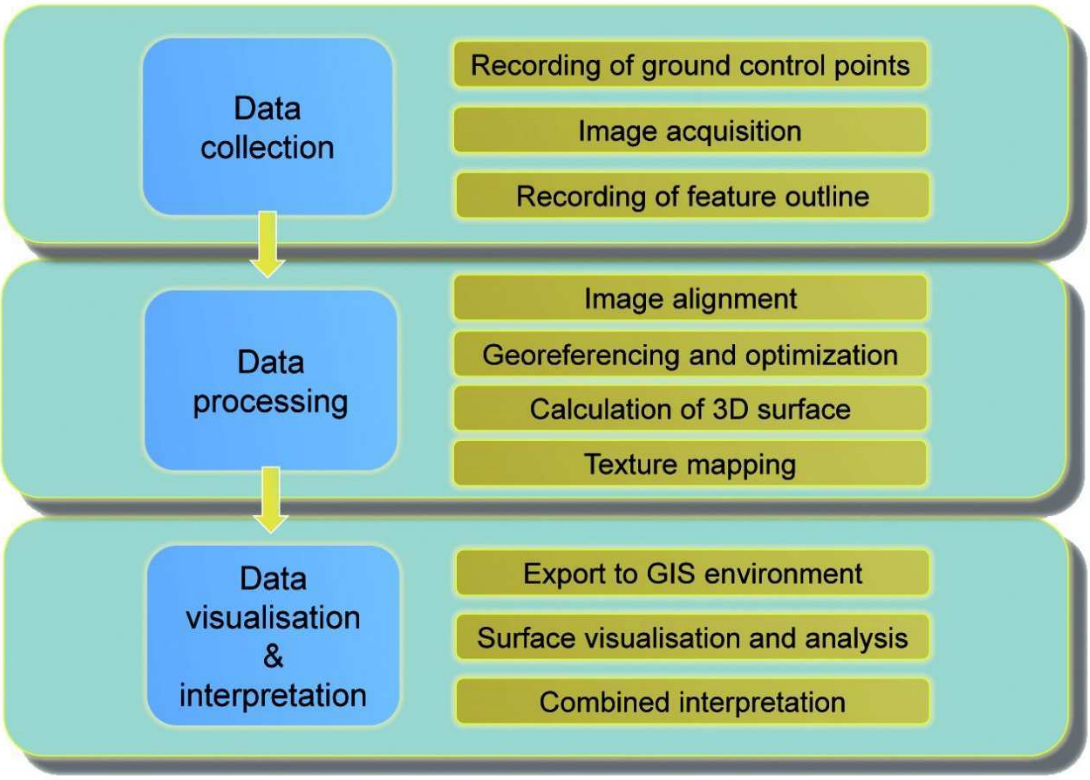

Fig. 2 – Workflow of a systematic single surface documentation with SfM.

Data Collection

The first step, data collection, has to be done entirely during the excavation process and causes the only fixed costs for the implementation of image based recording within excavations, as data processing and interpretation are not necessarily a part of field work and can be done at a later point after the definition of research questions (in particular in the case of rescue excavations). Collecting the proper data provides the opportunity to calculate and georeference the models at some point in the future.

Recording of ground control points

For georeferencing purposes at least three ground control points have to be distributed consistently around or within the stratigraphic unit in question. Do not use reflective markers – reflections interfere with automatic feature recognition! The use of more than three ground control points compensates measurement errors and increases the accuracy of georeferencing.

Image acquisition

For image acquisition overlapping photographs have to be shot from many different camera positions. Keep in mind that the angular separation between consecutive images should be small. Otherwise it is hard to achieve a stable image network(VERHOEVEN et al. 2013, p. 43). The best strategy for a high coverage of three-dimensional structures is taking concentric image sequences of the object. The individual images should overlap (and sidelap) about 60–80%.

They should have a high depth of field as well as uniform illumination conditions. Shadows should be avoided (WENZEL et al. 2013, p. 257). It is recommended to use the camera's own RAW format (see VERHOEVEN 2010).

Fig. 2 – Pole Aerial Photography can be used to take overview shots as well as serial images for a systematic coverage of the surface. The levitating suspension ensures a vertical orientation of the camera.

In the case of Kleiner Anzingerberg ground based aerial photography was used to achieve a high stereo coverage of the images. Both, a telescopic pole and a photo crane, served as camera platforms for the production of serial vertical and overview shots (Fig. 3). Images taken that way can improve accuracy and point density as well as reduce the computing time required to build the models. (WEẞLING et al. 2013, pp. 249)

Recording of feature outline

It is very important to measure the outline of every documented surface with the total station, as it would be hard to distinguish the boundaries of the stratigraphic units later on. The outlines measured can also be used to clip the models. An additional record of height points is not necessary, as information about the relief can be picked up directly from the model.

Data Processing

The use of photogrammetric methods allows the reconstruction of three-dimensional information on the basis of sequences of two-dimensional images (REMONDINO et al. 2006). However, knowledge about the intrinsic (focal length, principal point position, lens distortion) and extrinsic (position and orientation of the camera in space) parameters of camera calibration is required. Structure from Motion estimates these parameters from a set of overlapping images, with the help of algorithms developed in the field of computer vision. The three-dimensional geometry of the scene analyzed is calculated trigonometrically via the position of corresponding features found in at least two images and the position of the viewpoints, from which the images have been taken (ULLMAN 1979). The result of this first step in the modeling workflow is a sparse point cloud. Each of the points in the point cloud represents a concordant feature. The sparse point cloud is optimized and georeferenced using imported ground control coordinates. In the next step, the sparse point cloud is transformed to a dense point cloud using Multi View Stereo algorithms based on the pixel value of the images. This point cloud is later meshed and texturized and yields a three-dimensional photo-realistic model. In the case study the commercial software Agisoft PhotoScan was used for data processing (fig. 4).

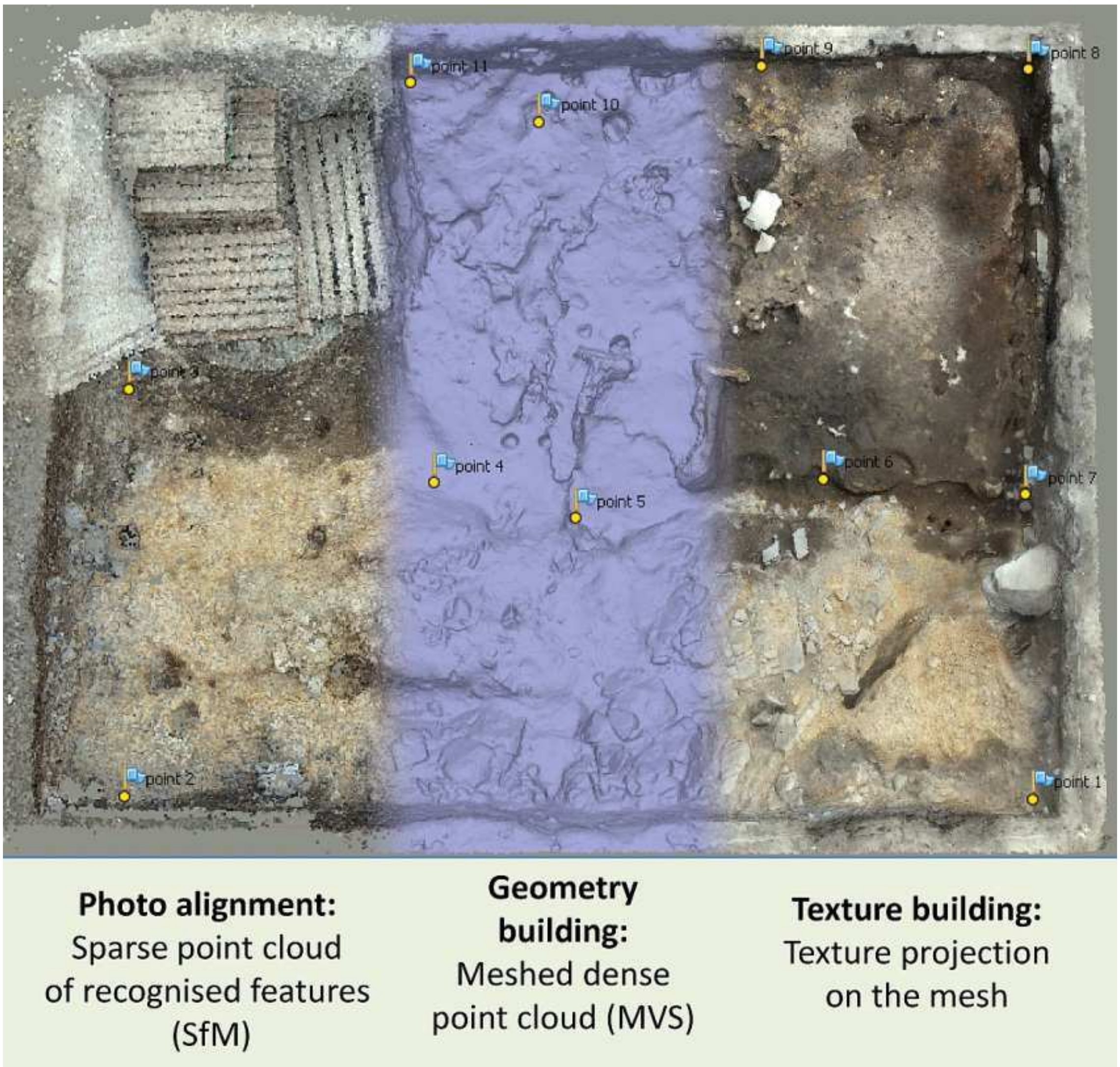

Fig. 4 – Structure from Motion and Multi View Stereo: stepwise calculation of a 3D model within Agisoft PhotoScan.

Data Visualisation and Interpretation

Especially in the fields of cartography (IMHOF 2007) and remote sensing (CHALLIS et al. 2011) several methods for the visualisation of surface models have been developed. They can be applied to SfM/MVS derived models as well. The surface models can be represented as two-dimensional images or within a three-dimensional space. Given the fact that stratigraphic units are related to each other temporally, even a fourth dimension can be added.

For further visualisation, interpretation and spatial analysis, the models can be transferred into a geographic information system (OPITZ et al. 2012).

2D Data Visualisation

Once imported in a GIS environment (e.g. esri® ArcMap), the digital terrain models can be displayed two-dimensionally; for instance as (shaded) relief models, as color coded elevation models or as true orthophotos. Cross sections can be created as well. The stratigraphic documentation method allows computing virtual profile graphs for every part of the excavation, displaying the stratigraphic sequence (fig. 5).

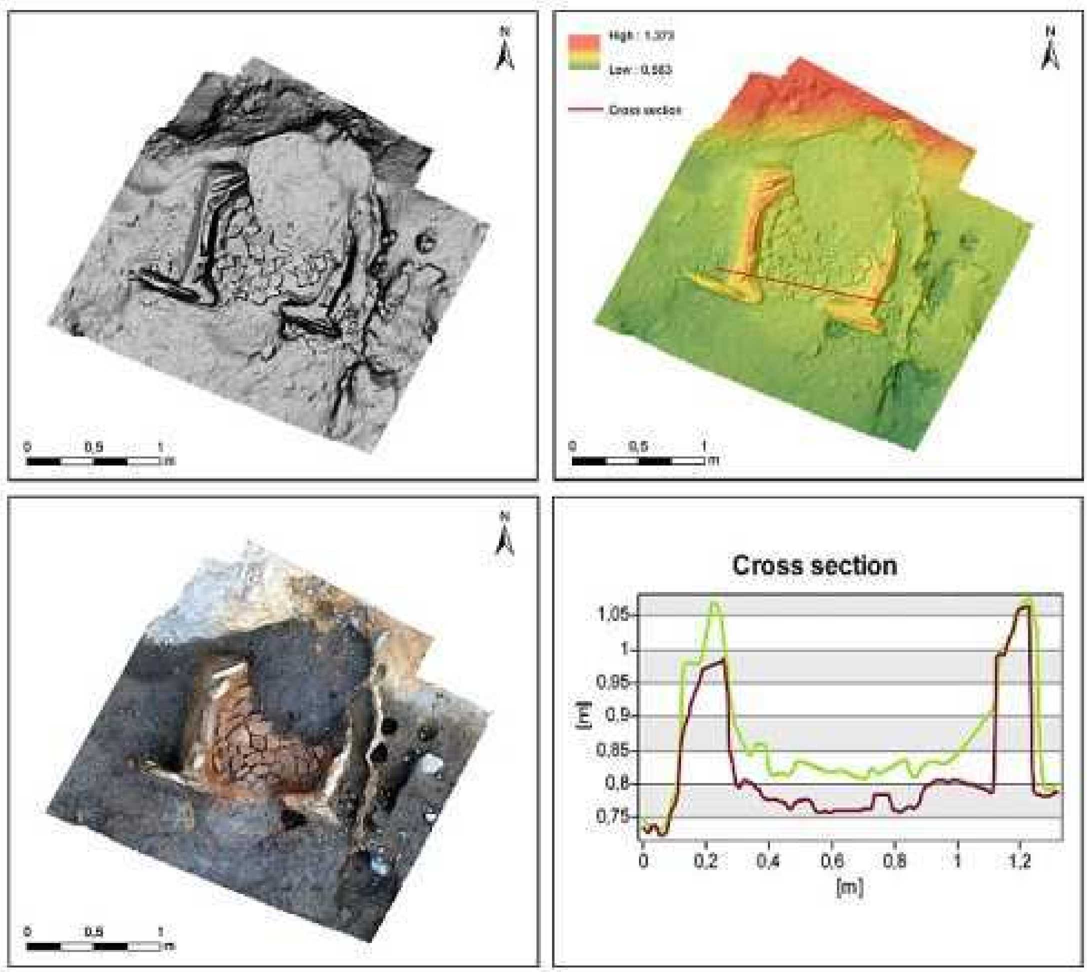

Fig. 5 – Visualisations of a two-dimensional surface: digital elevation model as a shaded relief and as a color coded model at the top; a true orthophoto of the surface and a cross section through two different surfaces at the bottom.

3D Data Visualisation

3D data should probably best be analyzed in 3D. The different spatial data streams collected during the excavation (outlines, artefacts, samples) can be displayed together with the 3D models (fig. 6). Additionally, within a GIS (e.g. esri® ArcScene), these data can be augmented with non-spatial information such as descriptions or interpretations. This is a rather forceful tool for a combined interpretation, based on "objective" data like 3D models as well as on "subjective" observations. However, it has to be stated that importing texturized 3D models into a GIS is still problematic in terms of the number of possible faces, texture size and coordinate transformation.

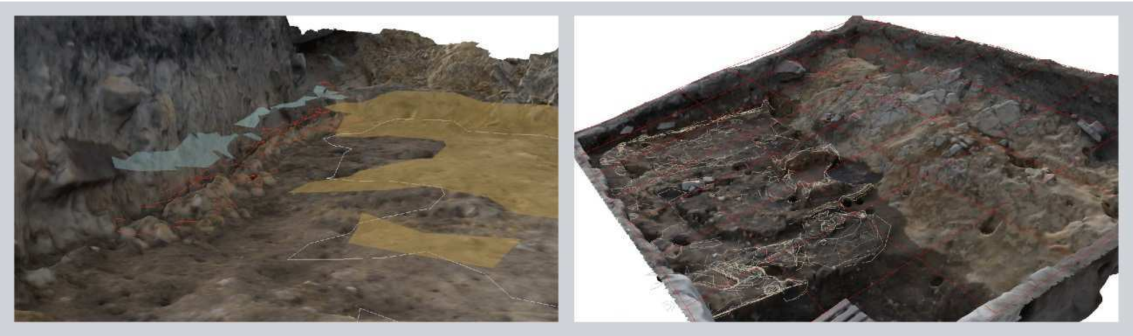

Fig. 6 – A combined visualisation of the collected 3D data within esri® ArcScene.

4D Data Visualisation

The 3D models can be animated in time. By moving through realistically texturized 3D models, sorted according to their stratigraphic position, a four-dimensional virtual reality (see BRUNO et al. 2010) can be constructed. With this technique, a digital copy of the recorded features, arranged in time and space, is still accessible after the destruction of the deposits examined and permits a virtual desktop based re-excavation of the site. Future developments may even lead to (semi)automatically created matrices based on topological relations of the models.

Evaluation of SfM for systematic and standardized documentation purposes

Requirements for three-dimensional documentation methods for everyday use on archaeological excavations are: high accuracy and reliability, mobility, low cost, fast data acquisition, flexibility and fast data processing (see REMONDINO et al. 2010, pp. 85).

Fig. 7 – 4D visualisation of the excavation process over time: in this example, each model shows another phase of a Copper Age cupola oven.

Reliability and Accuracy

The reprojection of the two-dimensional geometry of images into a three-dimensional space is based on SfM algorithms. These calculations provide only estimates of the actual values. The quality of the estimation (and therefore of the three-dimensional geometry reconstructed) is represented by the reprojection error. The reprojection error describes the distance between the original points (on the image) and the reprojected points, as calculated by SfM algorithms. The root-mean-square-deviation (RSME) of the reprojection error is automatically calculated and can be reduced with an optimization process integrated into the software, taking into account the ground control points measured with the total station. Even before this optimization process, the mean georeferencing error as calculated in reference to the ground control points was rather low in all cases (sub centimeter), indicating a high accuracy of the models.

Numerous comparisons of SfM and laser scanning have been published (e.g. WESTOBY et al. 2012 or BRIESE et al. 2012) and come to the conclusion that SfM is less accurate than laser scanning, but with small deviations only (KOUTSOUDIS et al. 2013). The accuracy of the SfM models depends on the position, composition, quality and resolution of the images used. In general, compared to laser scanning, image based methods result in less dense and more irregular point clouds. Particularly for sharp edges and clear contours laser scan data reflect more detail than SfM data. However, it must be noted, that the accuracy and detail reproduction of SfM seems to be more than sufficient for the documentation of most archaeological structures and definitely exceeds the quality of surface models computed from manually measured point clouds. Additionally, surface models produced with a laser scanner usually have limited texture qualities, whereas image based models exhibit a high degree of texture detail and color reproduction.

The reliability of SfM depends on the quality of the data acquired. Capturing the images in a deliberate and conscientious way is therefore an essential prerequisite for a reliable model calculation. Since the calculation usually cannot be performed directly on the excavation, which implies there is no possibility of immediate control, there is always some risk of no precise 3D model emerging. Appropriate guidelines for photographic documentation and the use of experienced staff may reduce this risk. So far, all the 118 surfaces recorded with SfM on the study site of Kleiner Anzingerberg proved to be properly modeled. The average number of photographs used per model is 70. On-the-fly reconstructions (WENDEL et al. 2012) and calculation methods for optimized camera positions (HOPPE et al. 2012) will probably eliminate this drawback in the future.

Mobility

Easy handling and agility of the devices used for data acquisition are important factors on most excavations. The application of SfM has a high mobility index. This applies both to the transportation to and the use on the excavation. SfM can be used for the documentation of most structures which can be covered by a camera. The operating range can be extended with the help of other technical devices such as poles, cranes or unmanned aerial vehicles.

Costs

As only archaeological standard equipment (measurement unit and camera) is needed for data-recording, no additional hardware costs are incurred in the field. However, image acquisition takes time and experience. The better the lighting conditions and the choice of camera locations the faster the post-processing, which might require additional hard and software (although freeware exists as well). Post-processing is quite time-consuming, but it has to be stated that (particularly concerning rescue excavations) there is often no need to compute the models prior to the definition of research questions. But taking suitable images and recording ground control points gives you the possibility to calculate and georeference the models at some point in the future (with the additional chance of soft and hardware solutions having developed further in the meantime).

Speed of Data Acquisition

The more complex the surface, the more time is needed for its documentation – this is true for almost all documentation methods. Concerning SfM, the mobility of the camera usually provides a fast image acquisition process. However, the shading of surfaces often needs many helpers or a technical solution. In addition, the background of the images should be free of moving objects and people, which can be problematic in the case of different activities taking place simultaneously on an excavation. As it is necessary to move the camera around and over the entire object, a systematic image-based documentation requires some foresight in planning, to avoid e.g. walking over surfaces already cleaned.

Time needed for Post-Processing

The time needed to create a model depends upon the software and hardware selected, the experience of the user, the data available (number and quality of the images, camera positions selected) and the result desired. The workload is higher when errors were made during the data recording: in this case, images have to be sorted out manually or cropped and image arrays calculated incorrectly have to be removed. Basically, model building processes are computationally intensive, which may result in computer run times of a few hours per model. Batch processing is recommended.

Flexibility

SfM can be applied on different scales. The resolution desired correlates inversely to the distance between the camera and the object, which also influences the number of images necessary. Reflective or monochrome surfaces (e.g. painted walls) are not suited for SfM, as they lack distinctive features that could be matched between the images. Hard shadows, varying light conditions and rainfall should be avoided.

Outlook

So far, all three-dimensional models mentioned in this article are surfaces, that is, two-dimensional models with an assigned height. True three-dimensionality is characterized by solids (WYCISK et al. 2003). Each archaeological deposit forms such a solid, from which a 2.5D model – comprising the upper and the lower surface – can be calculated. These individual surfaces of the filling can be combined to a 3D solid. As each 3D object represents a stratigraphic unit, the analysis of topological relations would allow a semi-automated generation of the Harris-matrix of the excavation. So far, the temporal arrangement of the models is based on the sequence of the layers as defined during the excavation.

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