

PHOTOGRAMMETRIC PROCESSING OF AERIAL PHOTOGRAPHS ACQUIRED BY UAVS

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INTRODUCTION

In the past decade 3D visualization has become an important part of archaeological research and the presentation of cultural heritage. In this paper a new photogrammetric method for archaeological applications is introduced; it will show the steps of the method from data acquisition to completion of the 3D model (DTM [digital terrain model] and orthophoto). With the presented method precise digital terrain models or georectified orthophotos can be created in order to document and visualize archaeological heritage for post-processing or presentation purposes.³ The aerial photographs have been taken with UAVs (unmanned aerial vehicles), which allow for data to be collected cost-effectively over large areas. The workflow will be reviewed from aerial photo acquisition, through presentation of Structure from Motion (SfM) and Multi-view Stereo (MVS) algorithms to the creation of digital terrain models and orthophotos.

Precise and detailed documentation of the excavation sites is essential in archaeology. An orthophoto of the site and its surroundings or a DTM, which represents the terrain with high precision, can play a very important role in this process.⁴ In addition, it could raise the quality of recording the conditions present. In our opinion the presented method will be able to alter practices for archaeological excavations. During archaeological field work the primary objective commonly is to discover archaeological phenomena and



Fig. 1: Fixed-wing UAV during waypoint flight

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³ De Reu, J. – Plets, G. – Verhoeven, G. – De Smedt, Ph. – Bats, M. – Cherretté, B. – De Maeyer, W. – Deconynck, J. – Herremans, D. – Laloo, P. – Van Meirvenne, M. – De Clercq, W.: Towards a three-dimensional cost-effective registration of the archaeological heritage. *Journal of Archaeological Science* 40 (2013), 1108–1121; De Reu, J. – De Smedt, Ph. – Herremans, D. – Van Meirvenne, M. – Laloo, P. – De Clercq, W.: On introducing an image-based 3D reconstruction method in archaeological excavation practice. *Journal of Archaeological Science* 41 (2014), 251–262. In March of 2014 we completed our connected research and development project, in which we examined the role and applicability of this technology compared to other techniques. Further information: <http://szime3dar.com/hu/>

⁴ Verhoeven, G. – Doneus, M. – Briese, Ch. – Vermeulen, F.: Mapping by matching: a computer vision-based approach to fast and accurate georeferencing of archaeological aerial photographs. *Journal of Archaeological Science* 39 (2012), 2060–2070.

finds, revealing their connections. But an excavation is an invasive research method, so it is crucial to record and document the state of each phase of the scene precisely. Thanks to technological improvements, high-resolution three-dimensional models can be created using two-dimensional aerial photos, facilitating the study of the site using documentation with supplementary precise site surveys.⁵

For the preparation of the models, photographs with proper resolution and software based on SfM algorithms are needed. In our case this software is PhotoScan developed by the Russian company Agisoft LLC.⁶ With the help of these algorithms the program determines the camera positions and constructs the three-dimensional point cloud, the representation of the actual object. The algorithms use photo sequences taken from different locations and angles around the site as input. Below it will be shown that an excavation site can be mapped relatively quickly with this workflow,⁷ and it can be used not just for processing aerial photographs but also for documenting finds.

FIELD WORK

The entire workflow basically consists of two parts: data acquisition in the field and post-processing of the photos (*Fig. 2*). The field work includes the measuring of the ground control points (GCPs)⁸ (if this is possible) as well as the acquisition of the aerial photos.

As regards the documentation of the excavation sites, orthophotos are taken that provide a great deal of information about the site and its surroundings as well.⁹ Photographs are taken nearly perpendicular to the earth's surface, but if it is necessary to calculate a DTM as well, it is also worthwhile to take oblique images.

It is essential to take photos of the site from different angles so the 3D reconstruction will include more details. In order to get a high quality model at the end of the workflow, resolution as well as flight altitude are of crucial importance. Generally speaking, the more images we have with higher resolution, the more precise the model is; however this increases the duration of processing and the hardware requirements for the calculations. To get an optimal result a resolution of at least 5 Mpx is necessary. However, if higher quality is required for the orthophotos, the recommended minimum resolution is 12 Mpx.

The 3D structure and the camera positions are derived from the overlapping portions of the photographs, so the best results are achieved with greater overlap. An orthophoto or terrain model can be obtained from either ordered or non-ordered photo sequences¹⁰ but it is important to take every photograph from a different position and viewpoint, and there should be sufficient image overlap (60% side and 80% forward overlap; *Fig. 4*). This can be set primarily during the course of waypoint flights.¹¹ During a waypoint flight the plane is controlled by the autopilot on a preset route and altitude.

⁵ De Reu, J. – De Smedt, Ph. – Herremans, D. – Van Meirvenne, M. – Laloo, P. – De Clercq, W.: On introducing an image-based 3D reconstruction method in archaeological excavation practice. *Journal of Archaeological Science* 41 (2014), 251–262.

⁶ Agisoft LLC (2013) Agisoft PhotoScan user manual. Professional edition, version 1.0.0. http://downloads.agisoft.ru/pdf/photoscan-pro_1_0_0_en.pdf (January 2014)

⁷ De Reu, J. – Plets, G. – Verhoeven, G. – De Smedt, Ph. – Bats, M. – Cherretté, B. – De Maeyer, W. – Deconynck, J. – Herremans, D. – Laloo, P. – Van Meirvenne, M. – De Clercq, W.: Towards a three-dimensional cost-effective registration of the archaeological heritage. *Journal of Archaeological Science* 40 (2013), 1108–1121; Doneus, M. – Verhoeven, G. – Fera, M. – Briese, Ch. – Kucera, M. – Nezbauer, W.: From deposit to point cloud: a study of low-cost computer vision approaches for the straightforward documentation of archaeological excavations. *Geoinformatics* 6 (2011), 81–88; Verhoeven, G. – Doneus, M. – Briese, Ch. – Vermeulen, F.: Mapping by matching: a computer vision-based approach to fast and accurate georeferencing of archaeological aerial photographs. *Journal of Archaeological Science* 39 (2012), 2060–2070

⁸ These are points with precise coordinates that can be clearly seen on the aerial photographs.

⁹ We consider it very important to employ this technology during the course of preliminary reconnaissance, since through the use of UAV devices it is possible to quickly and effectively survey archaeological sites along the path of even major projects.

¹⁰ Ordered photo sequences are, for example, the aerial photos derived from waypoint flights which are “in order”. Non-ordered photo sequences do not have any system; they are taken from random viewpoints.

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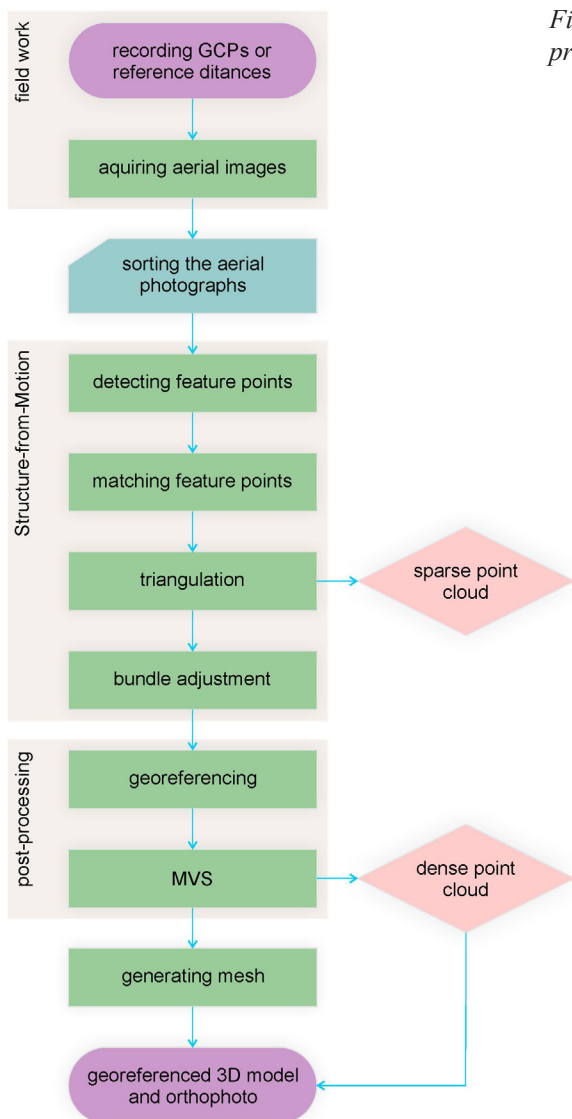


Fig. 2: Orthophoto and digital terrain model preparation process (detailed description in the text)

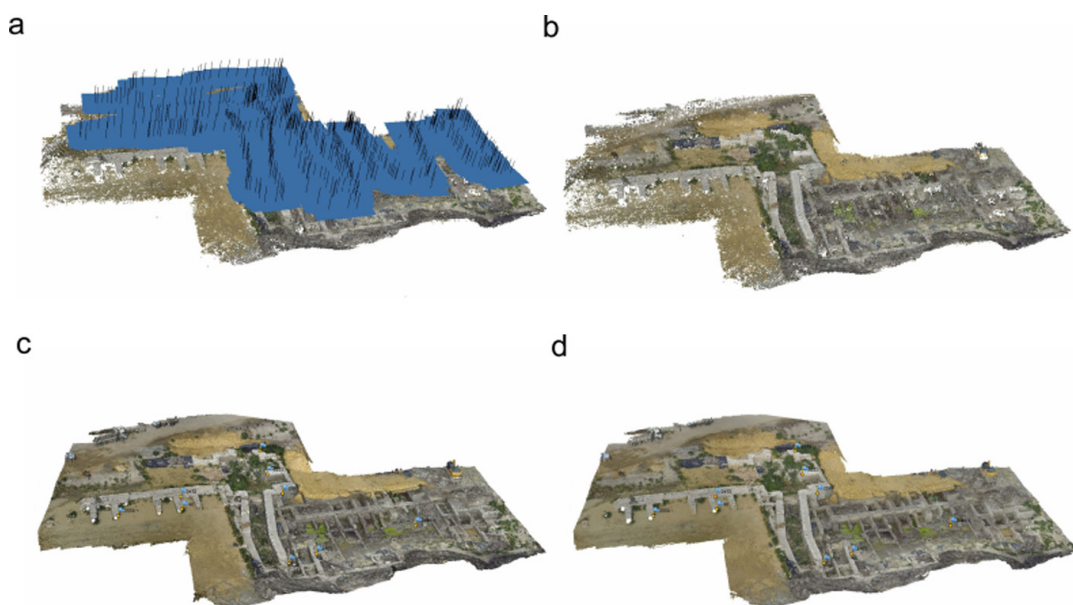


Fig. 3: The sparse point cloud with the camera positions (a); the sparse point cloud (b); the dense point cloud (c); the textured polygon mesh (d); excavation site at Dunakapu Square (Győr), date of aerial photography: 30 August 2013

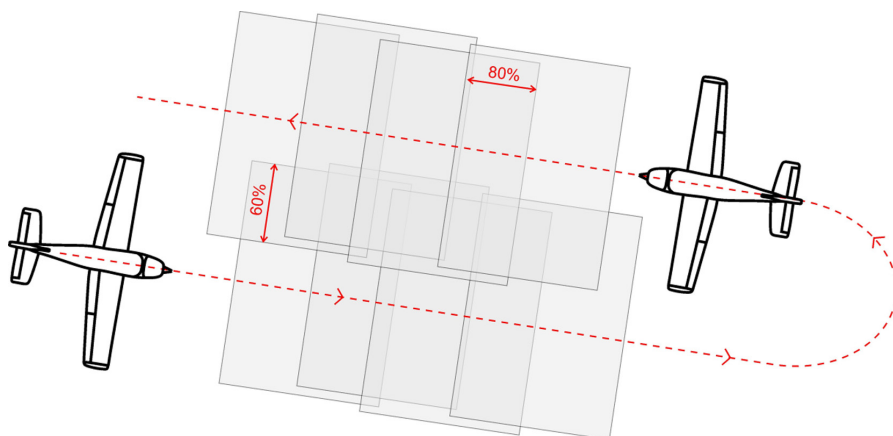


Fig. 4: Overlap between aerial photographs

The first step during field work is the acquisition of GCPs. A precise and georectified model can only be calculated with GCPs. However, if these are unavailable it is still possible to obtain the required precision, but only if accurate data on distances between well-indicated points are available.¹² In this case the model cannot be projected on a geographical coordinate system, but it will be accurate and measurements can be carried out.¹³

In our case the 3D reconstructions are automatically calculated 3D models using 2D images which are the exact representations of actual objects. Every 3D reconstruction method requires a device to record objects, providing data to calculate a 3D model with the help of photogrammetric software.

Fixed-winged RPAS (Remotely Piloted Aircraft System) vehicles are used to acquire aerial photographs to map large areas. The equipment consists of a Skywalker type model plane and additional systems designed specifically for FPV (First Person View; controlled with the aid of a camera) flights (Fig. 5). The operation of the plane is assisted by the C4S autopilot system developed in Hungary, which is capable of several flying modes (Manual, Stabilized, Waypoint, Return Home mode and flying around a given point, etc.). During waypoint flight, after the desired area is determined the autopilot automatically plots the flight route based on a previously set program. The flight plan can be customized for the given task with the various settings of the program (flight altitude, flight speed and the parameters of the camera). The flight can be tracked and controlled with the help of a video transmitter placed on the plane and a video receiver located on the ground. The task is automatically carried out by the autopilot but it can be aborted or the route can be corrected at any time. An LRS (Long Range System) assists the pilot during long distance flights. With the help of the LRS, the range of these devices can be safely extended to 5–10 km. The RPAS device's flight time is about 40–60 minutes but the flight route can be resumed after a battery change. There is a camera in the vehicle's body that is nearly perpendicular to the earth's surface taking photos at specific time intervals.

IMAGE PROCESSING

Aerial photographs, like any other photograph, are optically distorted. This is one of the characteristics of digital photographs, so aerial photography always results in distorted images. Every image has been taken from different flying altitudes and angles. To correct this and get accurate maps, it is necessary to perform

¹² Plets, G. – Gheyle, W. – Verhoeven, G. – De Reu, J. – Bourgeois, J. – Verhegge, J. – Stichelbaut, B.: Three-dimensional recording of the archaeological remains in the Altai Mountains. *Antiquity* 86 (2012), 884–897; Verhoeven, G.: Taking Computer Vision Aloft – Archaeological Three-dimensional Reconstructions from Aerial Photographs with Photoscan. *Archaeological Prospection* 18 (2011), 67–73.

¹³ De Reu, J. – Plets, G. – Verhoeven, G. – De Smedt, Ph. – Bats, M. – Cherretté, B. – De Maeyer, W. – Deconynck, J. – Herremans, D. – Laloo, P. – Van Meirvenne, M. – De Clercq, W.: Towards a three-dimensional cost-effective registration of the archaeological heritage. *Journal of Archaeological Science* 40 (2013), 1108–1121; Plets, G. – Gheyle, W. – Verhoeven, G. – De Reu, J. – Bourgeois, J. – Verhegge, J. – Stichelbaut, B.: Three-dimensional recording of the archaeological remains in the Altai Mountains. *Antiquity* 86 (2012), 884–897.

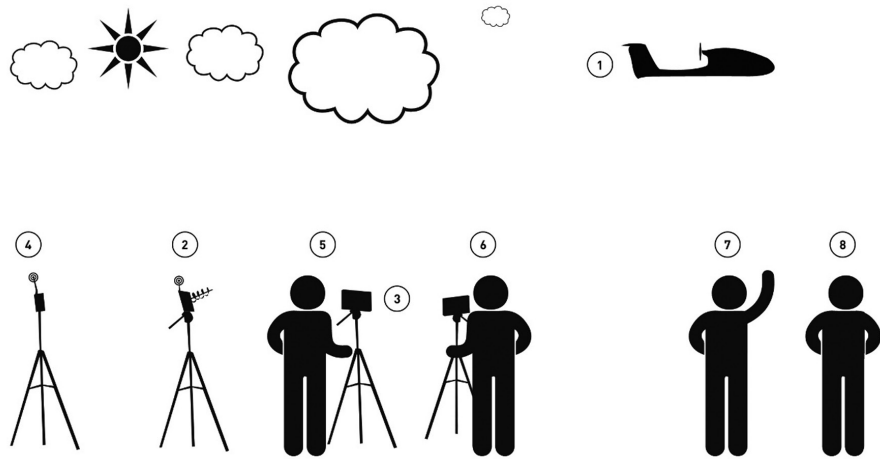


Fig. 5: Essential human resources and equipment for aerial photography: (1) autopilot; (2) video receiver system; (3) displays; (4) Long Range System; (5) pilot; (6) co-pilot; (7) auxiliary staff; (8) archaeologist

geometric corrections and georectify the photographs. Geometrical errors may occur for various reasons. They are induced by the optics of the camera, the topographical relief and the tilt of the camera (Fig. 6).¹⁴ The camera is located in a certain place in space and it has a certain direction. The position defines the projection centre with three coordinates (x , y and z), and the direction is defined by three angles (ω [pitch], ϕ [roll] and κ [yaw]; Fig. 6/c). These six variables provide the extrinsic camera parameters. During vertical photography flight ϕ and ω is nearly 0. The more tilted the photographs are to the earth's surface the more distorted the images will be (Fig. 6/b).

Distortion caused by topographical relief arises from adjusting the altitude of each point to the projection plane (Fig. 6/a).

After sorting and importing the captured images to PhotoScan it may be necessary to mask interfering, unwanted details (e.g. moving sections, untextured areas, water surfaces, shiny surfaces, sky) so the software will exclude them from the calculations. The next step is generating the point cloud. The result of this is (1) a sparse point cloud (Fig. 3/a, b) which represents the shape of the original object, (2) the soft-

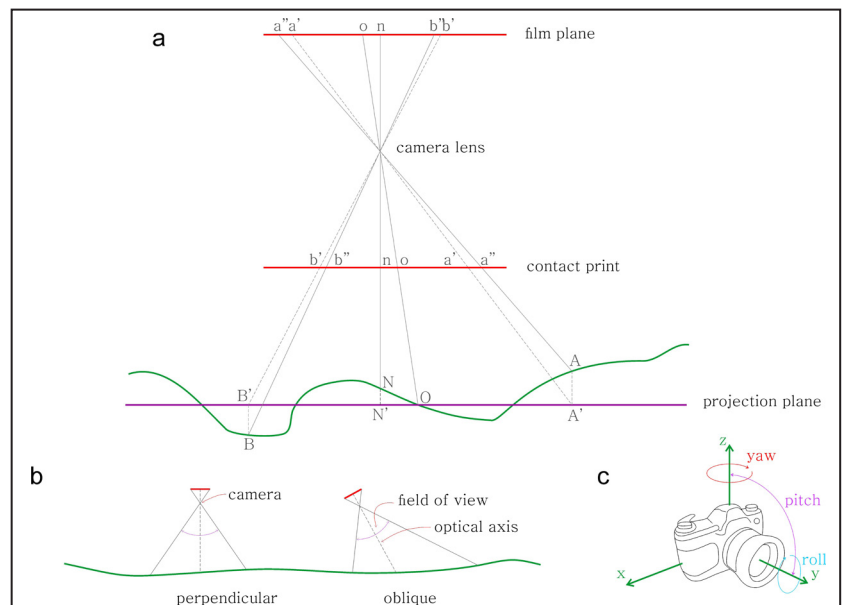


Figure 6: Illustration of the geometrical distortion of images: (a) topographical relief and (b) distortion caused by the tilt of the camera; (c) angles of camera direction

¹⁴ Verhoeven, G. – Sevara, Ch. – Karel, W. – Ressel, C. – Doneus, M. – Briese, Ch.: Undistorting the past: New techniques for orthorectification of archaeological aerial frame imagery. In: *Good practice in archaeological diagnostics. Non-invasive survey of complex archaeological sites*, eds Corsi, Cristina – Slapšak, Božidar – Vermeulen, Frank (Cham: Springer. 2013), 36–67.

ware calculates the camera positions at the moment of capturing the images and (3) calculates the intrinsic camera parameters: focal length, principal point, etc. (Fig. 2).

The first step of post-processing, namely the construction of the model, is detecting feature points in the images and then defining the matching points (Fig. 7). The number of these matching points depends on the texture and resolution of the original images, with higher resolution giving better results. The disadvantage of these features is that they increase the duration of the calculations, which depends greatly on the quality and quantity of the images and on the desired quality of the resulting model. The density, sharpness and resolution of the images define the quality of the point cloud. A single point should be seen in at least three images, and it is worth taking more photos of the given area.¹⁵

Detecting feature points, matching them and generating the point cloud are done by the software using SfM algorithms. SfM algorithms need related image sequences, which have some overlap between them, so the same points can be seen from different angles. The algorithm calculates the matching points as well as the camera positions and intrinsic camera parameters (focal length and geometrical distortions of the lens). SfM achieves this by connecting 2D feature points in the image pairs.

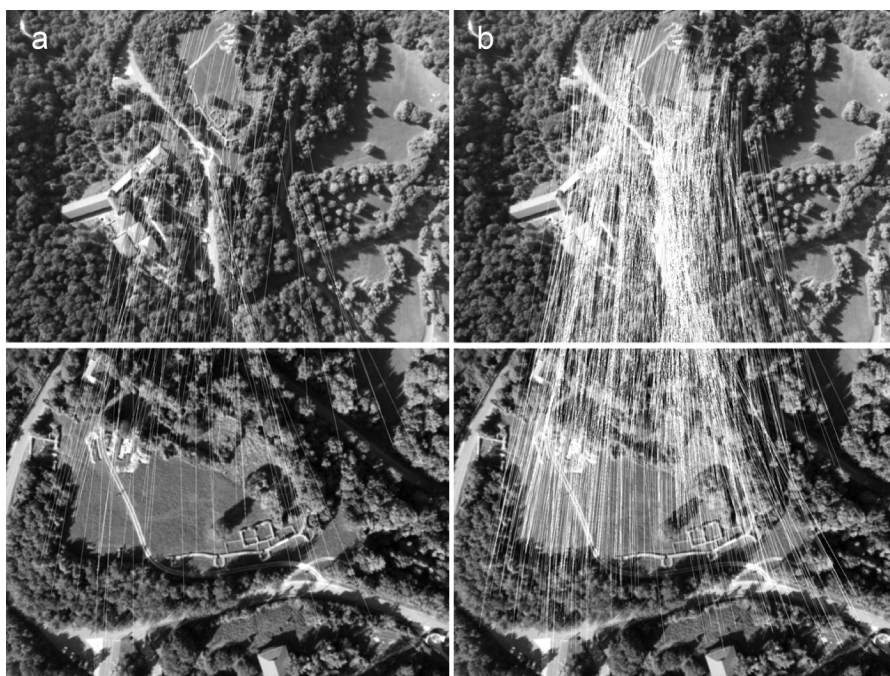


Figure 7: The SIFT (a) and ASIFT (b) algorithms detect a different number of feature points on the same image pair which is caused by the nature of the algorithms (the test was carried out with the aid of the website http://demo.ipol.im/demo/my_affine_sift/).

After generating the sparse point cloud, the next step is georectification which is the placement of the GCPs on clearly visible points and then the determination of the projection system. During data acquisition it is important that the GCPs are evenly distributed on the surveyed area and have measured x, y and z coordinates.

Based on the data required for georectification, a dense point cloud can be created which uses the output of the sparse point cloud generation to make a denser point cloud. This step is the implementation of MVS algorithm, which uses the output of the SfM algorithm (Fig. 3/c). This dense point cloud is required to calculate accurate orthophotos. The software calculates the polygon mesh from the point cloud and textures it (Fig. 3/d). Textures are created using the original images. After this, the textured orthophoto (Fig. 8) and digital terrain model (DTM; Fig. 9) is exported, which in turn can be imported into different software to perform geoinformatic analyses, for example.

¹⁵ Westoby, M. J. – Brasington, J. – Glasser, N. F. – Hambrey, M. J. – Reynolds, J. M.: ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* 179 (2012), 300–314.

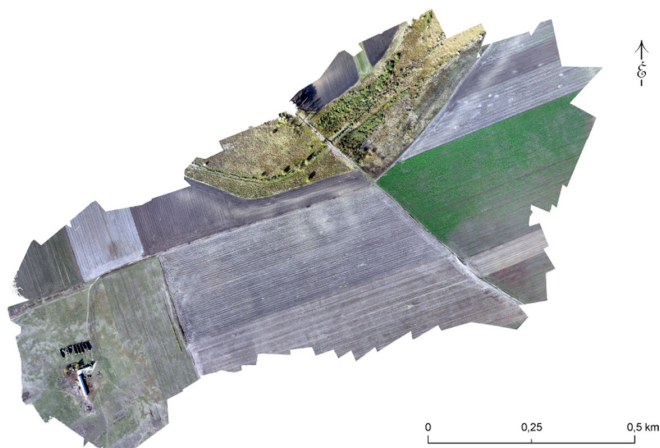


Fig. 8: Orthophoto of the Mezőcsát-Laposhalom area, BORBAS project, research area of Dr. Klára Pusztainé Fischl

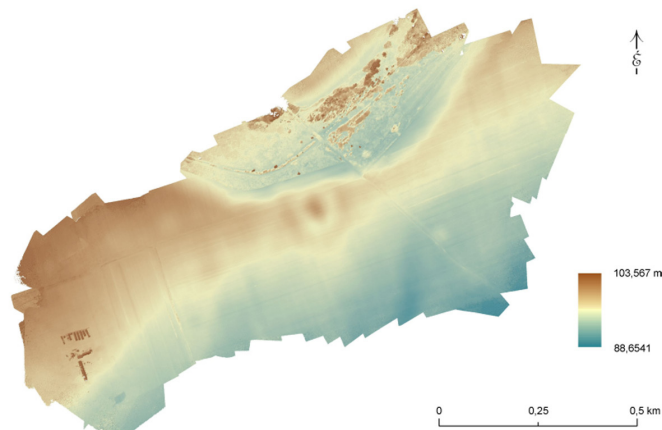


Fig. 9: DTM of the Mezőcsát-Laposhalom area, BORBAS project, research area of Dr. Klára Pusztainé Fischl

The hardware requirements for the calculations are rather high. For the creation of the examples presented here an Intel Core i7 4770 3.4 GHz, 32 GB RAM, Nvidia GeForce GTX 650 Ti configuration was used. Calculations with numerous images could take several days depending on the quality of the images and desired results. Using a powerful video card can reduce the duration thanks to the employment of OpenCL.¹⁶

SUMMARY

The method presented above allows for cost-efficient surveys. It is fully applicable for mapping excavation sites, creating orthophotos and DTMs. During surveying it is necessary to take a large number of images and to acquire accurate GCP coordinates for clearly visible points or to measure the aforementioned reference distances.

This kind of documentation helps in surveying endangered heritage and it can play an important role in cultural heritage conservation. Its advantages are that it is accurate, fast and non-invasive. Its drawbacks are the high hardware requirements and the need for expensive equipment for accurate results. In addition, the development and professional use of the RPAS devices demand great experience. Furthermore, it is necessary to adapt to weather conditions during surveying. Strong winds or rainy weather can render aerial photography impossible. Solar activity should also be considered because solar flares can cause GPS signal loss, and in worst case scenarios it can even lead to accidents. However, this technology's many advantages far outweigh its small number of disadvantages. Photogrammetric processing of aerial photographs acquired by UAVs is evolving constantly, has a great future and can play an ever more important role in archaeology and the preservation of cultural heritage.

RECOMMENDED LITERATURE

Agisoft PhotoScan user manual. Professional edition, version 1.0.0. 2013. http://downloads.agisoft.ru/pdf/photoscan-pro_1_0_0_en.pdf (January 2014)

DE REU, J. – DE SMEDT, PH. – HERREMANS, D. – VAN MEIRVENNE, M. – LALOO, P. – DE CLERCQ, W. On introducing an image-based 3D reconstruction method in archaeological excavation practice. *Journal of Archaeological Science* 41 (2014), 251–262.

¹⁶ OpenCL is a programming language which can use the processing units of the video card efficiently.

DE REU, J. – PLETS, G. – VERHOEVEN, G. – DE SMEDT, PH. – BATS, M. – CHERRETTÉ, B. – DE MAEYER, W. – DECONYNCK, J. – HERREMANS, D. – LALOO, P. – VAN MEIRVENNE, M. – DE CLERCQ, W.
Towards a three-dimensional cost-effective registration of the archaeological heritage. *Journal of Archaeological Science* 40 (2013), 1108–1121.

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3D digitization using Structure from Motion. *CEIG – Spanish Computer Graphics Conference* (2012).
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