Resurrection of the Steppe Empires: Data Recording, Reconstruction and Semi-Automated Interpretation

Application and development of advanced visualisation and edge detection methods in the context of the Uyghur capital of the 9th century

Huy DO DUC, HTW Dresden, Germany
Marco BLOCK-BERLITZ, HTW Dresden, Germany
Hendrik ROHLAND, DAI Bonn, Germany
Christina FRANKEN, DAI Bonn, Germany
Tumurochir BATBAYAR, Mongolian Academy of Sciences, Mongolia
Ulambayar ERDENEBAT, National University of Mongolia, Mongolia

Abstract: With the focus on segmentation for the identification of archaeological structures, 42 km² of elevation data is used. As a standard tool of archaeological documentation, the combination of UAVs and photogrammetry has been applied. The result of this investigation shall be an automatically generated city map from digital elevation data. The raw DEMs contain a lot of artefacts, which sometimes make interpretation challenging. Preparations were made to continue working with the corrected information. After the interpolation, scaling and georeferencing of geodata the actual processing could start. There are several visualisation techniques for digital elevation models. Hillshading, trend removal, sky view factor and topographic openness were tested. Each of the techniques has its own characteristics, but also limits. In order to use these techniques correctly, the results must be compared, to know which landscape suits which technique. To make the images more understandable, visualisation from remote sensing and methods from computer science were used together to enhance the visibility of certain landscape properties. Image preprocessing steps like edge detection, morphological operations or histogram stretching are required to display features more clearly. The combination of several technologies makes it possible to see different topographical features in one image. Although data processing and analysis is still in progress as the team experiments with different methods, first results demonstrate the capabilities of UAV-based mapping even at the scale of larger landscapes.

Keywords: *3D reconstruction—photogrammetry—image processing—steppe empires—urban archaeology—remote sensing*

CHNT Reference: Do Duc, Huy; Block-Berlitz, Marco; Rohland, Hendrik; Franken, Christina; Batbayar, Tumurochir, and Erdenebat, Ulambayar. 2021. Resurrection of the Steppe Empires: Data Recording, Reconstruction and Semi-Automated Interpretation. Application and development of advanced visualisation and edge detection methods in the context of the Uyghur capital of the 9th century. Börner, Wolfgang; Kral-Börner, Christina, and Rohland, Hendrik (eds.), Monumental Computations: Digital Archaeology of Large Urban and Underground Infrastructures. Proceedings of the 24th International Conference on Cultural Heritage and New Technologies, held in Vienna, Austria, November 2019. Heidelberg: Propylaeum.
doi: 10.11588/propylaeum.747.

Motivation and Introduction

The nomadic empires of Central Asia are particularly interesting phenomena in the history of the ancient civilisation. Despite the relatively small population and economy of the Eurasian steppes, they had huge impact on the course of human history. While these empires relied on the military strength and mobility of a mainly nomadic population, they time and again developed significant urban structures. For about twenty years, the German Archaeological Institute, the Mongolian Academy of Sciences and the National University of Ulaanbaatar have been jointly researching nomadic settlement structures, their characteristics and intercultural influences in the Mongolian Orkhon Valley.

Between 745 and 840, the nomadic tribe of the Turkic Uyghurs formed an empire in the Mongolian steppe. The Uyghur state stretched from Manchuria to Dzungaria and the Tarim Basin. They were military allies of the Chinese Tang dynasty. The military support of the Uyghurs was so crucial for the Chinese dynasty, that they had to grant favourable trading conditions and send presents and payments that numbered hundreds of thousands of pieces of silk a year (Mackerras, 1968). This wealth put the Uyghurs in a position to participate in the trade of the silk roads. They relied on Iranian Sogdians from Central Asia as traders and as advisors and administrators of their Empire (Golden 1992, pp. 172f). To facilitate trade, diplomacy and handicraft, the Uyghurs founded urban settlements (Fig. 1). Most prominent amongst them was their capital city, Qara Balğasun, which was situated in the "Ötükän" at the river Orkhon, in the sacred lands of the ancient Turkic royal ideology (Rosthorn, 1921; Gabain, 1950, pp. 33–35). The Arabian traveller Tamīm ibn Baḥr reported "[…] that this is a great town, rich in agriculture and surrounded by *rustāqs* full of cultivation and villages lying close together. The town has twelve iron gates of huge size. The town is populous and thickly crowded and has markets and various trades […]" (Minorsky, 1948, pp. 283). In 840 the city was destroyed by the invading Turkic tribe of the Kirgiz from the Upper Yenisei area. Upon the destruction of Qara Balğasun the Uyghur Empire also fell.

Only 30 km south from the ruins of the Uyghur metropolis, the Mongols founded Qara Qorum as capital of their emerging empire. Consequently, almost 400 years after the perishing of Qara Balğasun and the Uyghur Empire, the Orkhon Valley again became the centre of a steppe polity. Some sources claim that Genghis Khan himself chose the location of the city in 1220. In 1235 a city wall, a palace and a temple were erected. Further information on this city is provided through the reports of travellers and chroniclers from different cultures. Qara Qorum was a cosmopolitical centre, frequented by diplomats, noblemen, traders, missionaries and artisans from China, Central Asia, the Middle and Near East and even from Western Europe. Qara Qorum's zenith lasted until 1260, when Qubilai Khan usurped the throne of the empire and established his residences at Shangdu and Dadu (Peking) (Sagaster, 1999; Hüttel, 2005; Franken, 2015). Because of the historical significance of the ancient sites in the Orkhon Valley, UNESCO listed the whole region as a World Heritage Site in 2004.

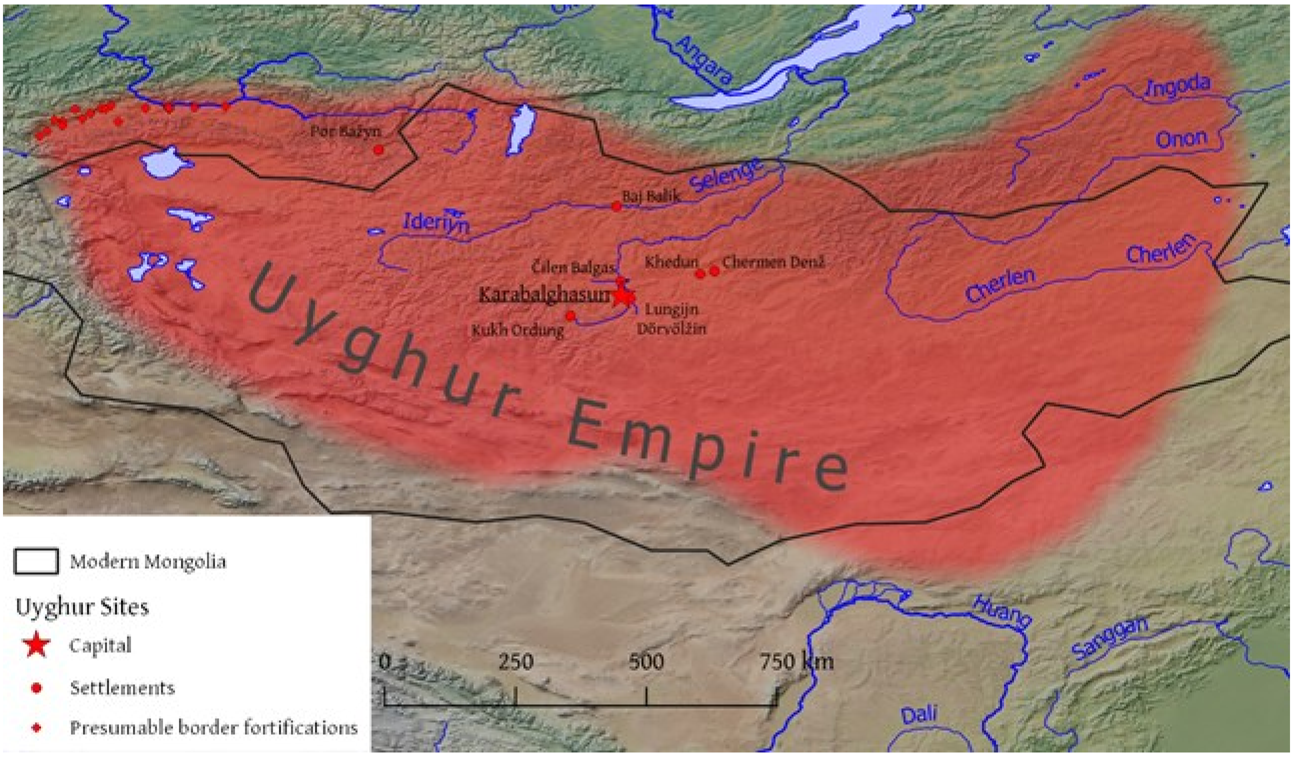


Fig. 1. The Uyghur Empire and its settlements and fortresses in the 8th to 9th centuries. (Mapping: H. Rohland after Dähne 2017, Basemap: Natural Earth, Naturalearthdata.com) (© DAI)

Despite basic information gained from historical sources, the history, structure and functions of the steppe capitals are, to a large extent, still a mystery. Excavations have been focused on monumental architecture such as palaces and temples, while the research on the overall structure of the cities and their hinterlands is still in its infancy. To address this issue, Mongolian-German joint research projects started with surveys and excavations in Karakorum in 2000, and in Qara Balğasun in 2007 (Hüttel/Erdenebat, 2010; Bemmann et. al., 2010; Franken et. al., 2014; 2017; Dähne, 2017). Detailed plans of the ancient remains on the surface are a crucial prerequisite for further research and understanding of the steppe cities. A Digital Surface Model has already been acquired for Qara Qorum by geodetic survey with a total station, painstakingly measuring over 80,000 points. The much bigger site of Qara Balğasun was surveyed with Airborne LiDaR by helicopter in 2007 (Hüttel, 2010). The results were amazing. The steppe provides almost perfect conditions for remote sensing techniques, due to its sparse vegetation and settlement (Fig. 2). However, LiDaR and pedestrian geodetic surveys are costly and therefore the surveyed areas were limited. Since the research on urban sites in the steppe is more and more interested in questions concerning the urban hinterland, urban sprawl and wider-ranging settlement patterns (Honeychurch and Amartuvshin, 2007; Waugh, 2010; Bemmann et. al., 2014), high-resolution mappings of huge areas are necessary. This poses the challenge to survey large areas in a short period of time with affordable equipment and to process the gathered data for scientific analysis.

Fig. 2. The remains of the Uyghur capital Ordu-Baliq, also called Qara Balğasun, in the mongolian steppe. The overview taken in the evening with low sunlight illustrates, that the conditions are almost perfect for photogrammetric approaches for the creation of DEMs (Digital Elevation Models) (© DAI/archaeocopter).

Data acquisition and 3D reconstruction

UAVs in combination with methods of photogrammetry have established themselves as a standard tool of archaeological documentation. Multicopters with good cameras are becoming safer and cheaper nowadays.

Recording strategy

In the Mongolian steppe, 42 km^2 were to be recorded in less than a week using standard multicopters. Two Phantom 4 were used for this purpose, each recording 526 m×526 m in parallel at a flight altitude of 100 metres. In this way, 4 flights covered 1.1 km^2 in just under 30 minutes (see Fig. 3).

Preparation of data

For the processing of the huge number of images different approaches where tested. DroneDeploy, a web service for UAV based mapping, offers a free trial version, which was used to assess the capabilities of this provider. The imagery was processed into 2.5D color scale representations of the terrain and also into point clouds. The best way to find structures is to create a contour map. In most cases of image processing, the image has to be converted to greyscale first. Unfortunately, the coloured elevation models from DroneDeploy were not usable for greyscaling. For example, the yellow to green areas turned out to be more difficult to interpret and some of the elevation models were incomplete, containing blank areas. Another issue was that the files were not correctly displayed in geographical information systems like QGIS.

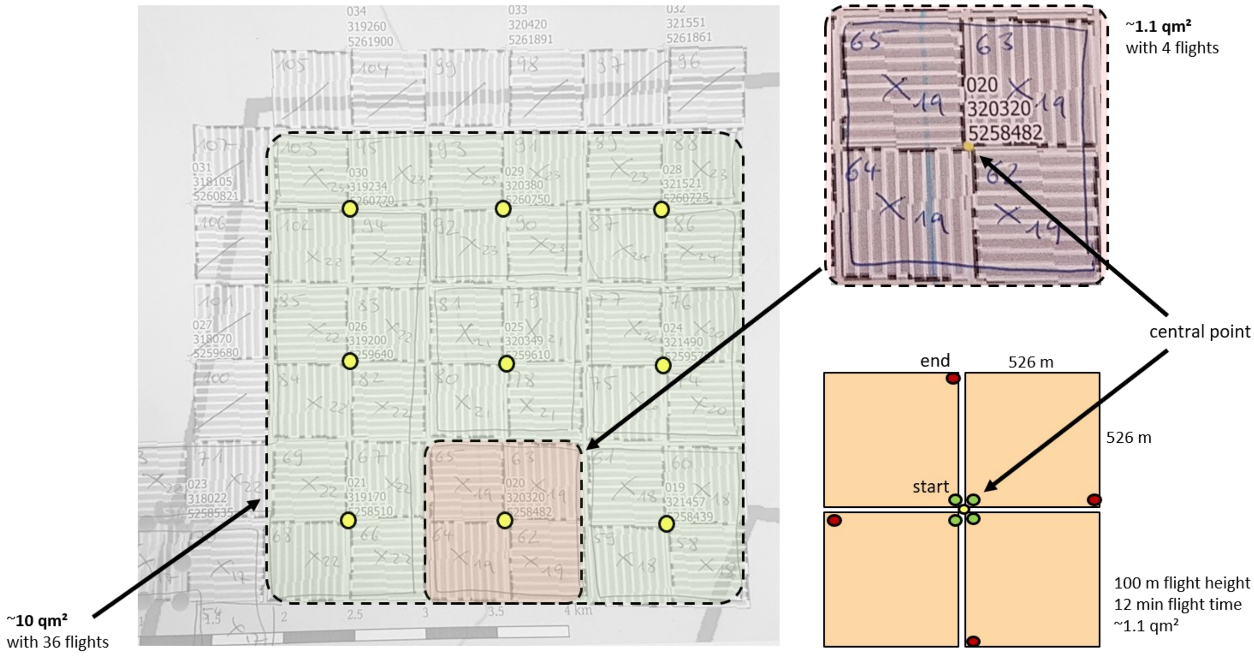


Fig. 3. Four flight areas with a common starting point were chosen and recorded in parallel with two copters each. (© Marco Block-Berlitz)

The solution to these problems was using the point clouds for the identification of structures, while the elevation models from DroneDeploy were essential for georeferencing. In addition to the elevation models, point clouds were exported as obj-File. The obj.-Files contain information of x,y coordinates with the z-values representing the elevation information. The first step was to interpolate the point clouds to elevation models. Interpolation is a way to estimate new points within a discrete number of known data points. In QGIS several methods are available and easy to use, for instance nearest neighbour, thin plate spline or inverse distance weighted. Accuracy of the elevation map borders are important when combining all raster data. The second step was to georeference the single maps.

For georeferencing two methods were tested. The first method was using QGIS and the plugin Georeferencer. To use this method, a reference map is necessary. Ground control points must be selected visually to match two maps. The disadvantage with this method is that every map must be georeferenced individually. The second method was using the georeferencing information of the exported elevation models from DroneDeploy. With the usage of the GDAL-library it was possible to extract the information on coordinate systems from the 2.5D images and apply it on the new interpolated elevation model. Most of the interpolated DEMs or raster data was not in the same resolution as the data from DroneDeploy. To apply the georeferencing information on interpolated point clouds, the raster data had to be resampled and resized.

Visualisation Techniques for DEMs

After the processing of interpolation, scaling and georeferencing the actual image processing could start. There are several visualisation techniques for DEMs. Each of the techniques has its own characteristics, but also limits. In order to use these techniques correctly the results have to be compared to establish which technique suits which kind of landscape. To make the images more understandable, visualisations from remote sensing and methods from computer science were used together to enhance the visibility of certain landscape properties. Hillshading, trend removal, sky view factor and topographic openness were tested and analysed. For the visualisation QGIS and SAGA-GIS were used. SAGA-GIS is an open software project, which focuses on geographic raster data analysis.

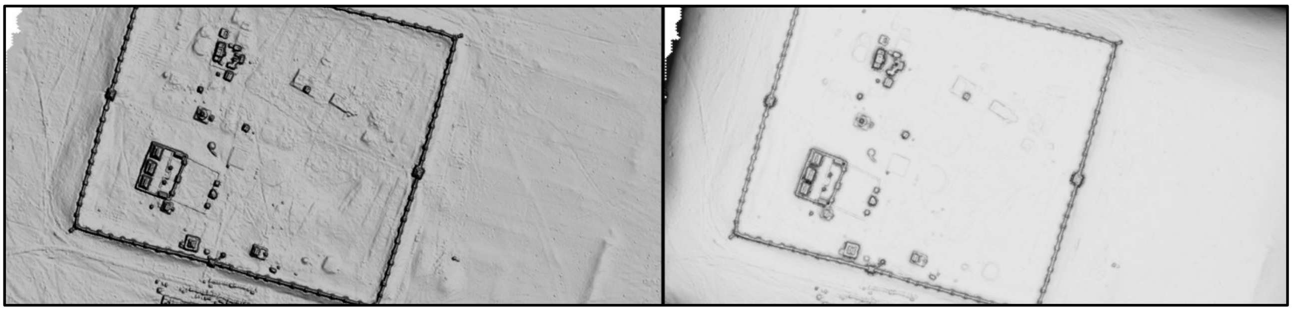


Fig. 4. Left: With low computational power hillshading produces understandable results. Small elevations are also visible. One issue is that only one side of the structure is dominant. Right: SVF presents mostly big building and elevations. Small archaeological features are hardly visible. (© DAI/Huy Do Duc).

Analytical Hillshading

Hillshading is well-known and easy to work with. It relies on the basic assumption that the relief is a surface illuminated by direct light from a fictive light source at an infinitive distance (Horn B., 1981). The light beam has a constant azimuth and an elevation angle for the entire area. The azimuth is the direction of the sun. An attempt was made with different settings to find the right parameters for the structures of interest. The advantage of hillshading is its simple, intuitive usage and fast calculation. Small elevations can be visualized by decreasing the angle of incidence and letting the light shine from an increasingly oblique angle. A disadvantage is the one-sided lighting, which makes some elevations unrecognisable since the cast shadows may occlude structures. When the azimuth is set in a way that the simulated sun rays are parallel to structures, then the structures are not recognisable. Several results with different azimuths were generated and attempts were made to combine several levels so that one-sided light exposure is not a problem.

Sky View Factor

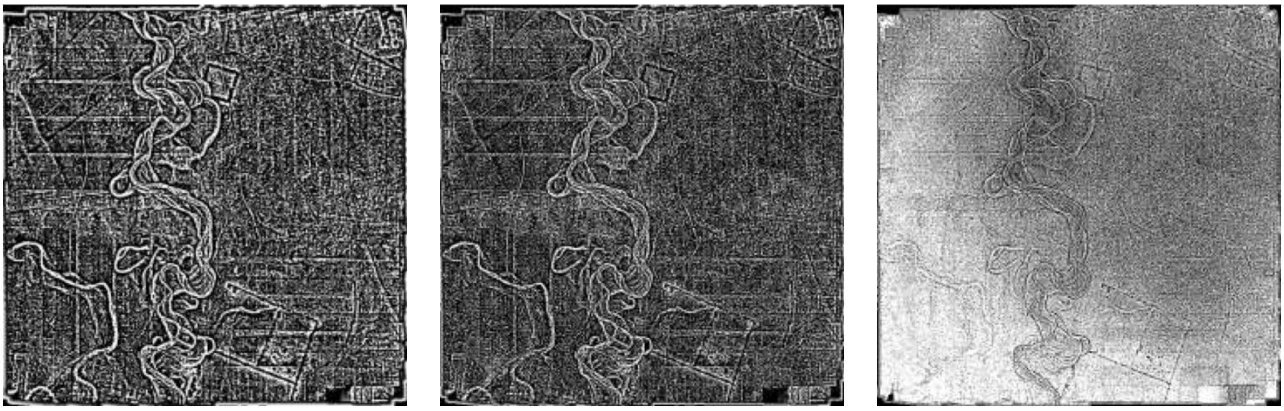
An alternative to the hillshading method is the concept of the sky view factor (SFV). Like hillshading an imaginary light source is used. An imaginary light source illuminates the relief from a hemisphere, which is centred at the point being illuminated (Zaksek, Oštir, and Kokalj, 2011). The computation of SVF is influenced by the search radius. The larger the search radius, the more generalised the result. A small search radius can be used to visualise and classify local morphological forms. For example, a 10 km search radius can be used in meteorological studies, while a 10 m search radius is suitable for archaeological features. Local flat terrain, ridges and earthworks which receive more illumination are highlighted and appear white, while depressions are represented by dark pixels because they receive less illumination. Different radius sizes were tested. Larger sizes required a significantly longer calculation time. Better results were achieved by using a smaller radius, since archaeological structures are not very big. Comparing hillshading and SVF, SVF produces better results on complex shapes (see Fig. 4). The output is clear and easily recognisable.

Topographic Openness

Topographic openness is similar to SVF, the only difference being that an entire sphere is considered. When using topographic openness, the first deliberation is to choose between positive or negative openness. Positive openness is specified for convex shapes and negative openness is used for concave shapes. Since the sky view approach is similar to topographic openness, the same factors have to be considered. The radius determines how much information is considered from the environment.

Trend Removal

Most of the time, the archaeological features are smaller in dimension than the dimension on the landscape forms on which they lie (Opitz, 2013). One procedure that separates small local features from large landscape features is the trend removal method. The information from rough landscape structures can be saved in a smoothed DEM.



a *b* *c*

Fig. 5. Trend removal is a way to focus on structures of a specific size. The smoothing filter effects and controls how much of the landscape information is ignored. The bigger the size of smoothing, the smaller structures are visible. Different sizes were tested a)5; b)9; c)17. (© DAI/Huy Do Duc)

This information can be subtracted from the original DEM, leaving only the local characteristics. The more the image gets smoothed, the more information will be subtracted from the original height of landscapes. If the smoothing is weak, the differences are minor. Various smoothing filters were tested on the smoothed DEM (see Fig. 5). Smoothing with the box filter can be calculated quickly. But the disadvantage is that the filter offers no distinction between homogeneous surfaces and edges. The Gaussian filter can distinguish between steep and slightly rising or falling changes. The level of smoothing is defined by the kernel size of the filter, where a smaller kernel exposes smaller features. The precise kernel size should reflect the size of the small-scale landforms. The method works best on terrain with gradual slopes, where it can produce artefacts where the relief is changing rapidly. Some tests show that trend removal works better for landscapes with a slight slope.

Certainly, more visualisation methods of digital elevation models exists. Nevertheless, it is necessary to know how different visualisation techniques work and how to use them to best advantage according to the data, general morphology of the terrain, and the scale and preservation of features in question. When a certain technique is chosen for detection or interpretation of features, it is particularly important to know what the different settings do and how to manipulate them. Because the techniques show various features in different ways, emphasising edges, circular or linear forms, a combination of methods is recommended.

Image Processing

Different surface forms can occur: flat surfaces, summits, sinks, mountain ranges, valleys, rises, concave or convex shapes. Each visualisation method reacts differently to the respective forms. Looking closer at the unprocessed DEMs, different structures are already visible. With the combination of visualisation methods and image processing structures, building remains, and interesting patterns should be found. It is important to know what these structures look like and how significant they are, to distinguish them from the remaining landscape features. The structures vary in shape and complexity, so it was difficult to filter out certain features. Image preprocessing steps like edge detection, morphological operations or histogram stretching are required to display features more clearly.

Morphological Operations

Morphological operations or filters were originally developed for binary images in order to either connect, strengthen, thin out or separate geometric structures (Kaur and Garg, 2011). An alternative usage for the morphological filters is to remove noise. There are two types of morphological operations: erosion and dilation. By combining these two morphological operations structures can be opened or closed, meaning that they are merged or separated, depending on their shape and proximity (see Fig. 6).

Fig. 6. Combining the Canny edge detection and morphological operations is a good way to analyse specific areas. The first row of images shows different thresholds of the canny algorithm. The second and third rows present the usage of dilation and erosion. Through the combination of dilation and erosion it is possible to close or open structures, especially useful for noisy data. (© DAI/Huy Do Duc)

Image Segmentation

When segmenting, the goal is to separate contiguous areas from the rest of the image. There are methods that are based on pixels, regions or edges. Adjusting and testing different edge filters were necessary to make hidden structures more visible. In this work, the key focus was on edge detection. The limits of classic edge filters had been reached. The Canny algorithm (Canny, 1986) provides clear edge images when the threshold values are selected correctly. Nevertheless, the Canny edge filter is only able to detect local differences. Certain thresholds can work for only one image, but they have to be adjusted for another image. Further context information is not considered. Deep learning could solve this problem. The holistically edge detector (HED) produces satisfying results for different kinds of images (Xie and Tu, 2015). It was tested how to see HED reacts to aerial photos and digital elevation models. The Canny edge detector provides a lot of edges, but too many lines lead to unclear interpretation (see Fig. 7). Many of the small, disruptive edges could be removed with morphological operations. Nevertheless, the results show that it still needs the help of a human to adjust the appropriate parameters to recognise certain structures.

Module DeepStructure in ArchaeoAnalytics

A tool named DeepStructure was developed and integrated in ArchaeoAnalytics to help users find interesting areas in large data sets quicker and make them more visible. A pipeline was created that combines the strengths of visualisation techniques and image processing. The automation of individual phases simplifies the work and enables a faster processing of data. Generating a map from point clouds takes several steps. Some of these steps were automatized. Scripts were written for the interpolation of point clouds and georeferencing a batch of images. Visualizations such as hill-shading, sky view factor, trend removal and topographic openness can now be performed on several data in one step.

Preliminary Results and Outlook

An attempt was made to improve existing visualizations and to create meaningful images that preserve the positive properties of individual technologies. The combination of several technologies makes it possible to see different topographical features in one image. Nevertheless, there is a risk of wrong use. Important landscape features might be missed or even removed. It is therefore of great importance that the information about the raw data, scan density, methods of generating the DEMs and the visualization methods used are well documented. Thus, the assessment of artefacts can be performed better later.

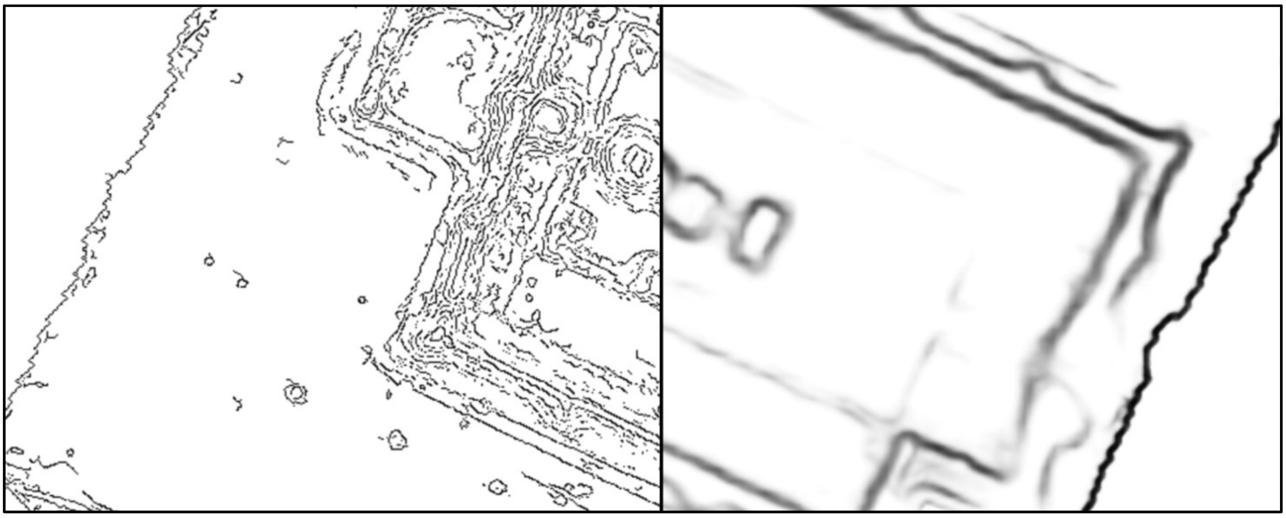


Fig. 7. Comparing the canny and the holistically edge detection the results are quite distinguish. The canny algorithm shows a lot of small lines. HED produces fewer structures which are thicker. From distance the results of HED are clearer but on the other hand small features get lost. (© DAI/Huy Do Duc)

While the methods explained above all have their strengths and weaknesses, a first assessment of simple hillshade visualisations already proved the high potential of the collected data. The digital elevation models (DEM) derived from the UAV imagery by the webservice DroneDeploy allow even faintest remains of human settlement activities such as eroded walls, platforms, ditches and fields, to be distinguished. However, the DEMs also have some quality-issues. There are a lot of artefacts visible on the DEMs, which sometimes make interpretation difficult. Experimental tests with other Structure-From-Motion algorithms will show if better results are possible with the data gathered in the field. This would improve the basis for the application of the visualization and image processing methods detailed above.

Although data processing and analysis is still in progress as the team experiments with different methods, a first glance on the results shall be given here. The most important achievement of the data collection campaign in Mongolia 2018 was that a complete high-resolution DEM of the ancient site of Qara Balğasun was accomplished. A schematic drawing of the structures visible in the DEM shows interesting patterns. The remains of the city sprawl over 44 km². It had the shape of a crescent with its convex side facing to the west and its flat side facing east. The so-called temple and palace complex or “imperial city” is situated at the centre of the straight eastern border (Termed “HB 2” in Fig. 8). This is a genuinely nomadic layout of a city, resembling a royal encampment. This is an interesting contribution to the discussion on urbanity in a nomadic context (Franken et. al., 2020). These first results demonstrate the capabilities of UAV-based mapping also for large sites and even on the landscape scale. In future projects the team aims to further develop the methodology and to extend the surveyed area to approach a more holistic view of settlement and land use at the urban sites of the Orkhon Valley.

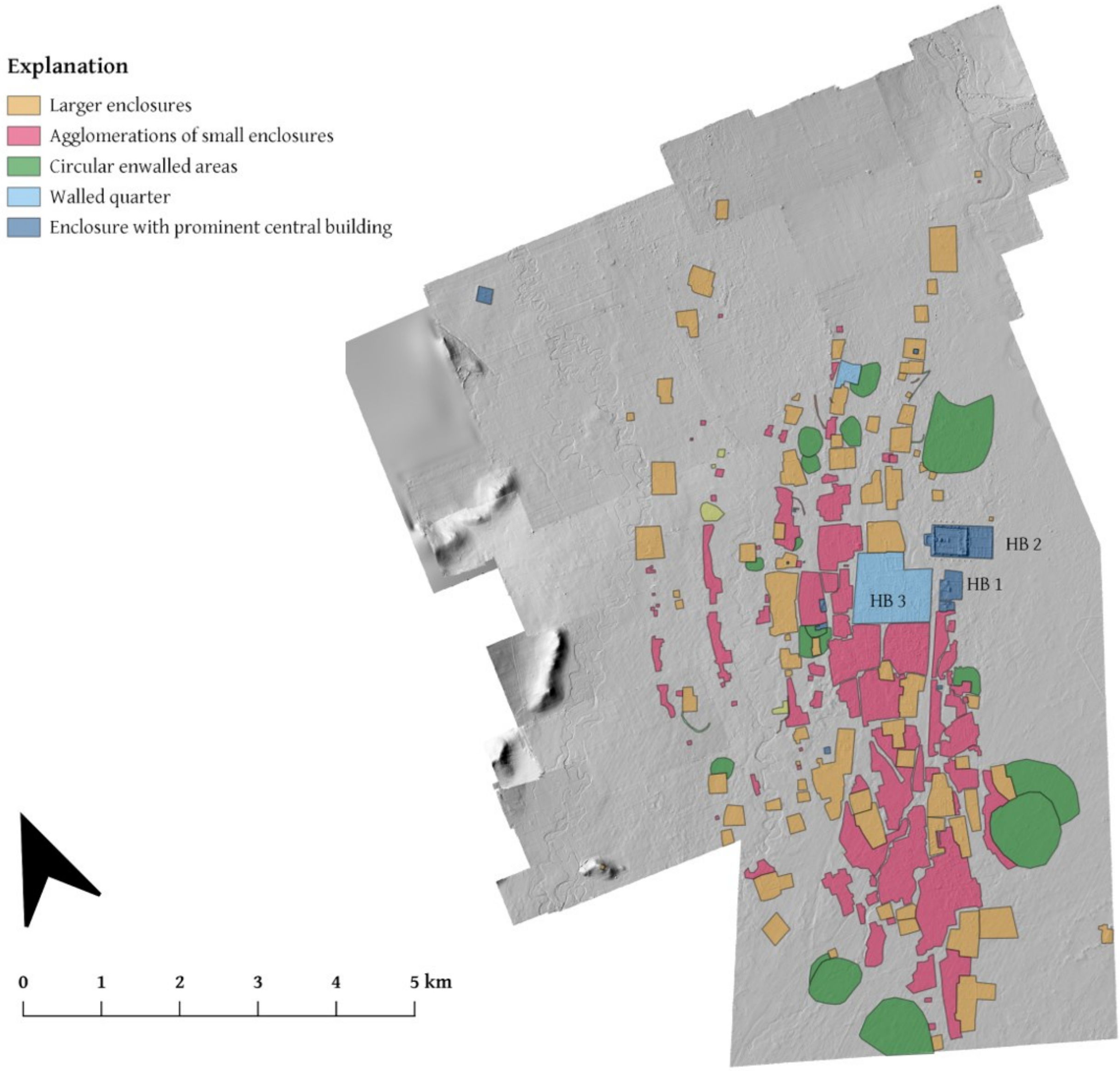


Fig. 8. Schematic rendering of the remains of Qara Balğasun. The temple and palace complex is marked as "HB 2". (© DAI)

References

Canny, J. (1986). "A computational approach to edge detection," IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. PAMI-8, pp. 679–698.

Block, M.; Franken, C.; Rohland, H.; Haferland, A.; Gehmlich, B.; Görsch, N. and Bochmann H. (2018) 'Documenting more than 5000 ha in Mongolia in five days using low-cost drones', Congress Visual Heritage, 23th Conference on Cultural Heritage and New Technologies (CHNT 23) in Vienna/Austria. Available at https://www.chnt.at/documenting-more-than-8000-ha-in-mongolia-in-ten-days-using-low-cost-drones/

Bemmann, J.; Lehndorff, E.; Klinger, R.; Linzen, S.; Munkhbayar, L.; Oczipka, M; Piezonka, H. and Reichert, S. (2014). "Biomarkers in Archaeology: Land Use around the Uyghur Capital Karabalgasun, Orkhon Valley, Mongolia". *Praehistorische Zeitschrift* 89, Nr. 2 (2014), pp. 337–370.

Bemmann, J.; Erdenebat, U and Pohl, E., eds. (2010). Mongolian-German Karakorum Expedition: Excavations in the Craftsmen Quarter at the Main Road. Bd. 8. Forschungen zur Archäologie Außereuropäischer Kulturen. Wiesbaden, 2010.

Dähne, B. (2017). Karabalgasun – Stadt der Nomaden. Die archäologischen Ausgrabungen in der frühuighurischen Hauptstadt 2009–2011. Wiesbaden.

Franken, C., Erdenebat, U., Batbayar, T. (2014). Erste Ergebnisse der Grabungen des Jahres 2013 in Karabalgasun und Karakorum/Mongolei. Zeitschrift für Archäologie Außereuropäischer Kulturen 6, pp. 355–372.

Franken, C., Rohland, H., Erdenebat, U. (2017). Aktuelle Ergebnisse der archäologischen Forschungen in den spät-nomadischen Stadtanlagen Karabalgasun und Karakorum im mongolischen Orchontal. Zeitschrift für Archäologie Aussereuropäischer Kulturen 7, pp. 385–408.

Franken, C. (2015). Die "Große Halle" von Karakorum. Zur Archäologischen Untersuchung des ersten buddhistischen Tempels der alten mongolischen Hauptstadt, Forschungen zur Archäologie Außereuropäischer Kulturen 12 (Bonn 2015).

Franken, C., Rohland, H., Block-Berlitz, M., and Batbayar, T. (2020). Remote sensing of large-scale areas at the urban sites of the Mongolian Orkhon Valley using low-cost drones – Preliminary results and some thoughts on the urban layout of the Uyghur capital Qara Balğasun. Journal of Global Archaeology 1, 2020, pp. 261–275.

Gabain, A. von (1950). Steppe und Stadt im Leben der ältesten Türken. Der Islam 29 (1), doi: 10.1515/islm.1950.29.1.30.

Golden, P. (1992). An introduction to the history of the Turkic peoples. Ethnogenesis and state formation in medieval and early modern Eurasia and the Middle East. Turcologica 9. Wiesbaden.

Horn, B. (1981). Hillshading and the reflectance map, Proceedings of the IEEE, vol. 69, pp. 14–47, 02.

Hüttel, H-G. (2010). "Berichte für die Jahre 2007–2008 der Projekte der Kommission für Archäologie Außereuropäischer Kulturen des Deutschen Archäologischen Instituts: Ausgrabungen und Forschungen des DAI und der Mongolischen Akademie der Wissenschaften im Orchon-Tal, Mongolei, 2007–2008". Zeitschrift für Archäologie Außereuropäischer Kulturen 3, pp. 279–296.

Hüttel, H.-G./Erdenebat, U. (2010). Karabalgasun and Karakorum – Two late nomadic urban settlements in the Orkhon Valley, Ulaanbaatar.

Honeychurch, W., Amartuvshin, C. (2007). Hinterlands, Urban Centres, and Mobile Settings. The "New" Old World Archaeology from the Eurasian Steppe, Asian Perspectives 46, pp 36–64.

Kaur, B. and Garg, A. (2011). Mathematical morphological edge detection for remote sensing images, 978-1-4244-8679-3/11 IEEE.

Mackerras, C. (1972). The Uighur Empire. According to the T'ang dynastic histories; a study in Sino-Uighur relations, 744–840, Asian publications series 2, Canberra.

Minorsky, V. (1948). Tamīm ibn Baḥr's Journey to the Uyghurs. Bulletin of the School of Oriental and African Studies 12(2), pp. 275–305.

Opitz, R. and Cowley, D. (2013). Interpreting archaeological topography: Lasers, 3D data, observation, visualisation and applications, Interpreting Archaeological Topography, Occasional publication of the Aerial Archaeology Re-searchGroup, vol. 5, pp. 1–13.

Rosthorn, A. v. (1921). Die Hochburg von Zentralasien, in: B. Schindler (Hrsg.), Hirth Anniversary Volume. Asia Major Introductory Volume, London, pp. 286–297.

Sagaster, K. (1999). Die mongolische Hauptstadt Karakorum, Beiträge zur Allgemeinen und Vergleichenden Archäologie 19, 1999, pp. 113–125.

Waugh, D. C. (2010). Nomads and Settlement. New Perspectives in the Archaeology of Mongolia, The Silk Road 8, pp. 97–124.

Xie, S. and Tu, Z., (2015). Holistically-nested edge detection, CoRR, vol. ab-s/1504.06375.

Zaksek K., Oštir K., and Kokalj Z. (2011). Sky-view factor as a relief visualization technique, Remote Sensing, vol. 3.