

CONPRA
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3D Digital Recording of Archaeological, Architectural and Artistic Heritage

Edited by Ján Zachar, Milan Horňák & Predrag Novaković



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CONPRA PROJECT PUBLICATIONS AND THE PRACTICE OF PREVENTIVE ARCHAEOLOGY

Predrag Novaković (University of Ljubljana)

Preventive archaeology, in some countries also known as development-led archaeology, nowadays accounts for more than 90% of the archaeological work across Europe. In almost all European countries preventive archaeology is clearly the result of the implementation of the La Valletta Convention (1992) on the protection of archaeological heritage.

It is safe to say that, since then, the number of archaeological projects increased by 500% to 1,000%. Such an increase would not have been possible without radical changes in a number of factors that rule preventive archaeology, its concepts and practices: new legislation, introduction of preventive archaeology into spatial planning processes, a new financial principle (polluter – payer), new (digital) technologies for data retrieval and recording in field-based projects and, last but not least, a substantial increase in the number of active professional archaeologists.

With the emergence of preventive archaeology and its present dominance in the disciplinary practice,¹ the divide between academic and preventive archaeology became even more accentuated, and raised numerous discussions about the unity of the archaeological discipline and its future. While these two strands do not, and will not, differ in terms of the scientific methods and tools implemented in their research, they indeed differ in the reasons for undertaking archaeological research, and in their business and organisational contexts. Whilst these differences did not have such an influence on the nature of the archaeological discipline in the past, today, when more than 90% of projects are of a

¹ For more on concepts and development of preventive archaeology in the last two decades, see Bozóki-Ernyey Katalin (2007), Guermandi and Rossenbach (2013), Novaković et al. (2016).

preventive nature, and the majority of them are funded from non-academic resources, it is very important to understand the differences and consider them when discussing the future of the archaeological discipline. Already for some time it has been very clear that by far the greatest amount of new discoveries and forms of evidence in archaeology derives from preventive research, thus rendering archaeology a 'data-driven' discipline. One could hardly find another discipline where the quantity of new data has increased by several orders of magnitude, almost without any control of what research, and where, takes place.

This situation requires serious reconsideration for the future of the archaeological discipline. On the other hand, this is not the case with disciplines traditionally considered close to archaeology, e.g. art history, history, anthropology or ethnology, where one could hardly speak of any new pieces of evidence discovered 'by chance'. In another paper (Novaković, Horňák 2016, 32), we have posed a rhetorical question – what would happen with our knowledge of ancient history, and ancient history as a discipline, if over the last two decades some 10,000 new fragments of written sources were discovered 'by chance' in the Mediterranean? The comparison is, of course, rather exaggerated, but it nevertheless illustrates the situation in archaeology today, where it is the 'chance' discoveries that sustain the discipline. In this sense, a great deal of archaeological practice is moving away from the traditional goals and disciplinary practices of the humanities and getting closer to the engineering sciences, providing a series of science-based practical services.

The discussion about whether preventive research achieves the levels, standards, and state of the art of academic research is, to some extent, misleading. It actually refers more to current practices and routines than to conceptual frameworks of both academic and preventive archaeology. The truth is that, in many situations, planning large fieldwork campaigns in preventive circumstances may not be optimal due to the lack of time, infrastructure, other resources, and funds; also, the implementation of fieldwork may be substantially conditioned by time pressure, inadequate temporary living conditions and highly stressful working conditions compared to the academic research context. But although the conditions in preventive contexts may not be optimal, this is not the key difference between the two. The essential difference is in the conceptualisation of research: whereas academic archaeology performs its fieldwork with a particular problem-oriented research design in mind, no such design is possible in preventive research, and even less in rescue and salvage situations.

But this does not necessarily diminish the potential and quality of preventive research. Instead, detailed individual problem-oriented designs should be replaced with standards against which the quality of preventive archaeology must be measured. These standards cannot include specific research questions or agendas, but, on the other hand, they can provide a suitable framework for addressing at least some of the major research issues in archaeology (e.g. adequate description of the evidence, chronology, classification of finds, stratigraphic history of sites, phasing, cross-referencing stratigraphy and finds, and a kind of 'general' interpretation of sites and finds). It is fair to say that sometimes the sampling and collection strategies, accuracy of measurements, and objects of observation would not satisfy the requirements of individual, problem-oriented research designs; but, on the other hand, the evidence acquired in preventive work would often be completely missed in academic research, and would never pose new research questions.

Indeed, what we see here is actually more the question of how to combine the research standards of preventive archaeology and various academic agendas.

The question of standards in preventive archaeology is beyond the scope of the CONPRA project and its publications, and should be addressed by national bodies responsible for heritage protection and also involve academic institutions. While most countries in Europe implement various kinds of preventive archaeology, only a few have adopted true standards which guarantee quality (e.g. the UK, the Netherlands, Slovenia). Indeed, it is difficult to overestimate the importance of standards in preventive archaeology and, for that matter, in archaeology in general. With the development of preventive archaeology, numerous new professional subjects (public and private) performing research and associated services have emerged and are competing in the market of archaeological research services. In such circumstances, it is the standards (and their fulfilment) which are the most efficient tool in securing adequate quality control.

In countries lacking standards of archaeological research, their place is, more or less implicitly, occupied by the long-standing procedures and routines practiced by top academic institutions. There are many reasons why this is not a good substitute for standards; academic institutions simply have different archaeological agenda and priorities, less experience in day-to-day fieldwork in stressful conditions, and normally do not train personnel for preventive research. Moreover, there is no assurance that, for example, one detailed academic problem-oriented excavation would adequately treat evidence not directly related to the research problem. This is not because one would consider such evidence less important, time-consuming or, even worse, too expensive regarding the allocated research budget, but simply because of a lack of standards (i.e. the necessary level of recording and treatment of data and objects). It all comes down to professional ethics. And it is here where the subjects in academic and preventive archaeology are not in equal positions. Archaeological stakeholders in preventive research need to go through a series of frequently painstaking negotiations, compromises, and improvisations in order to secure adequate working conditions, funding and appreciation of their work. The developers are not looking for the most excellent archaeology, but instead for the cheapest.

By saying this, we are not trying to widen the gap between academic and preventive archaeology, but rather to attempt to bridge it. Indeed, there are many aspects in which academics can take part in preventive archaeology. By this, we do not envisage academic institutions simply competing in the market of archaeological services in preventive contexts, which seems to be the case in countries where academic institutions have to survive serious budget cuts and personnel shortages. Instead, good knowledge and experience in organising and implementing preventive projects on different scales, strategies of heritage protection, and some sound reasoning may lead to highly effective involvement of academics in preventive practice. They may act as consultants, reviewers, or specialists for a number of different analyses; and, why not, academic institutes can be members of consortia created ad hoc for meeting the most challenging demands in preventive archaeology. There are some exemplary cases of these practices. The final result is not only more and better developed archaeology, but also the creation of more productive frameworks for facing the challenges of a highly data-driven discipline.

And there are also some great advantages of preventive over academic archaeology. First and foremost is the great coverage of different areas which, under normal conditions

and circumstances, would not be investigated to such a scale and extent by academic research alone. Let us just think of the thousands of sites and new lines of evidence discovered in urban zones. No academic research programme would have a chance to excavate even a small percentage of urban areas that are under constant pressure from land development projects. Though these urban 'windows of opportunity' are normally open for a very short period of time, it is they that have yielded extraordinary evidence for the history of our towns.

Although one could say that preventive research has little influence on the choice of locations to be examined, and hence their contribution to major scientific questions is less harmonised with academic agendas, it is in the long run that preventive archaeology demonstrates its high relevance for academic research. It does not provide quick answers to individual research problems, but by undertaking thousands of trial trenches, surveys and excavations over a decade or two, whole regions or countries are 'sampled' in an extraordinarily detailed way, with no ecological, morphological, settlement or historical area left out. A lot of the results of such continuous 'sampling' are yet to be properly evaluated, but what is already clear is that these results, though in many cases still interim and partial, generate new important research questions and influence academic research agendas. The most illustrative cases are numerous projects along motorways or similar linear features crossing large areas of space, which have brought to light so much new evidence that successfully challenged and contrasted with long-existing interpretations of demography, settlement and chronology, and that shed a completely new light on our past.

Another important outcome of the developments in preventive archaeology is the considerable increase in the number of trained professional archaeologists capable of day-to-day coping with the unprecedented amount of preventive research. The truth is that such an increase in the amount of work conducted was only possible with the increase in the number of archaeologists, but it is also true that a wider professional community could put more pressure on improving the quality of heritage protection and its practices. This is the aspect that the CONPRA project is especially focused on. The development of digital technologies for data retrieving, recording and processing, coupled with the recent developments in remote sensing techniques, non-invasive archaeological methods, and integrative powers of geographic information systems, web servers, and IT technology in general, pose a great challenge to archaeology professionals. To put it simply, if a developer hires a team of experts able to produce a final detailed building plan of a new settlement using e.g. LIDAR, aerial mapping, underground surveying, modern CAD tools, field laser scanning, 3D modelling, etc., within a period five times shorter than some ten years ago, similar is expected from preventive archaeology. The challenge can be confronted only by using the same tools as professionals in other fields and developers.

This, of course, raises the question of the education of archaeologists. It is illusory to think that students will quickly get familiar with a myriad of new technologies that emerged during their studies. Simply, there is not enough time, resources and trained teachers to promptly react to all the novelties appearing daily. New techniques and technologies also need to be properly contextualised and experimented with prior to becoming routine in archaeological practice. And, in many cases, they also have to be properly acknowledged by the professional communities and bodies responsible for protection

of the archaeological heritage. With the great increase in the number of preventive projects, it becomes even more evident that training in new techniques and procedures is a career-long endeavour, and could be implemented in a number of different ways, not all akin to academic training. Here we refer to different forms of apprenticeship, secondments, various ad hoc courses, and different forms of learning-through-work. It is important to note that a great deal of today's archaeological 'experts' in CADs, GIS, 3D scanning, 3D photogrammetry, LIDAR, geophysics, various laboratory analyses, etc., are originally archaeologists by academic training, but self-taught in the course of their careers and practice.

The initiative for the CONPRA project came, indeed, from such a self-taught population of younger professionals from private and public (academic) institutions working in preventive archaeology. The CONPRA project was primarily aimed at assisting in building capacities for facing current challenges in the practice of preventive archaeology. The project partnership is composed of two small private enterprises: Via Magna s.r.l. (Martin, Slovakia) and Terra Verita s.r.l. (Prague, Czech Republic), and two university departments of archaeology (University of Ljubljana, Slovenia and University of Belgrade, Serbia). Except Serbia, in all the other countries the market of archaeological services has developed more or less in parallel (and in association) with preventive archaeology. The development of the market of archaeological services created new situations in archaeological preventive practice which, until the 1990s, used to be completely in the domain of public institutions and negotiations between (mostly) public stakeholders of spatial development.

In observing such markets in Slovakia, Slovenia and the Czech Republic, a very important fact was identified, that of the rather locally based work of private enterprises. These enterprises mostly work close to their home base, have very few (if any) contacts with enterprises outside their country (or even their region), and cannot easily follow the developments and achievements in academic archaeology on a trans-national level; their major contacts with academia are through students they occasionally hire and occasional contacts with professors or established researchers in the case of very interesting discoveries. They are also lacking in professional associations (such as for example CIFA – the Chartered Institute of Archaeologists in the UK) which could lobby for their professional interests, develop and promote common standards and codes of conduct, analyse trends and fads in the market, and so on.

Such conditions are definitely not favourable for investing in new knowledge, skills, and equipment, if clear economic gains are not anticipated in the near future. The fact is that, in all European countries, markets of archaeological services are quite volatile. Mostly dependent on the intensity of development and spatial planning, it is archaeological markets which are the first to experience crises in the development and construction sectors. Being a 'miner's canary' (Schlanger 2010, 108) is not a favourable role for any economic enterprise. On the other hand, academic institutions in the CONPRA countries (and elsewhere as well) also suffered substantial setbacks due to the global economic crisis since 2008, which excluded them from a great deal of investments in developing and applying new technologies in archaeological research.

A large number of enterprises in preventive archaeology in the CONPRA countries fall into the category of small or micro-enterprises. Very few of them have more than 10

permanently employed professionals in archaeology and associated fields pursuing archaeological research. Most of their work is done in the field (e.g. archaeological excavation, archaeological surveys, archaeological monitoring) and also includes processing of the field data and the material evidence. In circumstances where most of the enterprises could employ only a very small number of experts, narrow specialisation for certain aspects of archaeological work is rarely the case. Quite the opposite, it seems that it is the 'general' field archaeologists for whom the demand is the greatest, those able to competently and efficiently master a large span of archaeological skills in the field and in data processing.

CONPRA publications are targeted primarily at this profile of experts and enterprises who have certain experience in conventional archaeological fieldwork, and who can considerably enrich their skills by using several new techniques and tools in their everyday work. Indeed, while it is of crucial importance that field archaeologists understand these methods and techniques, it is even more important to understand where and how their routine work can be upgraded and made more efficient or accurate, and hence more competitive.

The CONPRA project was focused mostly on the development (and transfer) of knowledge in those aspects of archaeological fieldwork which are currently among the most promising and 'prolific' in archaeological practice, and which have shown clear advantages in terms of efficiency, accuracy, and time and labour requirements. They are all strongly based on new digital technologies of data retrieval and processing, and have proved successful in various types of archaeological research, both academic and preventive. It is not by chance that most of them are well-suited for non-invasive archaeological research (various surveys, remote sensing and other types of reconnaissance) since it is these methods and techniques that are crucial for making the ultimate decision for an entire excavation. Preventive archaeology is, in the first place, about testing and sampling, and providing sound evidence for prescribing costlier actions, e.g. excavation. In a certain sense, it is successful testing and sampling that are the ultimate proof of the relevance and necessity of preventive archaeology.

The CONPRA Series comprises four volumes, which are all a result of the joint work of secondees, tutors and other experts involved in the project:

- *3D Digital Recording of Archaeological, Architectural and Artistic Heritage* (Vol. 1)
- *Using Aerial Photography and LIDAR in Archaeology* (Vol. 2)
- *Introduction to Managing Datasets in Archaeology* (Vol. 3)
- *Virtual Reconstructions and Computer Visualisations in Archaeological Practice* (Vol. 4)

It is these fields, we believe, where major improvements have been made in recent years, and which will gain in importance in the future. All four fields are strongly based on modern IT and digital technologies, and it is essential that practitioners in preventive archaeology implement them in their everyday practice. These technologies will increase the capacities of many private or semi-private SMEs and other practitioners in preventive research, not only in the sense that they could complete their tasks faster and more accurately, but also that they will be able to significantly contribute to the positive image of (preventive) archaeology as a whole, thereby increasing its relevance in modern society.

At the end of the day, it is always the question of relevance and added (social and other) values against which preventive archaeology and heritage protection are measured. Our societies do recognise heritage as a value worth protecting and enjoying. To this end, a series of legislative documents were produced and a number of public institutions established with the aim of protecting the heritage. Yet, heritage, archaeological in particular, is always challenged by spatial development. Whilst weighing the values of development and heritage, both are primarily considered as a resource, and it is in this context, especially at local levels, that heritage protection is frequently considered an obstacle to development or even an unnecessary cost. Heritage is a resource where investments bring 'profit' in the very long run, whilst a great deal of development (especially privately funded) is expected to pay off in a much shorter period of time. But let us look for a moment at the historical centres of many European towns. They all attract large masses of tourists and generate substantial income, yet this was possible only through decades of implementation of a careful protection policy and long-term efforts.

The 'frustrations' that developers are facing can be even more severe if preventive archaeological research is not done according to the highest professional standards or, even worse, if very costly excavations turn out almost 'fruitless'. As has been already said, developers would go for the cheapest archaeology, and not the highest-quality one. Unfortunately, recent evidence from many countries (e.g. Aitchison 2009; 2014, and accompanying national reports; also in Guermandi and Rossenbach 2013) shows that enterprises are willing to charge prices that barely cover their costs, just to be able to survive another season. Such a situation is increasingly worrying, since it undermines the quality of preventive archaeology in general and, to remedy this situation, the most urgent task of the relevant public bodies and legislators is to secure adequate minimum conditions for preventive research.

In the meantime, it is up to the enterprises and all other subjects acting in the field of preventive archaeology to invest in knowledge and skills, in order to make them more competitive and diversified. The CONPRA publications aim to contribute to this process.

INTRODUCTION

Milan Horňák (Via Magna)

Nowadays, excavations constitute a significant part of the overall archaeological activity. Archaeologists conducting excavations face financial limitations on one hand, and the demand for a comprehensive and efficient execution of field work on the other. Because of the destructive nature of archaeology, high-quality archaeological documentation is of utmost importance in archaeological excavations. Given the characteristic present-day time pressure and resulting lack of on-site interpretations during the excavations, the accurate and exhaustive documentation becomes even more important, as post-excavation interpretations are entirely based upon it. The traditional measuring means and manual recording have been replaced by digital documentation, including the total station and Differential GPS. Three-dimensional (3D) recording stands at the front-end of modern technological innovations in archaeological documentation. A similar situation can be observed in the field of historical architecture survey. Current construction activities usually lead to a substantial change in the layout of historical structures. 3D data acquisition can be applied here as a way of storing 3D information on previously existing structures, which can in the future be used for further evaluation.

Although new technologies, such as terrestrial laser scanning, enable fast, accurate and comprehensive acquisition of cultural heritage data for subsequent analyses, the lack of financial means and technical knowledge of rescue archaeologists and conservators has so far hampered incorporation of 3D digitalization into the documentation workflows established over the years (which are generally based on the total station measurements combined with photographs and pencil drawings).

However, the recent boom in computer vision programs that combine Structure from Motion (SfM) approach with dense Multi-View Stereo (MVS) algorithms changed this

situation. These packages enable generation of accurate 3D models from a collection of photographs in a straightforward and cost-effective manner, without the need for extensive photogrammetric and computer vision knowledge of the user, or the information on geometrical properties of the scene. As such, they became a regular element in the documentation practice in many research and commercial fields, including cultural heritage monitoring and preservation. Furthermore, laser scanning technology nowadays demonstrates a remarkable progress, especially regarding user-friendliness, which makes it more accessible to a broader spectrum of potential users. Moreover, the increasing application of structured light technology, incorporated mostly into handheld scanners, causes substantial price drop and enables scanning to be affordable in the cultural heritage domain.

The main aim of this publication is to deliver a broad overview of technologies available for digital documentation, primarily focusing on 3D digital recording and its importance for preventive archaeology and other branches of cultural heritage management. The book is not intended to bring in-depth and comprehensive research evaluation of all digital technologies currently available. On the contrary, its objective is to present a practical approach to digital documentation, show its potential, limits and problems, as well as possibilities to overcome them. The core of the book is represented by case studies illustrating different strategies and practices of 3D digital recording in some particular fields of archaeology, art history and conservation. Different experience with the applied technologies is described, including problems encountered in the data retrieval and processing. Each category of the case studies is discussed separately and from the point of view of the relevance of the applied technological strategy, as well as possible practical improvements. Finally, remarks on the possibilities of 3D modelling for further documentation purposes are made.

3D DIGITAL RECORDING: BASICS

Seta Štubec (University of Ljubljana)

TERMS

3D model

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

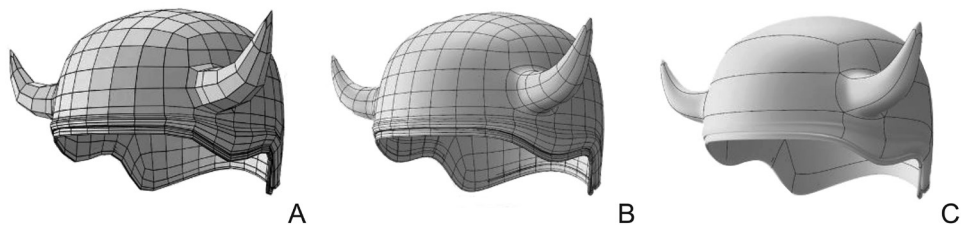


Figure 1. 3D model surface types: A: mesh-quads, B: mesh-quads, smoothed, C: NURBS.
(Available at: <https://andrewevs92.wordpress.com/2012/11/19/127/>).

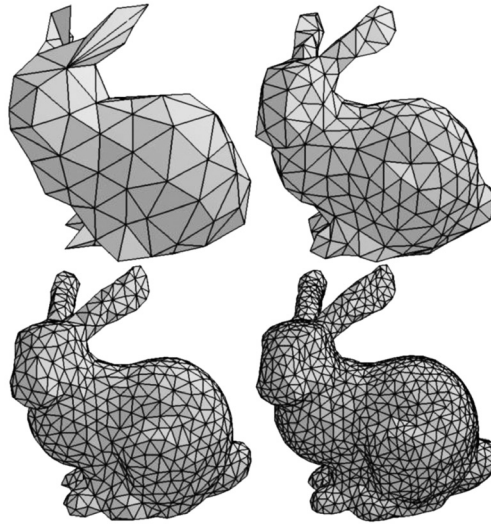


Figure 2. 3D mesh-triangles with different resolution (3D Modelling for programmers. Available at: https://cathyatseneca.gitbooks.io/3d-modelling-for-programmers/content/3ds_max_basics/3d_representation.html).

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

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

3D modelling

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

3D digital documenting/digitisation

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

3D digital reconstruction

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

A BRIEF HISTORY OF 3D DIGITAL RECORDING IN ARCHAEOLOGY

3D recording is not a new phenomenon in archaeological documentation. Since the ‘birth’ of photogrammetry in the middle of the 19th century, its principles were first used by aerial archaeologists in the 1920s to map larger areas (Fryer 2001). Later, from the 1960s onwards, archaeologists started to use photogrammetry to document archaeological excavations (Whittlesley 1966), mostly using low-altitude aerial images acquired from the top of poles and ladders. Photogrammetric processing at that time was based on analogue stereo images that were observed through a stereoscope to get the notion of the third

dimension. Only after the so-called digital revolution in the 1990s, digital photogrammetry gradually took over and some techniques slowly merged with the research field of computer vision (Štular, Štuhec 2015). The development of the latter is to be situated in the 1970s and originates in the field of robotics and artificial intelligence whose task, among others, was to give a computer the same vision and understanding of a scene as in humans. At first, the task did not seem too challenging but, in the attempts at solving it, a new research field emerged (Szeliski 2011).

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

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

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

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

One of the first larger projects completely dedicated to the use of 3D in archaeology was called 3D MURALE. The project was aimed at the creation of a tool for recording, inspecting, reconstructing and visualising all kinds of archaeological remains (Cosmas et al. 2001). In the 2000s, several projects were carried out with a similar goal. Probably the most successful were the project EPOCH¹ and its successor, 3D-COFORM². In 2005, in the framework of the EPOCH project, a software package MeshLab³ for 3D data processing and analysis was created. A year later, the launch of the online image-based 3D modelling service ARC3D⁴ marked more-or-less the beginning of the so-called digital image-based 3D modelling revolution in archaeology (although the same authors already published several archaeological publications at the end of the 1990s, i.e. Pollefeys et al. 1998, 2000, 2001). Afterward, several other programs and online services were established, such as Microsoft Photosynth and Bundler, followed up by Autodesk 123D Catch, Eos Systems PhotoModeller Scanner, Visual SfM and Agisoft PhotoScan, to name a few. This technological development caused an immense and sudden increase in the usage of 3D digitisation in archaeology. The previous, rather small group of people that was dealing with virtual archaeology suddenly grew into an extensive community.

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

ADVANTAGES AND APPLICATIONS OF 3D MODEL

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

1 <http://epoch-net.org/site/>.

2 <http://www.3d-coform.eu/>.

3 <http://meshlab.sourceforge.net/>.

4 <http://www.arc3d.be/>.

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

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

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

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

Taking all their characteristics into account, digital 3D models can, therefore, be used to document, present, share and analyse archaeological objects, buildings or areas. Through the use of internet database systems, it is possible to share the models with a wider scientific and lay public. Objects and features that would otherwise be inaccessible (such as artefacts in museum depots, very fragile objects, archaeological remains physically difficult

to reach, stratigraphic contexts that were destroyed during the excavation process, etc.), could be viewed from anywhere in the world. Such databases can also join 3D models of objects that are kept away from each other, but belong to the same period, area or interest group. There have been several projects aiming at creating a database that would allow researchers to view and/or inspect archaeological remains with common characteristics. The *Carnuntum Database* (www.carnuntum-db.at), for example, includes 3D models of objects found in the Roman city of *Carnuntum* in Austria (Humer et al. 2010). The Virtual Zooarchaeology of the Arctic Project (VZAP) is a virtual, interactive, osteological reference collection for the study of northern vertebrates hosted on <http://vzap.iri.isu.edu/>. Another 3D model database is hosted by the project Digitizing Early Farming Cultures (DEFC)⁵, which includes the most representative shards from the F. Schachermeyr's Neolithic pottery collection originating from Thessaly, Greece. The 3D models uploaded online are not isolated, but are instead interconnected with the rest of the database containing information on the Neolithic sites and finds in Greece and Western Anatolia (Štuhec et al. 2016). Several other 3D databases are trying to enrich the 3D models by connecting them to other types of data. MayaArch3D is an example of such an interactive platform that also includes several different analytical tools (Billen et al. 2013). Apart from these relatively local projects, there has also been an initiative for a Europe-wide collection of 3D models. This initiative was called the CARARE project⁶ and was carried out from 2010 until 2013 in the framework of the *Europeana* (D'Andrea, Fernie 2013).

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

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

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

⁵ <http://defc.digital-humanities.at/3Dmodels/>.

⁶ <http://carare.eu/>.

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

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

3D SCANNING

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3D scanning as a technological procedure is aimed at collecting information on the shape and colour of the object scanned. The acquired data help build a basis for the construction of digital, three-dimensional models useful for a wide variety of interpretative purposes. Currently, there are a lot of different technologies and 3D scanning devices available, each one coming with its own limitations, advantages and costs. Prime properties of the 3D scanning solution are its ability to effectively capture digital description of the objects and meet the required level of accuracy and data clarity. According to the source, applied scanning, laser scanning and structured light scanning can be distinguished.¹ The three principle types of scanning technology include Time-of-Flight (TOF), Phase-Shift (PS) and Triangulation-based systems. Scanning technology is connected to other system factors, including the acquisition distance, the acquisition rate and the data resolution/accuracy.

There is a wide range of 3D scanning technologies available for different items within the sphere of cultural heritage, ranging in size from small archaeological finds to large structures. There have been many studies that illustrate how 3D scanning, implemented in the protection of cultural heritage, generates excellent results, both in terms of speed and of accuracy. Until now, a lot of large scanning projects in the field of cultural heritage management and archaeological research have demonstrated the relevance of this method as a modern and, in many cases, fundamental documentation practice.

¹ As a unique category, image-based scanning should be mentioned. Formerly, it used to be defined as 3D photogrammetry, but this is not a proper term.

LASER SCANNING

3D laser scanning is a non-destructive, non-contact method of capturing data that can be used for rapid and accurate creation of three-dimensional files, for archiving and digital manipulation. A 3D laser scanner emits a narrow laser beam that hits a target object, gathering millions of closely spaced measurements in a matter of minutes. These scanned measurements are put together and grouped into compressed point cloud databases, which can be processed to generate a 3D dense representation of the object (Arias et al. 2005; Yastikli 2007; Cheng et al. 2015).

In the most general terms, 3D laser scanning, also referred to as 3D digitising, entails the utilization of a three-dimensional data acquisition device for acquiring a multitude of X, Y and Z coordinates (points) + their RGB values. Furthermore, returning distance signals generate intensity information registered for each of the points. The intensity – often called ‘the fourth dimension’ – is a very useful parameter for visual enhancement of various architectural features, especially in the dense and complex point clouds (Staiger 2003). Each measured point is thus precisely defined in space, in a global or local coordinate system, with X, Y, and Z coordinates. The collection of all these points is defined as a ‘point cloud’. The typical file format for point cloud data contains the X, Y and Z (possibly + RGB and intensity) values for each point, or a polygonal mesh representation of the point cloud (Slob, Hack 2004).²

Laser light is coherent, which means that a laser beam can propagate over long distances and can be focused to very small spots. Laser light may be visible, but most lasers actually emit in other spectral regions, in particular the near-infrared region, which human eyes cannot perceive. The first working laser was demonstrated in May 1960 by Theodore Maiman at Hughes Research Laboratories.³ Although laser scanning was developed in the 1960s, it was not used for surveying structures until the late 1990s (SurvTech Solutions 2015). So far, laser scanning has proven to have an essential role in large scale cultural heritage projects as it provides a highly useful tool for global monitoring and damage detection (Pieraccini et al. 2001).

Airborne laser scanning (LiDAR)⁴

Airborne laser scanning (LiDAR = acronym for ‘Light detection and Ranging’, also LIDAR) is a scanning technique for capturing data on the features of, and objects on, the surface of the earth. It is an important data source in environmental studies, since it is capable of mapping topographic height and the height of objects on the surface to a significant vertical and horizontal accuracy, and over large areas. Airborne laser scanning is an active remote sensing technology able to rapidly collect data from vast areas. The resulting dataset can be used as a base in digital surface and elevation models. Airborne laser scanning is often coupled with airborne imagery; therefore, the point clouds and images can be fused together, thereby increasing the quality of the final 3D product – the high-quality 3D representation of a landscape (Vosselman, Maas 2010).

2 At present, there are plenty of file formats determined for point cloud data storage (e.g. ASCII, PLY, LAS/LAZ, etc.).

3 https://en.wikipedia.org/wiki/Theodore_Harold_Maiman.

4 LiDAR *per se* represents a substantial topic, thus we here provide a very brief outline.

Terrestrial laser scanning

Terrestrial laser scanners (TLS) are positioned directly on the ground, or on a platform placed on the ground, and are normally mounted on a tripod. TLS is, in its essence, an improved version of the laser tachometric measurement toolkit (the so-called total station) that is based on the combination of distances and angles measured from a fixed point. Tachometric laser scanners digitise objects of interest with a frequency of 1000 Hz or higher. Each point is measured per one oblique distance and, additionally, two orthogonal angles are measured (Vosselman, Maas 2010). Most TLS are long-range devices (see below) used for 3D documentation of large landscape areas or complex structures. Nowadays, a great variety of TLS is available with different range and pulse frequencies (Figure 3).



*Figure 3. Basic types of terrestrial 3D laser scanners (TLS) – a brief overview.
A: Faro Focus 3DX130, B: Leica C10, C: Riegl VZ serie,
D: Topcon GLS 1500, E: Surphaser 105HSX, F: Stonex X300.*

Handheld (portable) laser scanning

There has recently been an increase in the application of handheld scanners. Their basic advantage is their portability. Scanners that are attached to light portable stands fall in this category as well, even though they are not 'handheld' in the true sense of the word (Figure 4). Primarily used in reverse engineering, nowadays they are very often employed in digital documentation of moveable cultural heritage objects (especially objects kept in museums). Although most handheld scanners are based on structured light technology, there is an obvious expansion in the usage of laser portable scanners. Most handheld laser scanners exploit triangulation mechanism (see below), often with the application of calibration targets attached to the object being scanned.



Figure 4. Basic types of portable scanners – a brief overview.

A: Artec Eva, B: Artec Spider, C: David Scanner, D: Sense Scanner, E: Microsoft Kinect, F: Breuckmann Smart Scanner, G: Faro Scanner Freestyle, H: ZScanner, I: Creaform Go!SCAN. A-F, I: Structured light scanning (SLS) technology; G,H: Laser technology.

Long- and short-range laser scanning

There is a variety of technologies for digital acquisition of the shape of a 3D object. A well-established classification recognizes two types: contact and non-contact. Non-contact solutions can be further divided into two main categories, active and passive. Based on the principle of technology, in combination with the scale and ranging, the categories described below can be established.

There are two different types of scanners that are commonly used in long-range 3D laser scanning: Phase-Shift (PS) and Time-of-Flight (TOF). The TOF method works by sending a laser pulse of light and then measuring the amount of time it takes to travel from the scanner to the object and back, allowing the scanner to calculate the distance (Armesto-González et al. 2010). An essential part of TOF measurement is the detection method for determining the range and the time of flight. The detector will generate a time-tagged trigger pulse depending on the implemented criterion. Some detection methods take characteristic points of the path of the pulse as the decisive factor (Vosselman, Maas 2010, p. 5). The speed of light is precisely known, so if the information on the time it takes the laser to reach the object and reflects back to the sensor is also known, the location of the object can be determined. A fundamental property of the light wave is its propagation velocity. In a given medium, light waves travel with a constant but finite velocity. The measurement itself is represented by time delays (referred to as the ‘time-of-flight’) created by light travelling in a medium from the source to the reflective target surface, and back to the source (Vosselman, Maas 2010, p. 3). The advantage of this technology is the significant increase in the speed of the data capture – currently up to several million points per second. TOF is typically used for exterior civil/survey applications such as

topographic surveys of roadways and buildings, since the key benefit of this type of laser scanning technology is its capability of capturing data from a greater distance (from several hundred up to several thousand metres), while maintaining the accuracy in the order of centimetres or smaller units (Pieraccini et al. 2001; Yastikli 2007; San José et al. 2011).

PS scanners work by sending out a continuous laser beam with a modulated signal embedded in the laser. The scanner compares the phase of the signal at the source with the phase of the laser light once it has travelled to the object and reflected back to the scanner; the change of phase of the laser light is measured and this allows the scanner to calculate the distances (Armesto-González et al. 2010; San José et al. 2011). In comparison to TOF scanners, PS scanners have a lower operational range (80 metres, with some systems reaching up to 120 metres), but can capture more points per second with a higher precision. Generally, PS scanner operates similarly to TOF scanner. The main difference is that PS scanner calculates the time of flight by measuring the difference in the phase of the laser as it returns to the scanner (Bhurtha, Held 2007; Armesto-González et al., 2010). Phase-based scanners are typically used in industrial applications such as plants and refineries, or interior architectural spaces.

While mid- and long-range laser scanners are usually based on TOF technology, systems designed for measuring distances smaller than 5 metres often use the triangulation principle. Triangulation systems typically have an operating range from 0.5 metres to few metres and can collect data with the micron-level accuracy. Short range scanners are used to scan individual small or middle-sized objects, inscriptions and details of architectural features. All short-range scanners are, in fact, portable/handheld devices (Remondino 2011).

The principle of triangulation is based on the laser or light (in the case of structured light scanning) being emitted and returned to a specific location on a CCD array of an inboard camera (Bohler 2006). Most triangulation systems come with a set of lenses that alter the field of view of the system. Most triangulation systems also include an internal RGB capture option, which means that, for accurate colour capture during scanning, a special lighting setup must be used (Pieraccini et al. 2001). Laser triangulation scanners use either a laser line or a single laser point to scan across an object. The sensor picks up the laser light that is reflected off the object and, using trigonometric triangulation, the system calculates the distance from the object to the scanner. The distance between the laser/light source and the sensor is known, as well as the angle between the laser and the sensor. The process of defining these values is called 'calibration of the device'. The scattered light from that surface is collected from a vantage point distinct from the projected light beam. This light is focused onto a position-sensitive detector. The knowledge of both the projection and the collection angles relative to the baseline determines the dimensions of the triangle and hence the coordinate of a point on the surface (Vosselman, Maas 2010; Feng et al. 2001).

Workflow notes

Laser scanning is usually carried out by experts, and the customer in most cases gets the final product. On the other hand, it is always desirable for the technologist to cooperate on site with a cultural heritage expert (or an archaeologist) in order to achieve satisfactory results and, especially, not to omit important parts of documented structures (e.g. critical details) which require higher level of accuracy. This applies especially to TLSs, given that, in terms of the price, handheld scanners are more accessible to a broader public and are affordable to cultural heritage institutions.

DATA COLLECTION AND PROCESSING⁵

The basic requirement for carrying out a project involving TLS documentation is a proper reconnaissance of the site/structure that is the object of scanning. During this step, basic information on the terrain configuration (flat land, hilly terrain, open land, trees with extensive canopy, etc.), as well as the characteristics of the structure (building material, height, type of roof, the level of occlusion, etc.) is collected. The scanning strategy should be based on the information acquired through reconnaissance. The core part of the strategy is the proper plan of scan positions – the so-called ‘stations’. Planning of the stations distribution must accommodate the demand for the total scan coverage, with as few digital shadows as possible. Some parts of the site documented may not be accessible to the scanner device (roofs, upper parts of high buildings, etc.). In such cases, additional technology (like image-based modelling procedure), with the help of unmanned aerial vehicle or a pole, should be involved. It is always good to include in the scanning procedure sketching of the stations positions on a plan, which then helps in orientation in the subsequent scan registration. In this sense, it is advisable to give names to particular scans according to the applied system, which would indicate their position.⁶

It is necessary for the scanning procedure to set the scanning accuracy, which is mostly defined as per distance. The level of accuracy is dependent upon the scale of the project and the commissioning arrangement. In the case of architectural structures, scanning accuracy should not go below 6 mm per 15 metres. For subsequent registration⁷ of particular scans, (ground) control points ((G)CP) have to be captured. These points are marked on the spot and scanned with the help of a special prism. Then, they are measured with the total station. The level of the measurement accuracy should not exceed 6-7 mm; otherwise the final registration of the scans can cause ‘ghosting’ effect.⁸

Most laser scanners are equipped with an inbuilt camera which can generate composite photos. The final scans derive RGB information from the photos taken at the same position where the scan was created. Unfortunately, most scanner cameras have unsatisfactory sensors, with small resolution, so the final RGB values are of very poor quality.⁹ In addition, processing softwares have limited possibilities for managing certain RAW files. Therefore, it often happens that some parts of the scanned structure have underexposed or overexposed RGB values, which are then very difficult to fix during the final texturing (Figure 5). To achieve a good texture, it is necessary to use proper external camera for photo documentation, which can be afterwards used in texturing the final mesh in external software.¹⁰ Moreover, the possibility of merging laser scan and image based scan data has recently emerged with the application of Capturing Reality’s RealityCapture software.¹¹

The basic output of laser scanning is a point cloud of a specific density and resolution. The majority of native scanner processing software can export the point cloud either in

⁵ This chapter is primarily concerned with TLS since the data acquisition by portable laser scanners is very similar to that of structured light scanners.

⁶ If scanning a building, it is advised to name the scans according to the rooms, floors, wings, etc.

⁷ In scanning technology, the term ‘register’ is used in place of a more general expression ‘align’.

⁸ Especially in case of flat surfaces (e.g. walls), inaccuracy can generate double structures.

⁹ This does not involve Riegl scanners, which use standard external DSLR cameras attached to the scanner.

¹⁰ The majority of external point cloud processing software packages enable texturing of the mesh using external photos (e.g. Geomagic Design X, Geomagic Wrap, PolyWorks, MeshLab). The procedure involves manual selection of common reference points on the photo and on the 3D model.

¹¹ Capturing Reality RC requires laser scan data format PTX as an input, in order to read the scanning positions and align them with the image data.

the scanner's native file (e.g. FLS – Faro native format, PTZ and PTG – Leica native format, etc.) or in the generally interchangeable file formats such as PTS, PTX or ASCII.¹² Both file types store point clouds with the topographic information (X, Y and Z coordinates of each point) and intensity and colour information (R, G and B values of each point). Furthermore, the PTX file format contains information on the position of particular scanning stations.¹³ This format contains the above-mentioned data as well, but, due to its structure, it is very difficult to work with when it contains a large amount of data.¹⁴

The first step of scan-data processing is scan registration, i.e. the alignment of all scans of particular scanning stations into one common point cloud. Scan registration can be carried out either in the scanner's native processing software using the measured GCP, which is the preferable option, or in an external software (commercial or open-source). External software is predominantly used for the registration of common points in point cloud pairs which are defined manually, or it applies semi-automatic aligning process based on fusing common parts of the point clouds (e.g. Autodesk ReCap). In the latter case, sufficient overlapping between registered point clouds is required.

After all the scans have been registered, the final, aligned point cloud is generated and this is then subject to further processing. Depending upon the needs of the project, it can be subsampled. The final step is mesh generation. Most native scanner software packages are not very good in doing this. Nowadays there are many meshing algorithms included in a number of software packages, both commercial and open-source. The main drawback of the majority of software is the limitation in size of the point cloud and the final mesh they are able to handle.¹⁵ Currently, the most common algorithm used for meshing a point cloud is the so-called 'Poisson reconstruction' (for details see Khazdan, Hoppe 2013) which tends to build watertight mesh by interpolating missing data and giving a smooth result, while maintaining the surface details. Another option is the basic triangulation with software-specific variations, which delivers the exact surface structure.

Software	License	Point cloud registration	Meshing algorithm
Geomagic Design X	commercial	manual, semi-automatic	Native, based upon triangulation
Geomagic Wrap	commercial	manual, semi-automatic	Native, based upon triangulation
PolyWorks	commercial	manual, semi-automatic	Native, based upon triangulation
3D Reshaper	commercial	manual, semi-automatic	native
Thinkbox Sequoia	commercial	manual, semi-automatic	native
Capturing Reality RC	commercial	manual, semi-automatic	native
Autodesk ReCap	commercial	manual, semi-automatic	no
CloudCompare	open-source	manual, semi-automatic	Poisson
MeshLab	open-source	manual	Poisson ²³
VRMesh	commercial	manual, semi-automatic	Native

Table 1. Overview of the most commonly used point cloud editing and meshing software.¹⁷

¹² In case of airborne LiDAR data, LAS or LAZ file format is the most common.

¹³ It is also called 'structured scan file format' because it enables special forms of visualisation and lighting. PTX files are usually much larger than PTS files.

¹⁴ Notably, opening an ASCII file containing more than 10 million points can, in some cases, be an issue.

¹⁵ Most software packages have problems with meshes containing more than 80 million triangles.

¹⁶ Beside Poisson reconstruction, MeshLab also offers other meshing algorithms, e.g. Ball pivoting and VCG, but Poisson surface reconstruction is the most suitable option in the majority of cases.

¹⁷ In open-source software, there can be constraints in the readability of particular RAW files; also, some of the mentioned editing tools may be missing.

STRUCTURED LIGHT SCANNING (SLS)

Structured light scanners use trigonometric triangulation as the basic technological means, but instead of looking at laser light, these systems project a series of linear light patterns onto an object using either an LCD projector or another stable light source. Light patterns are collected, or, rather, recorded with a camera. Then, by examining the edges of each line in the pattern, the software calculates the distance from the scanner to the object's surface. Essentially, the camera sees the edge of the projected pattern and calculates the distance and size of the scanned object. In order to obtain the structure of the scanned object, the light source also needs to contain all basic colours, i.e. red, green and blue (RGB), and emit them towards the object being scanned. The reason for this is the working principle of RGB cameras as data capturing devices. The SLS technology is very popular, especially in light portable (handheld) scanners.

There are two components of which SLS typically consists: a light source and a camera. The light source transmits patterns of the surface scanned. The patterns consisting of parallel stripes are most commonly used, although many other variants of projection are as well in use. Displacement of the stripes allows for an exact retrieval of 3D coordinates of details on the object's surface (Fofi et al. 2004). The light patterns are recorded with RGB camera. Then, by examining the edges of each line in the pattern, the software calculates the distance from the scanner to the object's surface (see above).

Generally, there are two types of these scanners. The first type has the ability to change the distances between the camera and the light source, which leads to changes in the angle between the camera and the light source. In this kind of system, the calibration panel is used to determine the position and the angle of the light source and the camera. The second type has a fixed light source and a camera. In this case, the distance between them is constant and does not change through the process. Thus, in this method, it is necessary to set a good distance between the object and the scanning pair (camera and light source). In some cases, video projector can be used as a light source.¹⁸ Principally, the stripes generated by display projectors have small discontinuities due to pixel boundaries; however, these can practically be ignored as they are ironed out by slight defocusing. A typical measuring assemblage consists of one stripe projector and at least one camera. Placing two cameras on opposite sides of the projector can also be useful (Fofi et al. 2004).

There has recently been a significant increase in the use of structured light portable/handheld scanners, especially due to their increasingly accessible price. A number of projects have demonstrated their possible applications, as well as the limitations of their use in archaeology and in cultural heritage management in general (Buchón-Moragues et al. 2016; McPherron et al. 2009). On the other hand, traditional laser scanning approach usually provides higher accuracy rate.

The following comparison is based upon personal end-user experience and not upon any scientific analysis.

18 David SLS scanner uses LCD video projector for emitting light patterns.

Laser Scanner Method	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Can be used in virtually any indoor lighting condition • Can be used to scan parts of any material and colour • Provides excellent depth resolution for measuring details of features, compound curves, cracks, etc. • Little noise in point cloud • Highly reliable accuracy 	<ul style="list-style-type: none"> • ‘Speckle-effect’ may sometimes pose limitations to the resolution and accuracy • Higher prices
Structured Light Scanner Method	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Fast when measuring objects with many low-curvature surfaces • Good lateral resolution along the two axes • Eye-safe • Customer-friendly price 	<ul style="list-style-type: none"> • Sensitive to ambient light. Best used in a dark room • Cannot be used to scan shiny surfaces • ‘Occlusion’ effects require taking additional images • Slow when measuring objects with many intricate details • In terms of accuracy, usually less reliable than laser technology

Table 2. Comparison of light and laser technologies.

As mentioned above, SLS is almost invariably used in handheld or portable scanners (Figure 4). The structured light-emitting source is either represented by an ‘independent’ device, mostly a projector that is in some way connected to the capturing device, or is directly integrated into a single device (e.g. Artec scanners: Eva and Spider). Just like in the case of TLS, SLS’s main task as regards data capturing is to avoid digital shadows and cover the whole object scanned. This can be a delicate issue, as SLS usually requires a certain distance from the item being documented. To this end, it may be impossible to capture occluded parts of the object’s surface with only one SLS scanner type.¹⁹ SLS has limitations in view of the scanning distance, which is reliable up to one metre at the most; so it is obvious that it is suitable primarily for digital documentation of small- and medium-sized objects. Therefore, this technology is used mainly in museum collection documentation. Some SLS devices cannot operate under direct sunlight, which can cause problems in open-air work. In such cases, portable tents or shelters are required to block the direct sunshine.

¹⁹ In the case of Artec scanners, type Eva operates within longer distances from the object, while the Spider type works within a closer range and is capable of capturing fine occluded details.

SLS technology usually functions by gathering data with its native software. Hence scanning, in this case, necessitates the use of a notebook or tablet, which enables real-time preview of the scanning process. Some native scanning software may require specific notebook/tablet configuration especially concerning the CPU (processor), GPU (graphic card) and RAM. Unlike TLS, most SLS software carry out complete processing and post-processing of the data acquired from the point clouds registration, meshing and texturing, so there is no need to use external software. Besides native software, most present-day portable SLS scanners can use Artec Studio for previewing the scanning process as well as data processing. Artec Studio was designed as native software for Artec scanners and provides workflow for the entire procedure – from the registration of particular scans to mesh processing and editing.



Figure 5. Manor house at Žehra, Hodkovce, Slovakia. Point cloud with RGB values showing exposure inconsistency due to poorly exposed composite photos taken by the native scanner camera (Leica C10).

DIGITAL PHOTOGRAMMETRY

Seta Štubec (University of Ljubljana) & Ján Zachar (Via Magna)

According to the basic formal theoretical definition, "photogrammetry is a science dealing with the reconstruction of shape, size and position of objects displayed on measurement photogrammetric images. Measurement image, or else the reference model, essentially forms the basis of photogrammetry as a measurement and mapping technique". It enables achieving the most precise and fastest depiction of natural and artificial objects on the Earth's surface. Under certain conditions, the measurement image can become an exact central projection of the photographed image, which means that it is a method of optic measurement. Measurements are taken on photogrammetric images or on the optic model¹ created from the measurement images. Based on these definitions, photogrammetry can be perceived as a separate geodetic and cartographic method. Photogrammetry follows the principle of transmitting information from the central projection to orthogonal projection using graphical, optical or mechanical and analytical tools. This means that distinct geometric relations that existed between the object and its image during the time of exposure can be reconstructed on the basis of geometric quantities depicted on the image (Bitterer 2006).

Recording of measurements on photogrammetric images or on reference models, which substitutes recording of measurements directly on the object or in the field, represents the basic specificity of photogrammetry that distinguishes it from the number of other geodetic methods. This prospect introduces significant benefits that, to a large extent, make the measurement work easier, save time and, to a certain degree, reduce costs. A considerable benefit lies also in the fact that measurement on the basis of photogrammetry is performed without direct contact with the object. Photogrammetry has found

¹ <http://svf.uniza.sk/kgd/skripta/fotogrametria/kap01.pdf>.

mass application in the era of transition from analogue to digital platform, the process generally related to the advantages of digital photography as such. 'Digital photogrammetry' is currently widely applicable in many areas and scientific disciplines, especially due to its diverse potential and the fast development of digital technology. It works with digital images and mathematical models of analytical photogrammetry. In general, it can be established that digital photogrammetry provides:

- high resolution of the details measured,
- measurement of objects changing and moving at the time of imaging,
- high accuracy of measurement,
- orthophoto images and 3D models in a computer environment (Bartoš, Fraštia 2011).

It is especially the creation of orthophoto images and 3D models, which forms the focus of this publication, that is essential from the perspective of practical needs of different areas of cultural heritage.

Photogrammetry, that is, its different aspects, can be categorised according to various criteria. From the perspective of sensing position, we distinguish aerial and close-range photogrammetry.

- Aerial photogrammetry represents one of the techniques of the Earth's surface remote sensing, which also includes satellite imaging. As the name suggests, aircraft represents the basic carrier for sensing. Large- or medium-format digital camera is used as the sensor. An important piece of equipment is the navigation system, as well as the system for direct orientation of the sensor.
- Close-range photogrammetry deals with the evaluation of measurement image from fixed terrestrial positions, whereby it utilises several methods that allow obtaining spatial information about the objects depicted in the image. Thanks to its wide scope of application, it is one of the most widespread measurement techniques. It is used for making 2D and 3D documentation of objects and situations by means of non-contact measurement of their images. The accuracy and geometric resolution depend on the distance of imaging and the size of the focal length of the objective. Close-range photogrammetry works with object distances of between 0.1 m - 350 m, where both the lower and the upper end of the range are not strict.

Photogrammetry (especially close-range) can be classified, from the perspective of the methodology of collection and processing of the data, into single image photogrammetry, stereophotogrammetry, convergent photogrammetry and image-based modelling.

- Single-image photogrammetry represents the simplest method that uses one image of the given object, whereas the position is chosen to have the imaging axis approximately perpendicular to the measured object. The aim is to import the distorted image into orthogonal projection through projective transformation. This method is used for the reconstruction of planar objects; for spatial objects, additional information about the depth of the object documented is required. It is also used for measuring building facades and for the creation of photo-plans. Up until the onset of image-based modelling, this was the most frequently used photogrammetric method for documenting results of archaeological research. Basically, it is the classic 2D photogrammetry.

- Stereophotogrammetry is a multi-image photogrammetric method used for sensing spatially uneven objects or structures using stereoscopic perception. It is based on the correct identification of the same (G)CP on two or more images. In the past, this was the most efficient photogrammetric method, with benefits including high effectiveness and also the possibility of application of any photogrammetric system. Its application is presently declining, especially due to the popularity of image-based modelling.
- Convergent photogrammetry is another multi-image photogrammetric method. Camera axes are aimed approximately at the centre of the object measured, usually to have the object depicted in the largest possible area of the image, with the largest possible overlap. Methodologically, this is an alignment of the beam with the mathematical model of perspective photogrammetry. Nowadays, this method is slowly being replaced in the documentation practice by the method of image-based modelling.
- Image-based modelling is a method that is based on full automation of the process. The advantage of this method is in the fact that, instead of the time-consuming manual measurement of points on images, the required level of detail of the modelled areas can be achieved by choosing sufficient density of the point cloud. This is currently the most frequently used method due to the automation of the whole process and its reasonable price (Fraštia 2009).

2D PHOTOGRAMMETRY

2D photogrammetry has already become a regular element of the traditional documentation approach in archaeological excavations. In its essence, it is generally a single image photogrammetry.² Photographs are taken from above as vertically as possible using a ladder or a pole (if possible, an unmanned aviation vehicle (UAV) can also be employed). The photographs are then rectified and georeferenced using GCP measured by the total station or a GPS device. The archaeological units captured on such photographs are afterward vectorised and the result transferred into an orthophoto plan.

When taking a photograph, the analogue signal that is acquired and turned into a digital image is degraded in various ways. It has to be taken into account that geometrical distortions occur in every image because the three-dimensional (3D) properties of the scene are mapped onto a two-dimensional (2D) sensor plane. The mapping result (i.e. the final image) is influenced by a wide variety of factors, of which geometric errors induced by the optics, the tilt of the camera axis and the topographic relief contribute the most to the image deformations. Compensating for these deformations through some kind of geometric correction is essential for the extraction of accurate information by means of vectorisation. In general, there are two ways of dealing with these geometric deformations: simple rectification and rigorous orthorectification (Verhoeven et al. 2013).

Simple rectification

For tilted images, the scale will vary with direction: the background of tilted photographs features a scale smaller than the scale of objects in the foreground. The projective

² The theoretical background derives from the paper Zachar & Štuhec (2015). (Case studies: the Čachtice and Bratislava castles, Slovakia). The article was prepared within the frame of the CONPRA project.

transformation of a tilted image to a horizontal plane can remove the contortions caused by the inclination (and thus scale differences). Such a procedure is called (planar) rectification and the result is a rectified photograph. Often, the first and second order polynomials are also used to obtain (semi-)rectified photographs, although these algorithms differ to a varying degree from the aforementioned projective transformation.

In the absence of lens distortions and perfect flatness of the imaged scene, the rectified tilted image will be identical to a vertical image and the result will be a true orthophotograph. However, lens distortions are always present and truly flat surfaces are seldom found at archaeological excavations. Since differences in height will cause topographic (or elevation) displacements, any feature lying above or below the horizontal reference surface will be misplaced in a planar rectification. More advanced algorithms are thus required if accurate mapping from the photographs is needed (Wolf, Dewitt 2000).

Rigorous orthorectification

When the geometric image correction aims to compensate also for topographically- induced deformations and lens distortions, this is called orthorectification or differential rectification. The result of such correction is a planimetrically correct true orthophotograph. Until a few years ago, true orthophotographs could only be achieved with advanced photogrammetric packages such as the Trimble INPHO Photogrammetric System. Besides the high cost, these packages were also of limited use in excavation documentation because the photogrammetric skills were essential. However, due to the ever-expanding technological improvements in computer hardware and the significant advances made in the past fifteen years in the scientific development of computer vision, many cost-effective approaches exist today. Additionally, they allow for a straightforward workflow and can still produce metrically accurate true orthophotographs (Verhoeven et al. 2013). One possible solution is to pre-process the photo prior to the rectification process with the help of an appropriate image correction software that would compensate for the radial and tangential distortion.³

Practical approach in 2D Photogrammetry

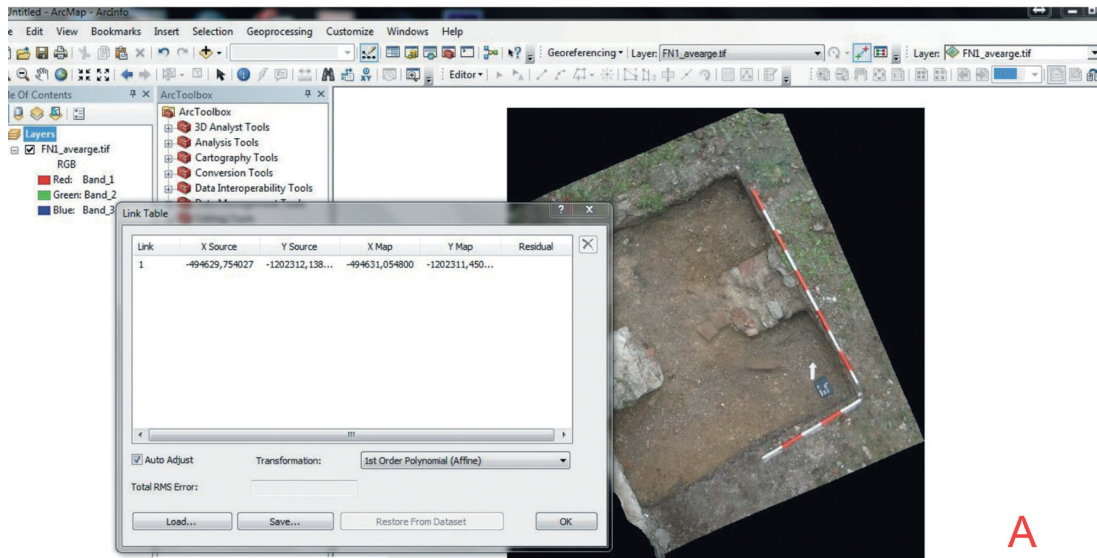
Nowadays there are plenty of tools available for photo rectification. Most commonly used are the ones implemented in CAD and GIS solutions. Autocad Civil 3D with Raster Design extension offers several rectification options. The polynomial transformation of the 1st grade usually turns out to be the most suitable choice. It is characterized by an independent scaling of x- and y-axis with no local rectification.⁴ Beside the 1st grade polynomial transformation, this software offers polynomials of the 2nd and 3rd grade (similarly to the ArcGIS georeferencing options) as well as the triangular rectification (Figs. 6, 7).

During the triangular rectification, GCP pairs are precisely coupled spatially, and the triangles between them are stretched and squeezed to fit by calculating the polynomial coefficient of each triangle. This is the most precise method with potential imperfections only 'inside' the triangles. The negative aspect is the fact that space outside triangles is not included in the final result (raster cropping of the convex hull). In order to check the accuracy, the root mean square error (RMS) is calculated. CAD software Microstation enables orthorectification procedure via warping options.

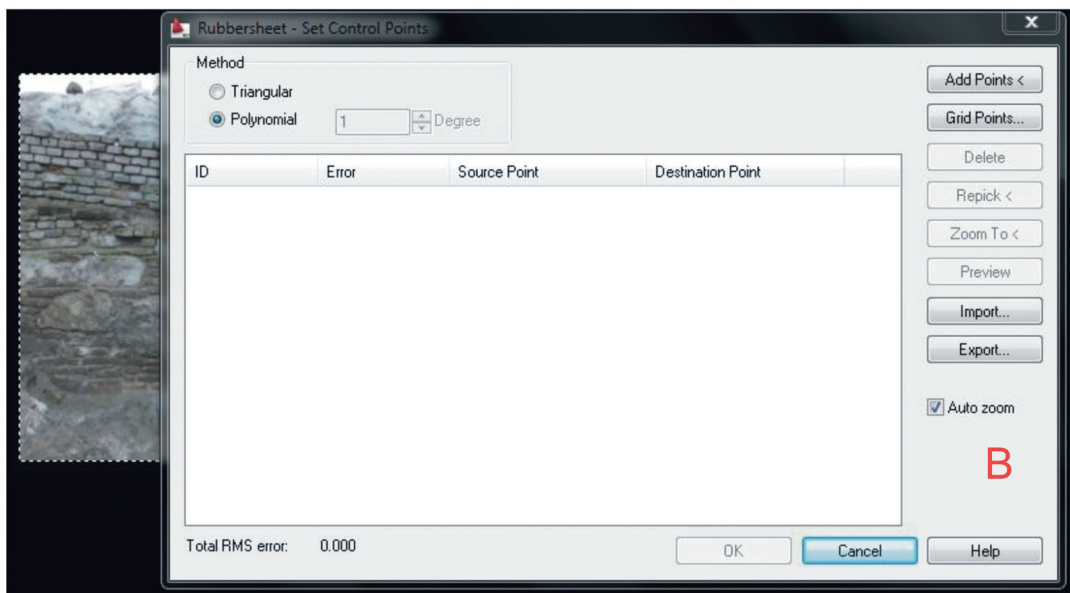
³ It is possible to use software that comes with the camera, or DxO Optics Pro, which compensates for the lens distortion by using appropriate camera optics module.

⁴ In the software-related terminology this procedure is referred to as 'rubbersheeting'.

As already mentioned above, the basic problem facing 2D photogrammetry is the insufficient tangential and radial lens distortion correction, which causes insufficient correlation of the plans of the captured scene characterised by great differences in height. This causes serious problems in the usage of 2D photogrammetry for documenting masonry structures that have a significant height distinction between the top and the bottom parts of the walls.



A



B

Figure 6. 2D Photogrammetry, orthorectification procedure.
A: ArcMap interface, B: Autodesk Civil 3D + Raster Design interface.

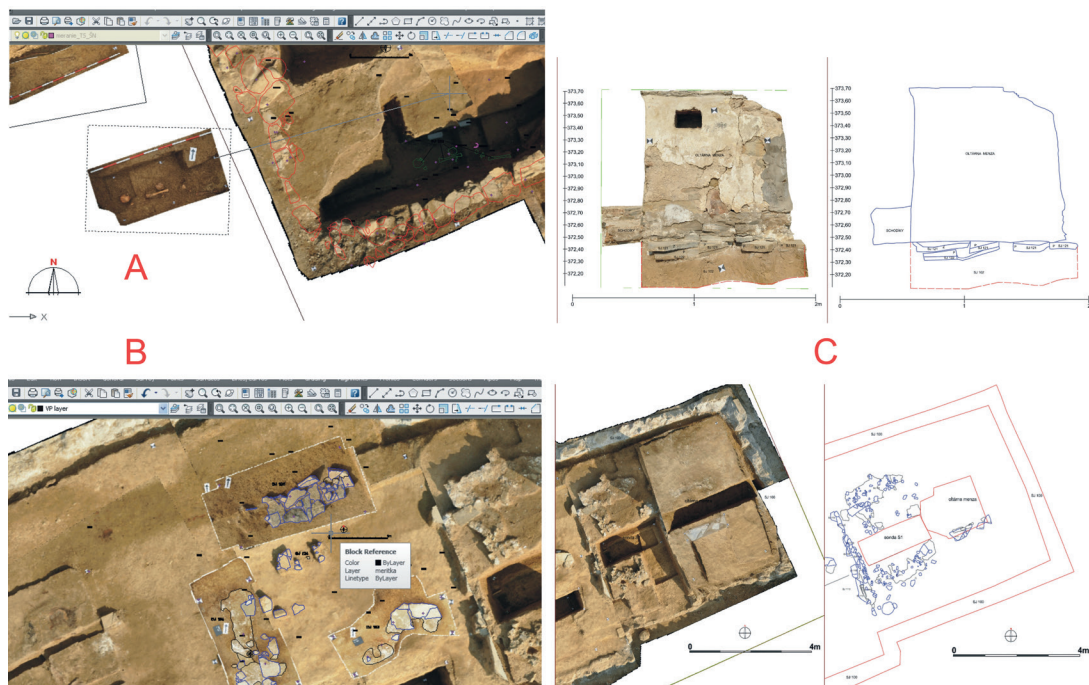


Figure 7. 2D Photogrammetry, basic workflow. A: georeferencing a photogram according to the measured ground control points (orthorectification), B: vectorisation of a photogram, C: print layout.

IMAGE BASED MODELLING (IBM)

Image-based modelling (abbreviated as IbM) represents an algorithmic extension of stereophotogrammetry, especially in the sense of process automation. The algorithmic basis of IbM is the image correlation of input data (image rasters) that substitutes the natural stereoscopic view. Such correlation subsequently automatically generates a point cloud of a certain density, which forms the frame of the future model. Image correlation (Figure 8) analyses the similarity and the possible match between the two data files. It is, basically, an assessment of the correspondence between image parts on two or more images. It concerns comparison of the pixel surroundings on the first image, the so-called reference comparison matrix, with the surroundings that at least approximately match the position of the other pixel on the so-called searching matrix. It results in the calculation of a correlation coefficient in each of the compared positions. The coefficient can range from 0 to 1, i.e. it can signal absence of any match between the matrices (0) or indicate a match (1). If the correlation coefficient reaches the maximum value, image coordinates of the pixel (image elements) can be used for the calculation of the spatial position of a given point (Maliariková 2011), whereby the mentioned point cloud is created as the basis of the 3D mesh.

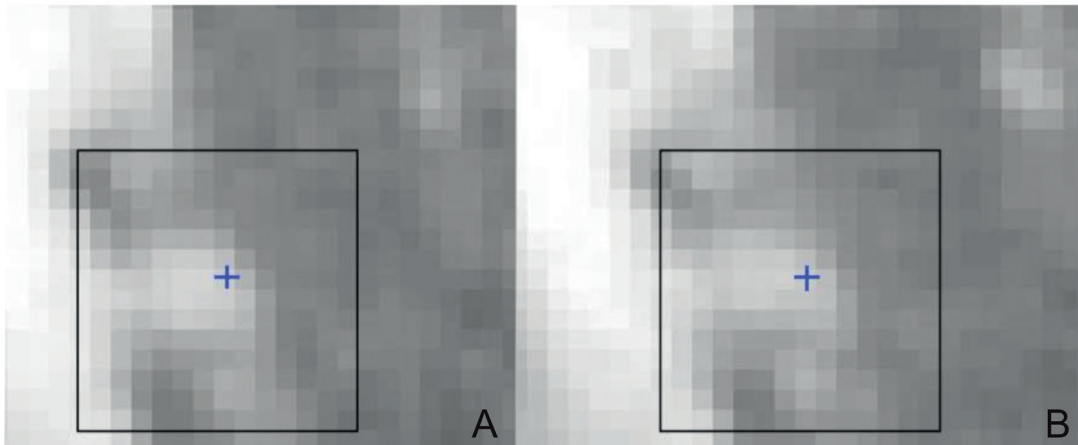


Figure 8. The principle of optical correlation.
A: reference matrix, B: searching matrix. (Maliariková 2011, Figure 5).

As pointed above, using Ibm techniques makes it possible to calculate the 3D location of points recognizable in two or more photographs. In order to do this, the exact external (camera position and orientation) and internal camera parameters (focal length, lens distortion coefficients, principal point) have to be obtained. This can be achieved automatically using mathematical techniques from the field of computer vision called Structure from Motion (SfM). By using these algorithms, the essential external and internal camera parameters are extracted, therefore the preliminary camera calibration is not needed. The first step of the SfM approach is to search for the image-specific feature points – the so-called ‘key points’ using the principle of the SIFT algorithm.⁵ Using the description of the features found, the algorithm matches them across the whole set of photographs (the bundle adjustment). These matches – the so-called ‘tie points’ – are then used to create the relative projection geometry (the internal and external parameters). Some software applications enable determination of a maximum number of key points and tie points in order to speed up this registration process.⁶

The result of this step is a sparse point cloud (i.e. a set of points with x, y and z coordinates) that represents the object’s geometry. Sparse point cloud may in some cases contain a lot of noisy points resulting from a high re-projection error or uncertainty in the reconstruction. Most software enable correction of the re-projection error through a specific refinement process that leads to cleaning of the sparse point cloud. The refinement of sparse point clouds is a delicate and important process as it significantly determines the quality of the final mesh.⁷

⁵ Scale-invariant feature transform (SIFT) is an algorithm in computer vision used to detect and describe local features in images that are independent of the changes of scale. The description of features is of a vector nature. The algorithm was published by David Lowe (1999).

⁶ Besides speeding up the alignment, setting an upper limit value for the generation of tie points filters out the points with very high re-projection error as well. However, when setting the maximum values for key points and tie points, it is necessary to keep the ratio of 2:1. Best results are usually achievable with key points: 80,000 and tie points: 40,000 or with key points: 120,000 and tie points :60,000. Lower values are possible but may result in the loss of surface geometry.

⁷ It is always necessary to find an optimal balance between a sharp and a noiseless sparse point cloud on one hand, and not losing too many points by cleaning process on the other hand, as this may lead to disruption of the geometry of the model.

The next step is called Multi-View Stereo (MVS) approach and is used to compute a denser point cloud. Such point cloud can afterward be turned into a mesh and used as a solid 3D model to which texture can be applied. Textured 3D model can be scaled or georeferenced according to the measured coordinates of ((G)CP) which are aligned with the markers detected manually or semi-automatically on photos in uploaded into the program. Most programs dispose of subsequently generated deliverables such as georeferenced orthophoto plans or digital elevation models (DEM) (Figure 9).

It is important to understand the basic principles of the SfM+MVS approach in order to be aware of its capabilities and limitations. For example, the SfM+MVS approach is useless if the object lacks distinct texture, which is necessary for the recognition of feature points. Shiny or glassy objects are also more difficult to reconstruct using these methods, as their highlights are constantly changing. The best result can, therefore, be achieved with distinctively coloured and textured objects. Finally, the correct photo capture procedure is essential to achieve the best possible results.

Software and on-line services

The recent boom in computer vision programs that combine SfM approach with dense MVS algorithms makes the calculation of 3D data from photographs accessible to non-professionals. Because of their straightforward workflow and a moderate cost, these SfM+MVS software packages do not require extensive photogrammetric and computer vision knowledge of the user, nor the information on geometrical properties of the scenes. This means that no special preliminary preparation is needed (i.e. camera calibration). As such, they became a common part of the documentation practice in many research and commercial fields, including the cultural heritage monitoring and preservation.

The straightforward generation of 3D content by these SfM+MVS tools also finds useful applications in documenting archaeological excavations, for which accurate and cost-effective registration techniques are of utmost importance. Besides the advantages of these accurately scaled digital surface models in presenting the archaeological heritage, georeferenced orthophoto plans and vector drawings can also be generated from them. Today there are plenty of SfM+MVS packages available, ranging from free and open-source to commercial ones. Some of them (such as ARC3D, 123D Catch, Autodesk ReCap, Autodesk ReMake) provide an online service that automatically carries out the entire procedure. These online approaches are very easy to use. All that a user needs to do is to upload the selected images and wait to receive the 3D model. However, the number of images is quite limited and, additionally, hardly any manipulation of the parameters is possible, which represents a significant constraint in the 3D model creation.

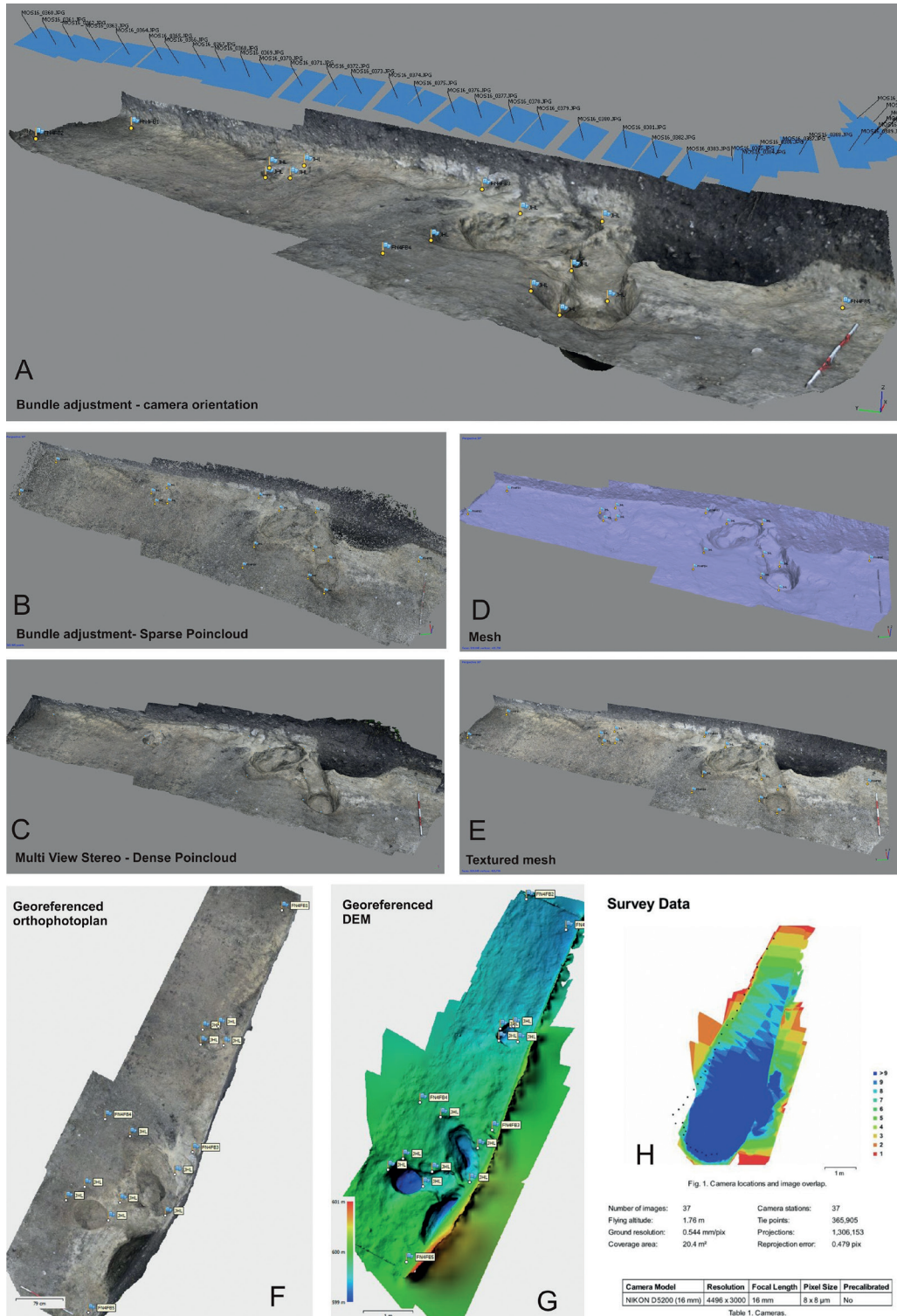


Figure 9. Structure from Motion workflow (software Agisoft Photoscan).
 A: bundle adjustment, camera calibration – outer and inner camera orientation definition, B: bundle adjustment, sparse point cloud generation, C: Multi-View Stereo, dense point cloud generation, D: mesh creation, E: textured mesh, F: georeferenced orthophoto plan creation, G: georeferenced digital elevation model creation, H: survey data accuracy, mode resolution and quality report.

On the other hand, a computer-based software package might take a bit more time to master, but the parameters can be tailored for each specific case. Some of these programs have also additional functionalities such as scaling, georeferencing, orthophoto plans extraction, etc. which is, in the case of open-source software, rarely possible. A short list of some of the programs and online services is provided below.

Software	Web	License	Solution
Photomodeler Scanner	http://info.photomodeler.com/	commercial	desktop
Agisoft Photoscan	http://www.agisoft.com/	commercial	desktop
Capturing Reality RealityCapture /RC/	https://www.capturingreality.com/	commercial	desktop
Pix 4D	https://pix4d.com/	commercial	desktop
Acute3D ContexCapture	https://www.acute3d.com/	commercial	desktop
3D Zephyr	http://www.3dflow.net/	commercial	desktop
ARC3D	http://www.arc3d.be/	open-source	online
Autodesk 123D CATCH	http://www.123dapp.com/catch	open-source	online
Autodesk ReMake	https://remake.autodesk.com/	commercial	online
Autodesk ReCap	http://www.autodesk.com/products/recap-360/overview	commercial	online
University of Washington, Visual SfM	ccwu.me/vsfm	open-source	desktop
Menci APS	http://www.menciSW.com/aps-en	commercial	desktop

Table 3. Overview of the most commonly used IBM software.

Image-based data collection: Basic rules

Because not a lot of metadata are needed, the above-described approach enables generation of a 3D content from almost any set of photographs. Nevertheless, in order to generate a 3D model successfully, one should follow certain rules when taking photographs on the site (Figure 10). The below listed basic principles of the photo shooting scenario refer primarily to the position and ‘movement’ of the photographer while taking the photos:

- Every photograph should be taken from a different location. If the photographs are taken from the same location, problems with alignment might occur.
- A higher amount of photographs does not necessarily mean a better result. It is, however, better to take more photographs and make a selection later. Only the feature visible on the photograph can be reconstructed, that is why it is important to capture everything.
- The photographs should be taken with a sufficient overlap. There should be at least a 60 % overlap, although 80 % often works better. A rule of thumb to follow is the ‘rule of three’, which states that each feature should be visible on at least three photographs.
- Photo sequences should be taken in a way in which the optimized mutual photo axis orientation is maintained. The angle between the axes of two adjacent photos should not exceed 25-30 degrees.

- An important element is also the image quality. Photographs should be sharp and acquired with good quality optics. If possible, it is advised to take the complete set of photographs with the same focal length and focus distance, it normally gives better results. lBM does not set any requirements concerning the image resolution. However, it is important to remember that the resolution of the input data influences the quality of the processing results. That is why it is strongly recommended to employ a camera with at least 5Mpx resolution. If the project's objective is to produce high quality/professional orthophoto maps, it is better to opt for a minimum 24Mpx⁸ resolution photography (sharpness is discussed in detail in the following chapter).
- Some software packages enable alignment, re-alignment and/or georeferencing using special targets – markers that come with the program and that can be calibrated. In this case, the targets should be clearly visible in the photographs (to create a texture, enough photographs without these targets should also be taken). It is possible to use non-calibrated markers as well. The size of markers should be adequate in relation to the extent of the project; the only limiting factor is that they should be visible on the photos. The distribution should be such that the markers cover the whole scene documented. In case of landscape surveys, it is advisable to measure coordinates of the markers (in this case GCP) by the total station in order to get as precise coordinates for georeferencing as possible.⁹
- SfM algorithm estimates the camera calibration parameters automatically; consequently, there is no need to run a pre-calibration procedure manually. However, since the algorithm in most software applies the Brown model to simulate lens assembly, automatic calibration works perfectly well only for 'standard' optics (that is, with 50 mm focal length (35 mm film equivalent)). Otherwise, if the source data is captured with a 'fish eye' or ultra-wide angle lenses, the operation is likely to fail. If this is the case, one should enter calibration data into the program for good results of the reconstruction.
- The final result of 3D lBM can be strongly influenced by the lighting conditions. Best results are usually achieved under coherent natural diffuse lighting, which is generally guaranteed in cloudy weather.

As already mentioned, each part of the scene that is to be reconstructed in 3D should be visible on at least 3 photos. This may be a problem when documenting architectural structures. In this case, taking photos just from the ground level causes 'digital shadows' in upper parts of the architecture. The best way to avoid this is the application of pole aerial photography or unmanned aerial vehicles (UAV) to reach parts of the structure that are not accessible from the ground level. Nowadays, especially UAVs (mostly micro-copters) are becoming a regular part of the data acquisition in lBM as they can fly in an autonomous mode using integrated GPS/INS, a stabilizer platform and digital cameras (or even a small range sensor), and which can be used to get data from otherwise hardly accessible areas.

⁸ On the other hand, the choice of camera should not depend only on the resolution. The optics, in combination with the camera sensor, is crucial for a good photo quality.

⁹ As for the number of GCP, it depends on the scale of the project. The basic rule is that they should build up representative information on the measurements.

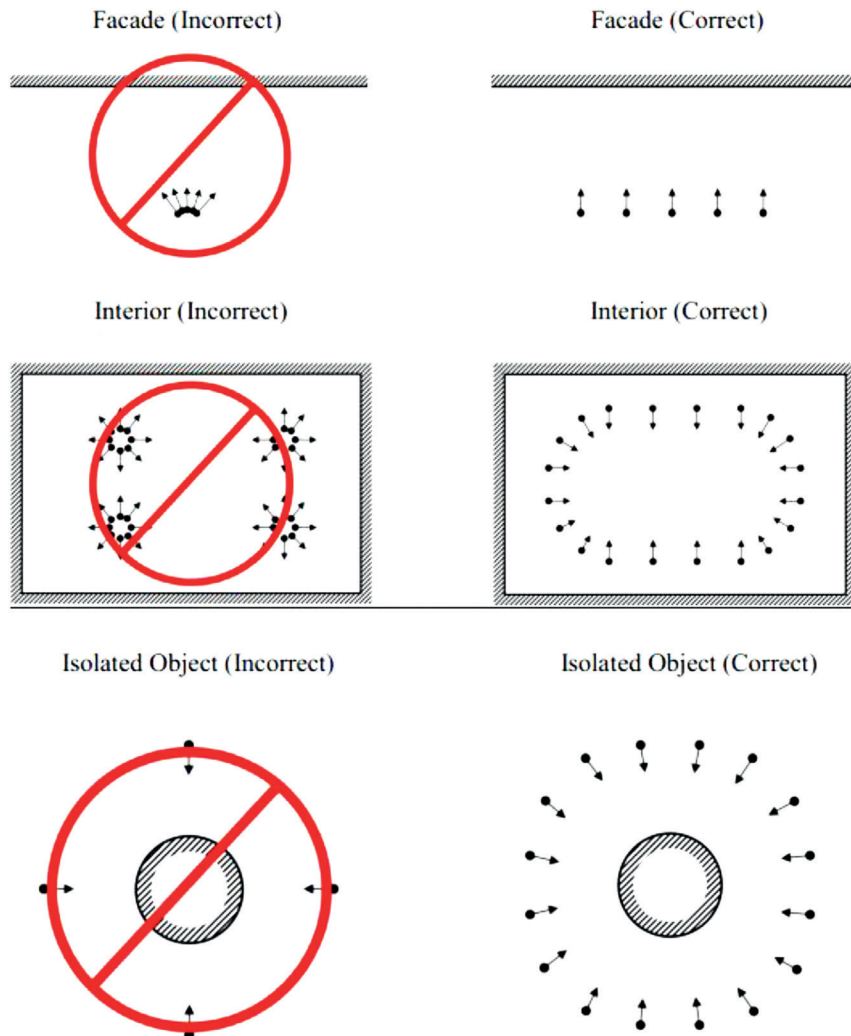


Figure 10. Photo shooting strategies for Image-based Modelling (IbM).
 (Available online at http://www.agisoft.com/pdf/tips_and_tricks/Image%20Capture%20Tips%20-%20Equipment%20and%20Shooting%20Scenarios.pdf).

Concerning the 'terrestrial' photo shooting scenario, there are, from the practical point of view, two basic methods:

- *The walk-around method* is mainly used for documenting objects outdoors. The method entails that a photographer moves around the object following the above-mentioned rules. In case this method is used for recording of a solitary object in an indoor environment, it is necessary to do appropriate camera settings with regard to the indoor lighting conditions (see the following chapter). Photo acquisition is done via several 360 degrees photo-shooting rings, with approximately 30-50 photos per ring, depending on the size of the object.
- *The turntable method* is, on the other hand, based on photo-shooting in a single direction, from a camera mounted on a tripod. The motion is obtained by changing the position of the object photographed. In most cases, the object is placed on a base that rotates (either operated manually, or automatically by an electronic device) while

the camera is taking pictures.¹⁰ Of course, the general position of the object has to be changed manually several times during photo-shooting in order to capture all possible sides of the object. In this scenario, precise light settings are essential in order to achieve good diffuse global light. Putting the object in front of a monochrome background is a good option as well, and it can help substantially in subsequent processing by generating a clear mesh with as little noise as possible (Figure 11). This shooting method is meant exclusively for portable object documentation created in internal environment.

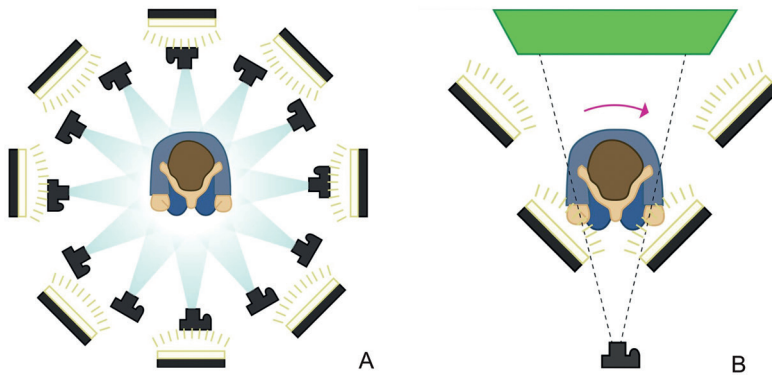


Figure 11. Photo-shooting scenario of a solitary object. A: walk-around method, B: turntable method. (Available online at <http://www.tested.com/art/makers/460142-art-photogrammetry-how-take-your-photos/>).

Pre-processing the data (taking and editing photos)

The basic material for IbM consists of source photos. As already outlined in the previous chapter, the quality of the acquired photos strongly determines the quality of the final 3D model. Therefore, paying extra attention to the image quality is a key factor for successful accomplishment of the projects. Since the sufficient number of SIFT points (key points) detectable on the image is crucial for further workflow, a high resolution, high overall sharpness and a high contrast of the photo are required.

Based on the experience obtained from the case studies, the best procedure for taking photos is through the use of a standard DSLR camera with fixed lens.¹¹ Creating RAW files is preferred to creating JPGs. Although RAW files consume much more SD card memory, they definitely contain a much higher amount of data that can afterwards be processed according to particular needs. On the other hand, the processing potential of JPG files is rather limited. Photographs should be taken in aperture priority mode,¹² if possible with the help of a monopod or tripod stand.

The overall sharpness of the picture is of prime importance, so the aperture should be set to minimum 5.6 or higher, but should not surpass the 'sweet spot' point of the lens, since too-high aperture values introduce high light diffraction and thus additional noise and blur

¹⁰ Nowadays, there are a lot of examples of fully automated turntable data acquisition procedure, where rotation of the turntable and the camera shooting system are controlled by a computer.

¹¹ Transfocal lenses are not excluded, but the best achievable results are guaranteed by the use of fixed lenses.

¹² Fully manual mode would, of course, be most desirable, but is usually out of question with respect to the amount of photos taken (often hundreds, or even several thousands).

into the imagery.¹³ In order to keep the noise as low as possible, shooting at low ISO values is recommended. For the white balance correction, calibrated colour charts should be used. If shooting outdoors, the most suitable lighting condition is guaranteed by cloudy weather which generates diffuse light. If the scene or object documented are in sunlight, this can create big differences in luminance (e.g. sharp shadows) and it may be necessary to use protective shelter if possible, or create HDR photos (see below) which can be time-consuming.

Afterward, the RAW files are to be processed in specific software in order to enhance the sharpness and colour information. The following parameters should receive special attention:

- *White balance* setting enables correction of the white balance according to the calibrated colour charts or purely manually. This step is important in order to get the relevant and true colour information on the object/scene documented for the purpose of texturing of the final 3D model.
- *Exposure compensation* adjusts the global exposure of the image and thus its overall brightness/darkness.
- *Smart lighting* (available only in some software packages) optimizes the global dynamic range of the photo by unblocking shadows and/or recovering highlights.
- *(Selective) tone mapping* allows selective adjustment of the brightness of a given tonal range (highlights, midtones, shadows, blacks). This is a very important tool used to recover detail in the highlighted and the dark parts of the image, which is crucial in case of non-diffuse lighting in the photo shoot. It is usually carried out in a balanced combination with *smart lighting*.
- *ClearView/Dehaze* (available only in some software packages) enables improvement of the contrast and sharpening of the image by removing the effects of atmospheric haze or fog.
- Within the *contrast enhancement* option, *microcontrast* and *finecontrast* sub-options are usually available. Microcontrast enhances micro details or softens them, and can be used to shadow detail recovery.
- In most software, the two tools are merged together as one common tone mapping function. Within it, especially *white clipping point* and *black clipping point* options can influence the level of highlighting of small details, which is particularly useful for a textured image or when one needs to compensate for the lack of sharpness. Finecontrast enhances or softens medium-sized details. Furthermore, in most software, there is a possibility to constrain the effect of contrast on highlights, midtones (e.g. *Clarity* available in particular software) or shadows.
- For sharpening the image, the *unsharp mask* or *masked sharpening* is the most important tool. The tool adjusts the intensity, which determines the level of sharpening of the whole image. *Radius* sets the thickness of the sharpened edges. The *threshold* is a masking option of the tool; it sets the level above which details will be sharpened or, in other words, masks the parts of the image that will thus not be sharpened.¹⁴ Values that are too low may give sharper image but, on the other hand, amplify noise. Software masking can also be applied for determining the level of sharpening.

13 The aperture substantially determines the depth of field (DOF). The bigger the DOF, the higher the overall sharpness of the image.

14 Some software packages use the term 'threshold' and some use the term 'masking'.

- *Chromatic aberration* decreases aberrations introduced by the lenses (i.e. colour artefact that can appear in the areas of transition between dark and bright zones). Besides the intensity, the size and purple fringing should also be set. The size adjusts the width of the fringe to be suppressed. Purple fringing removes the ‘ghost’ in the form of purple fringe that appears along high-contrast edges of the image.
- *Noise reduction* is a tool included in all image processing software, but equipped with different levels of strength. In most cases, *luminance* (reduces fine grain) and *chrominance* (reduces colour artefacts) noise reduction options are offered separately.

In some cases, it is necessary to augment the curvature and plasticity of a structure to the level that lies far beyond the power of the above-mentioned tools. This may be required when documenting walls covered with fine, monochromatic plaster. Such structures display very low colour differentiation and curvature, which hampers SIFT point creation. In such a situation, HDR (High Dynamic Range) approach is required, which is able to enhance even very small variations in curvature and colour hue. HDR can be generated in special software by processing at least three exposure-bracketed photos, or within single RAW photo through the application of HDR filtering. In the first case, the procedure is based on the fusion of exposure of several photos taken with different exposure values¹⁵ and from the same position. In the second case, the procedure is based on the fusion of exposure values of the RAW file generated in a specific photo-editing software.¹⁶ The key goal of HDR photography is to maintain stability by taking bracketed photos in order to avoid blurring during processing.

Software	Web	License	Platform PC=Windows Mac=Mac OS
Adobe Photoshop Camera RAW	http://www.adobe.com/products/photoshop.html	commercial	PC, Mac
DxO Optics Pro	http://www.dxo.com/us/photography/photo-SW/dxo-opticspro	commercial	PC, Mac
Adobe Lightroom CC	http://www.adobe.com/sk/products/photoshop-lightroom.html	commercial	PC, Mac
ACDSee Ultimate	http://www.acdsee.com/en/products/acd-see-ultimate	commercial	PC, Mac
Phase One Capture One Pro	https://www.phaseone.com/en/Products/SW/Capture-One-Pro/	commercial	PC, Mac
Apple Photos	http://www.apple.com/macos/photos/	open-source	Mac
Serif Affinity Photo	https://affinity.serif.com/en-gb/photo/	commercial	Mac
ON1 Photo 10	https://www.on1.com/products/photo10/	commercial	PC, Mac
MacPhun Creative Kit	https://macphun.com/creativekit	commercial	Mac
RAWTherapee	http://RAWtherapee.com	open-source	PC, Mac, Linux
1. Picasa	www.picasa.google.com		PC, Mac
2. GIMP	www.gimp.org	open-source	PC, Mac, Linux
3. Paint.NET	www.getpaint.net		PC

Table 4. Overview of the most commonly used RAW file editing software.¹⁷

15 At least 3 photos should be taken, preferably with the help of tripod: one photo with custom exposure, one underexposed and one overexposed.

16 Most of the currently available photo-editing software enable generation of several exposure values in one RAW file.

17 In case of open-source software, there can be limitations in the readability of particular RAW files, and some of the editing tools mentioned in the text may be missing.

Software	Web	License	Platform PC=Windows Mac=Mac OS
Aurora HDR	http://aurorahdr.com	commercial	Mac
EasyHDR	http://www.easyhdr.com	commercial	PC, Mac
Photomatix Pro	http://www.hdrsoft.com	commercial	PC, Mac
HDR Projects 4	http://www.projects-SW.com	commercial	PC, Mac
Oloneo HDR	http://www.oloneo.com	commercial	PC
SNS-HDR	http://www.sns-hdr.com	commercial	PC
Machinery HDR	http://www.machineryhdr.com/	commercial	PC
Dynamic Photo HDR 5	http://www.mediachance.com	commercial	PC, Mac
HDR Expose	http://pinnacleimaging.com	commercial	PC, Mac
HDR Efex Pro	http://www.google.com/nikcollection	commercial	PC, Mac
Luminance HDR	http://qtpfsgui.sourceforge.net	open-source	PC, Mac
Picturenaut	http://www.hdrlabs.com	open-source	PC, Mac
Fusion HDR	http://fusion-hdr.com	commercial	PC

Table 5. Overview of the most commonly used HDR software.

Software	Web	License	Platform PC=Windows Mac=Mac OS
Adobe Photoshop	http://www.adobe.com/products/photoshop.html	commercial	PC, Mac
DxO Optics Pro	http://www.dxo.com/us/photography/photo-SW/dxo-opticspro	commercial	PC, Mac
Adobe Lightroom CC	http://www.adobe.com/sk/products/photoshop-lightroom.html	commercial	PC, Mac
ACDSee Ultimate	http://www.acdsee.com/en/products/acdsee-ultimate	commercial	PC, Mac

Table 6. Overview of the most commonly used software enabling HDR filtering.

All the above-mentioned principles of photo shooting strategy tend to generate RAW files with the as big depth of field (DOF) as possible within the given lighting conditions. Processing RAW files should lead to the achievement of a maximum possible level of contrast without producing artificial unwanted noise. Balancing these two requirements is a key factor in mastering the processing procedure (Figs. 12, 13).

After processing the RAW files, it is necessary to save it in common readable file, either JPG, PNG or TIFF. The best solution is to opt for TIFF file, which can contain former uncompressed photo resolution.

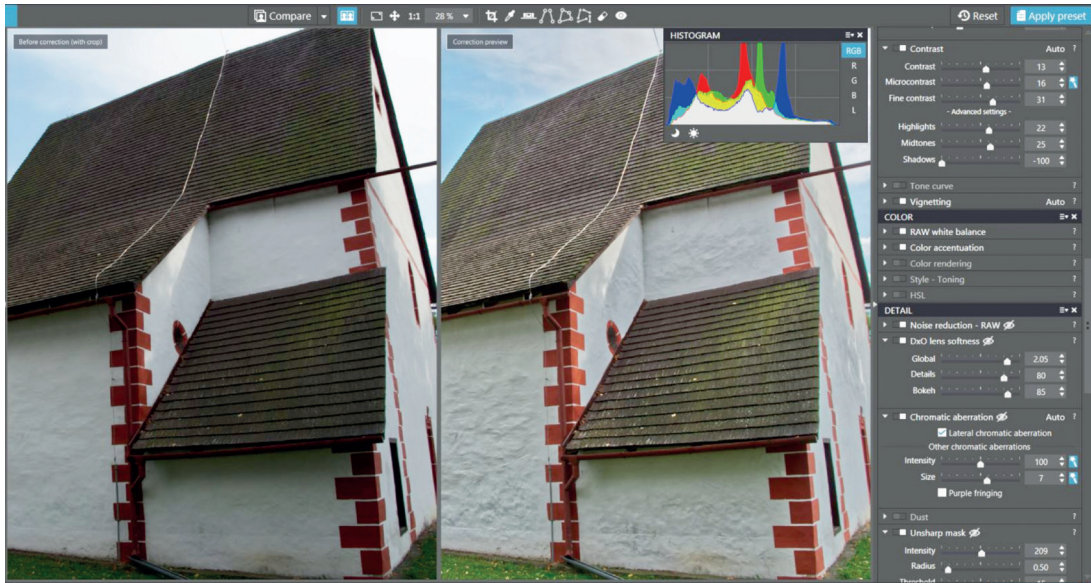


Figure 12. Processing RAW files. An example of an image before and after correction. DxO Optics Pro interface.

Data processing and post-processing: software applications

Every software package has its own characteristics. Nevertheless, there are several basic rules that apply to all software solutions. In the first step, all edited photographs prepared to be processed should be finally checked for sharpness and image quality artefacts (e.g. hot pixels or bending) and in the case of poor quality, they should be eliminated. Most software enables this through the native procedure.

After loading photos to working directory or working interface, it is always desirable to check for camera calibration parameters. Most software use automatic calibration procedure according to available EXIF data of particular photos. Refinement of calibration is done through alignment of photos when the inner camera (principal point, radial, and tangential lens distortion coefficient), as well as outer camera orientation (position of the camera in space), is calculated. In the case of wide angle lenses or the absence of EXIF data whole calibration information should be done manually according to the particular workflow of a given software. Masking photos is an optional step. It is used to eliminate the background or other features that might cause alignment errors (e.g. the wind can cause some movement in the background which may disable the alignment). However, background features are usually useful for the alignment. Masking itself can be done either in a native IBM software or in a third-party software¹⁸ (e.g. in Adobe Photoshop) and imported as an alpha channel.

Distribution of sparse point cloud as a product of photos alignment step can be refined through optimization of re-projection error parameters¹⁹ as well as through ((G)CP) with exact coordinates measured either by total station or differential GPS GNSS RTK rover.

18 Masking may be very useful when digitising portable artefacts, e.g. a museum collection. In this case, it is usually necessary to outline sharply the edges of an artefact against the background.

19 It is reasonable to achieve a RMS re-projection error of under 1px. The refinement procedure should be carried out carefully in order not to delete too many points by lowering the mean re-projection error value as this may disrupt coherency of the whole alignment.

Measured data are put into adequate markers detected or manually created on particular photos. Via (G)CP application and the correct coordinate reference system assignment, the global georeferencing and scaling of the scene is carried out. If no coordinates are known but some distance values are available, these can be used for scaling the scene by markers as well. The final step includes dense cloud generation and subsequent meshing and texturing. The whole process is done via software's native algorithm. Most software usually enable basic editing of the mesh and texture (above all decimation²⁰). It is however highly recommended to perform mesh editing in third party software.

Post processing strategy can be divided with reference to demands on the final output of the project. It can be 2D vector output, 2.5D digital elevation data (DEM) or fully 3D solid model. In the first two cases, 3D data are used as a mean for the extraction of 2D/2.5D data. Most lbM software offer additional functionalities such as scaling, georeferencing, georeferenced orthophoto plans and DEM extraction, which can be done in an easy straightforward manner. Once setting appropriate coordinate system and subsequent assignment of measured GCP to model or photos in lbM native software, georeferenced orthophoto plans with word file as well as georeferenced GeoTiff containing DEM are automatically exported with the given parameters (mainly resolution). These data can be subsequently put into GIS or CAD software for further processing (vectorisation, cross section generation) or visualisation. DEM creation is widely applicable in landscape survey while georeferenced orthophoto plans and their CAD vectorisation are broadly used in architectural and archaeological documentation.

In case that final output is a solid 3D model either in mesh or NURBS form, it is necessary to edit mesh in external software. The main aspects of such editing are cleaning, denoising, simplification in sense of decimation²¹, holes filling and finally retopologisation. Mesh retopology is usually a quite sophisticated procedure that is carried out by professionals. Its basic goal is to achieve selective simplification of the mesh while maintaining all the necessary details. Optionally it can involve transferring the triangulated mesh into quad variant which can be more precisely converted into NURBS, it means CAD friendly file format.

Custom UV²² texture map creation is very often part of retopology workflow as well. Most native lbM software generates texture parameterization which is very fragmented and thus not suitable for further editing like unwrapping or changing colour hue and saturation. Therefore, it is convenient to create UV map in special modeling software and import it back into lbM where texture information can be projected upon newly created parameterized UV map. Once a cleaned and retopologised mesh optionally converted into NURBS is created, it can be used as a source for wide range of virtual reality applications.

20 I.e. reduction of the size of the mesh by reducing the number of triangles it contains.

21 Decimation (reduction of triangles) of the produced mesh is the crucial operation, since the mesh usually contains up to tens of millions of triangles which is difficult to deal with in any software.

22 UV is used as an alternative expression for X and Y coordinates.

Software	Web	License	Retopology	Custom UV map
Geomagic Design X	http://www.rapidform.com/products/xor/overview/	commercial	yes	no
Geomagic Wrap	http://www.geomagic.com/en/products/wrap/overview	commercial	yes	no
PolyWorks	http://www.innovmetric.com/	commercial	yes	no
ZBrush	https://pixologic.com/	commercial	yes	yes
Autodesk Maya	www.autodesk.com/products/maya/overview	commercial	yes	yes
Autodesk 3DS Max	www.autodesk.com/products/3ds-max/overview	commercial	yes	yes
Autodesk MudBox	www.autodesk.com/products/mudbox/overview	commercial	yes	no
MeshLab	meshlab.sourceforge.net/	open-source	yes	yes ⁴⁹
Blender	https://www.blender.org/	open-source	yes	yes
3D Coat	3dcoat.com	commercial	yes	yes
Modo	https://www.thefoundry.co.uk/products/modo/	commercial	yes	yes
Instant Meshes	https://github.com/wjakob/instant-meshes	open-source	yes	No

Table 7. Commonly used mesh editing software.

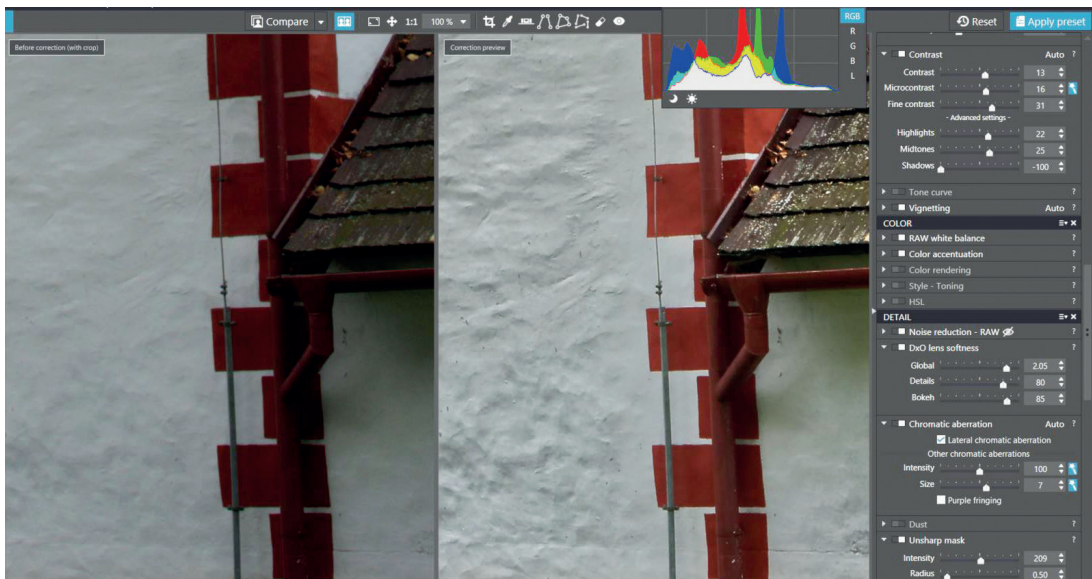


Figure 13. Processing RAW files. An example of an image before and after correction. Detail. DxO Optics Pro interface.

3D RECORDING IN ARCHAEOLOGICAL PRACTICE

Ján Zachar & Milan Horňák (Via Magna)

Within the framework of the preventive archaeology concept, the documentation of archaeological cultural heritage plays a crucial role. Until recently, the sphere of cultural heritage was dominated by tools of traditional 2D documentation, which were gradually expanded with modern geodetic tools such as the total station (TS) and differential GPS. However, these tools did not present any essential breakthrough in the documentation practice. It was basically an extrapolation of 2D documentation from analogue to the digital sphere. The real turning point came only with the mass expansion of 3D technologies into individual industrial sectors. The change was in the different concept of reality perception for the needs of the documentation practice. Recently, 3D documentation procedures have started to be applied more significantly also in the area of rescue archaeology.

One of the project CONPRA objectives was to test possibilities of application of 3D technologies in the recording practice of archaeological research, i.e. to verify their potentials and limits. It is especially the preventive archaeological research with its demands for tight time and budget schedules where suitable preconditions for the application of state-of-the-art technologies are created, especially from the perspective of the possibility to shorten the recording works in the excavation process. 3D technology also provides a significant improvement as to the accuracy of the documentation. On the other hand, general limiting factors of 3D documentation must be also taken into the account and problematic aspects of their utilisation, difficulties related to the application of individual procedures, as well as possibilities of dealing with the said in practice, must be also pointed out.

Archaeological cultural heritage is an internally structured category. However, for the purpose of the documentation practice, we can basically speak about the documentation

of ongoing archaeological research, whether rescue or so-called scientific, or about the documentation of partially preserved archaeological locality adjusted or secured for the purposes of tourism (e.g. archaeoparks). It is equally important in both cases to determine the morphological structure of the cultural monument; for example, whether it is dominated by a pedological component or by architectural elements (in case of documentation of ongoing archaeological research), or what terrain adjustments need to be conducted (e.g. in case of archaeo-parks). Each one of the mentioned aspects affects in its own way the work methodology and the results.

Here we present a selection of case studies with the aim to demonstrate possibilities and limits of 3D documentation in the context of various site situations. The presented models are mainly related to the conditions typical for Central Europe. All case studies were processed in a workstation with the following components: Intel(R) Xeon(R) CPU E5-2620 v2@ 2,10 GHz, RAM 128 GB, GPU NVIDIA GeForce GTX 780 3GB, OS W7; or in notebook Lenovo Y50 with these components: Intel(R) Core(TM) i7- 4710HQ CPU@ 2,50 GHz, RAM 16 GB, GPU NVIDIA GeForce GTX 860M, OS WIN 8. In the case of TLS application, the resolution was always set to 6 mm per 10 metres. For lBM, two types of software were used: Agisoft Photoscan and CapturingReality RC.¹ In Photoscan the following parameters were set for the batch processing workflow: step – align photos (high accuracy with the key point limit of 40,000 points and the tie point limit of 20,000 points); step – refinement of alignment (decreasing of global re-projection error to at least 1px); step – build dense point cloud (medium quality, aggressive depth filtering); step – build mesh (arbitrary surface type, dense point cloud as source data, interpolation enabled, custom face count: various values); and step – build texture (generic mapping mode, texture from all cameras, blending mode Mosaic, texture size 8192, texture count 1, and no colour correction). In case of RC software, the parameters were as follows: step – align photos (+ laser scans) (max. feature per image 120,000, pre-selector feature 60,000, image overlap medium, detector sensitivity medium, max. re-projection error 2px); step – reconstruction (normal detail); step – build texture (Guter 3, texture resolution 8192, large triangle removal threshold 10, maximal texture count style, visibility based texture style).

SITES WITH SOIL LAYERS AND SEDIMENTED DEPOSITS

Situations in which the pedological component is the dominant are a product of archaeological investigations that expose anthropogenic soil sediments. These are usually cultural layers which can represent or contain remains of former lowland or hilltop settlements, open or fortified, with buildings and other structures made of stone, wood and/or earth. These localities display only a low value of local micro-elevation. From the perspective of local morphology, this can either be flat, horizontal or inclined surfaces. The exception are hilltop-fortified settlements – hill-forts – where possibly significant local elevation can be present due to the existence of a fortification system (e.g. rampart).

This type of localities is currently a frequent area of research of preventive archaeology performed outside the settlement area. After the top vegetation layer is removed by mechanisation, individual anthropogenic layers are gradually excavated. Before the onset

¹ The application was chosen on the grounds of the license availability.

of 3D technologies, the said type of localities was documented by means of drawing archaeological situations, features and objects, or was recorded with the total station or differential GPS.

Radola, Koscelisko

Site type:	Mound
Location:	Radola (Žilina district Žilina, NW Slovakia); location Koscelisko
Dating:	Late Bronze Age
Research type:	Research for scientific and documentation purposes
Recording technology:	lBM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), TS, GNSS RTK Rover (differential GPS)
Software:	Agisoft Photoscan 1.2.6, AutoCad Civil 3D 2016 student version
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figs.14-16).
Short description:	The archaeological site was documented solely by lBM. The research was initially performed using test pits, which were then enlarged in order to expose the whole ground plan of the site composed of a stone ring of the original mound and a centrally located urn. In addition to the final stage of the research, the documentation also captured individual stages of the excavation. A handheld camera was used for the collection of data.



Figure 14. *Radola, Koscelisko (Slovakia). Burial mound, Bronze Age. lBM (180 photos, 24 Mpx). Textured 3D model.*

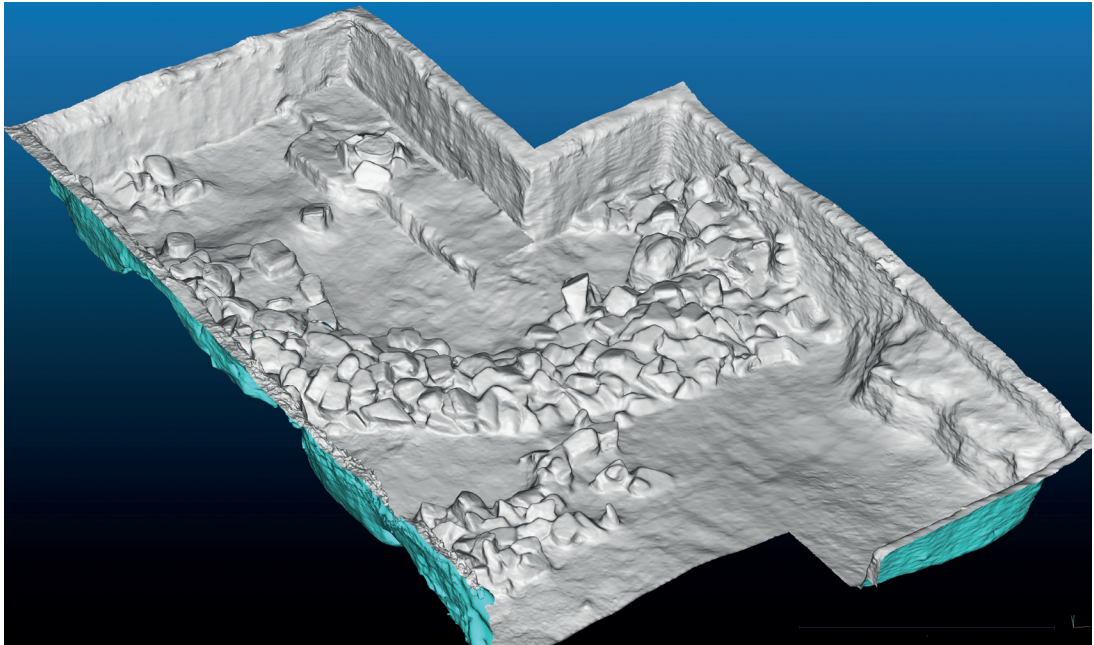


Figure 15. Radofa, Koscelisko (Slovakia). Burial mound, Bronze Age. IbM. Shaded 3D model.

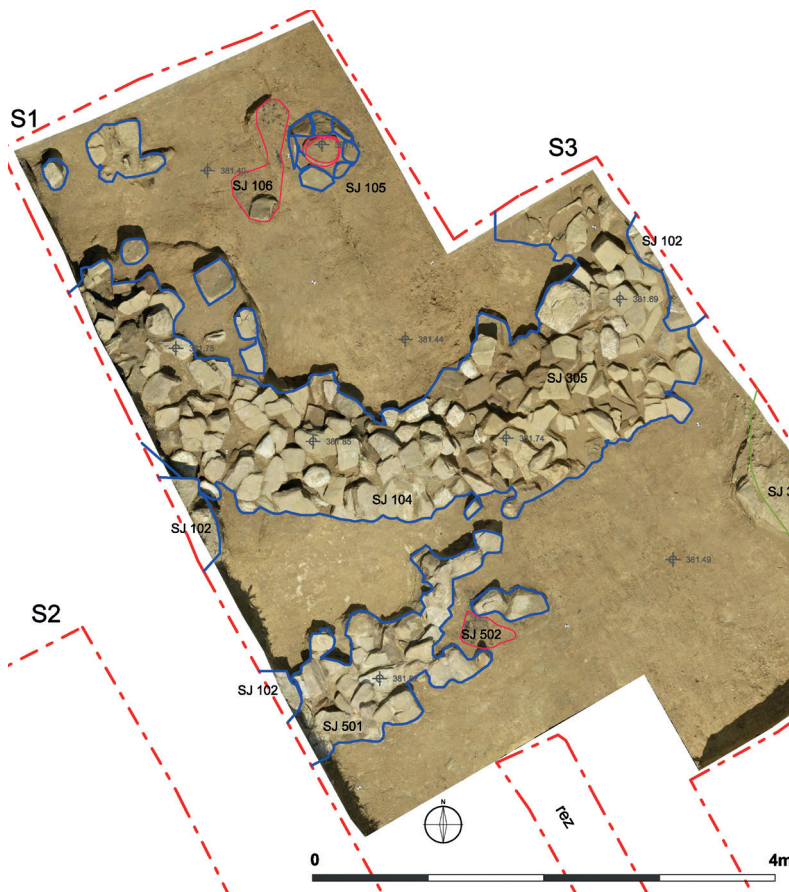


Figure 16. Radofa, Koscelisko (Slovakia). Burial mound, Bronze Age. An example of 2D documentation deliverables – vectorisation of the georeferenced orthophoto plan derived from the 3D model.

Rajec, Charubina

Site type:	Settlement
Location:	Rajec (district Rajec), location – Charubina, NW Slovakia
Dating:	Late Bronze Age, Middle Ages (12th – 13th century)
Research type:	Preventive research
Recording technology:	IbM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), TS, GNSS Rtk Rover (differential GPS)
Software:	IbM
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figs. 17, 18).
Short description:	The excavated site probably represents a large settlement from the Late Bronze Age and High Middle Ages. A residential structure with remains of a wall with external cladding was revealed, as well as several locations with significant accumulations of ceramics, scree and charred material. The excavations revealed a flat micro-relief, i.e. without any elevations. Individual stages of the excavation of the remaining traces of housing from the Bronze Age, as well as the individual accumulations of ceramic fragments were documented using IbM. No monopod stand or an UAV were used for the collection of raw data. TS was used for the measurement of GCP.

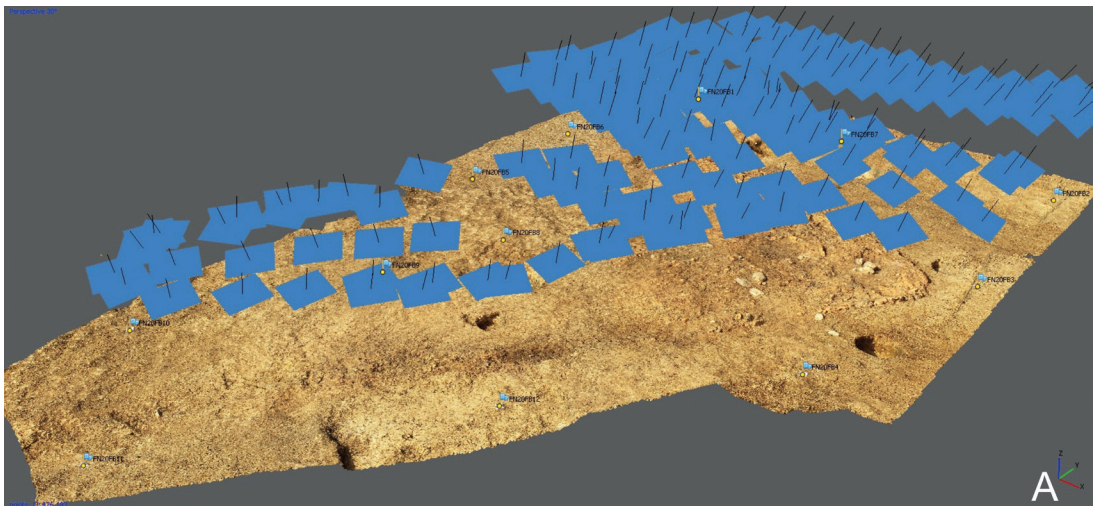


Figure 17A. Rajec, Charubina (Slovakia). Remains of dwellings from the Bronze Age. 3D model. IbM (193 photos, 12Mpx). Position of the cameras during data acquisition, B: textured 3D model, C: shaded 3D model.

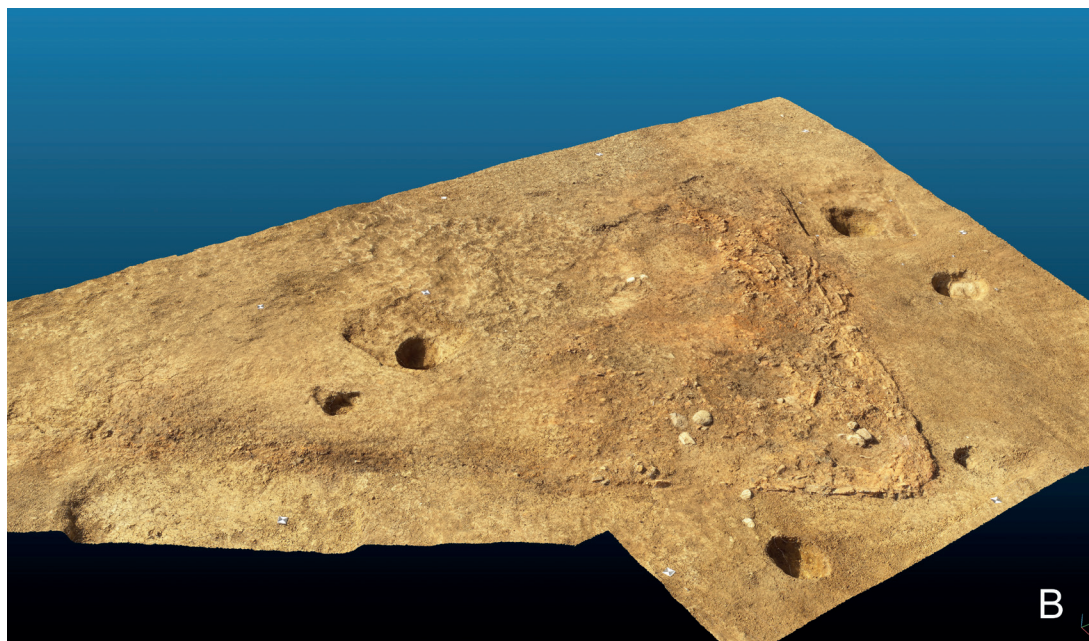


Figure 17B. Rajec, Charubina (Slovakia). Remains of dwellings from the Bronze Age. 3D model IBM (193 photos, 12Mpx). Textured 3D model. C: shaded 3D model.

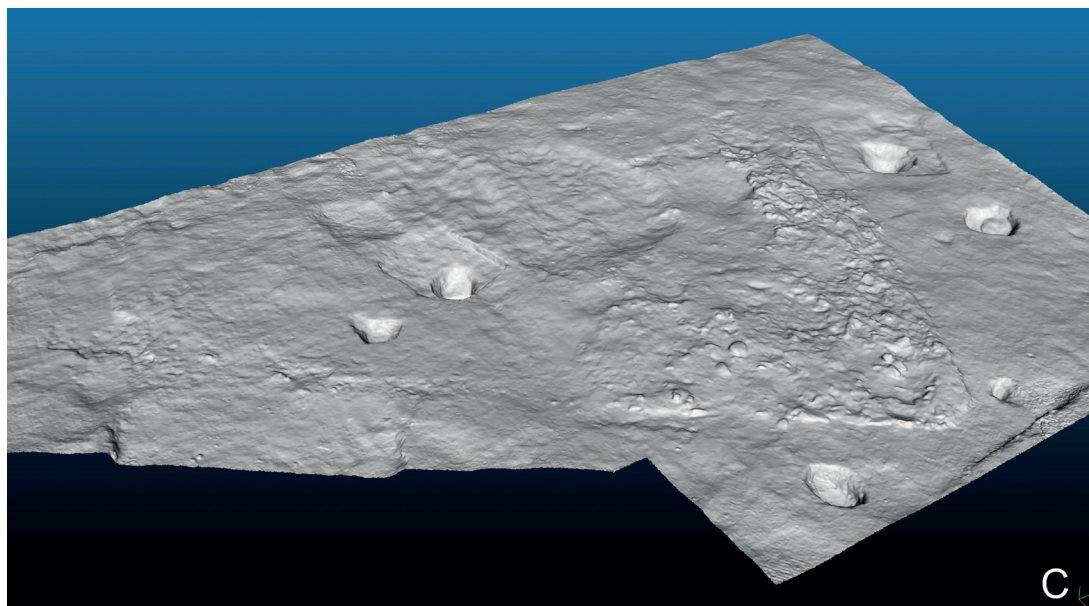


Figure 17C. Rajec, Charubina (Slovakia). Remains of dwellings from the Bronze Age. 3D model. IBM (193 photos, 12Mpx). Shaded 3D model.

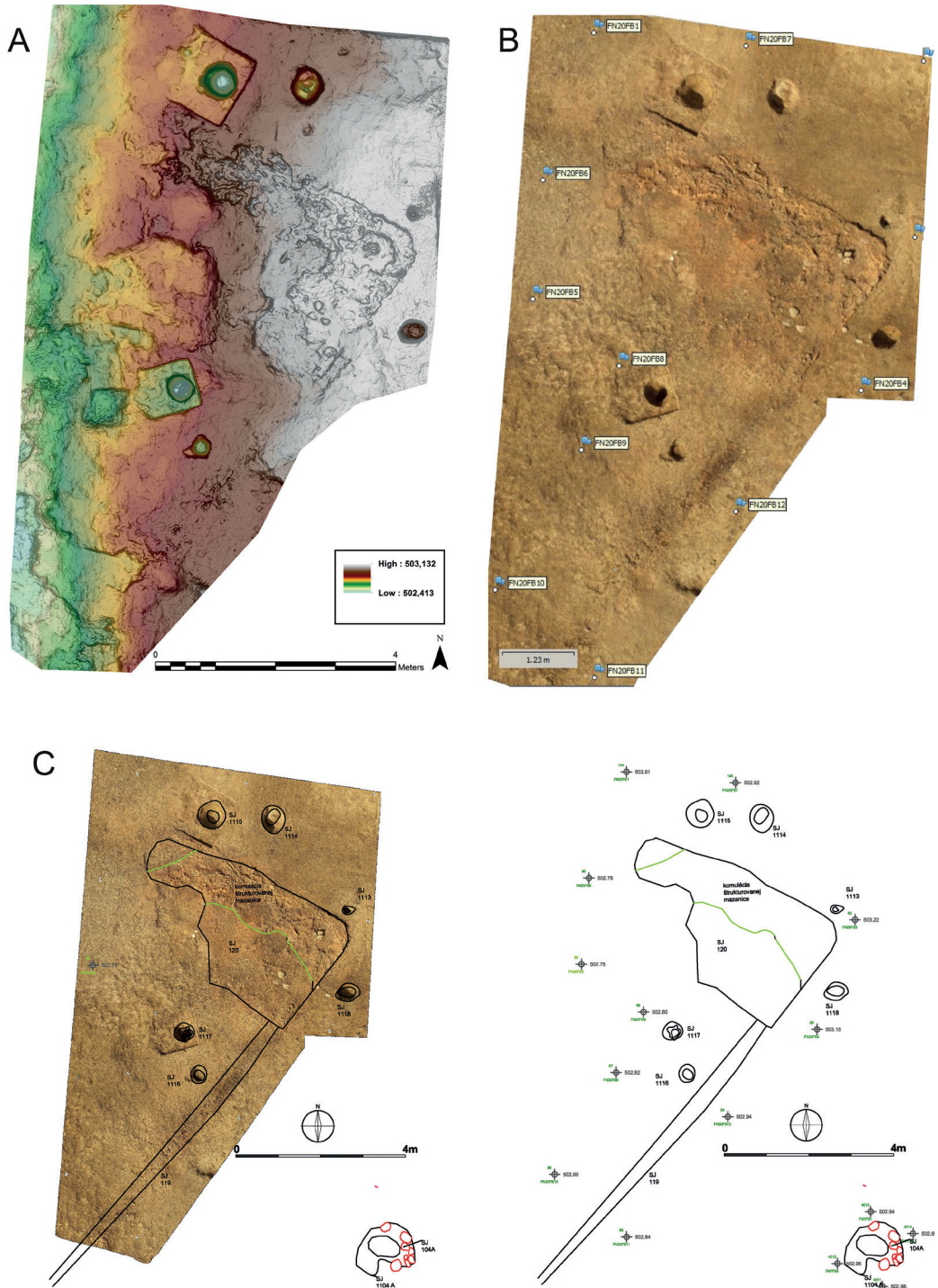


Figure 18. Rajec, Charubina (Slovakia). Remains of dwellings from the Bronze Age. An example of 2D documentation. A: digital elevation model (DEM), B: georeferenced orthophoto plan derived from the 3D model, C: vectorisation of the georeferenced orthophoto plan.

Mošovce, Hinterland of the residential area

Site type:	Settlement and its surroundings
Location:	Mošovce (district Turčianske Teplice), NW Slovakia
Dating:	Late La Tène period through later Roman period
Research type:	Preventive research
Recording technology:	lBM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), Nikon D90, TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan 1.2.6, AutoCad Civil 3D 2016 student version
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figs.19, 20).
Short description:	Although the site is situated in a considerably dynamic landscape, with significant elevation differences, the archaeological excavation revealed a flat micro-relief. The research included recording of the area disturbed by present-day logging. lBM was aimed at capturing profiles of the current road communication within partially disturbed settlement structures and cultural layers, as well as for a smaller area showing evidence of prehistoric metallurgical activities.

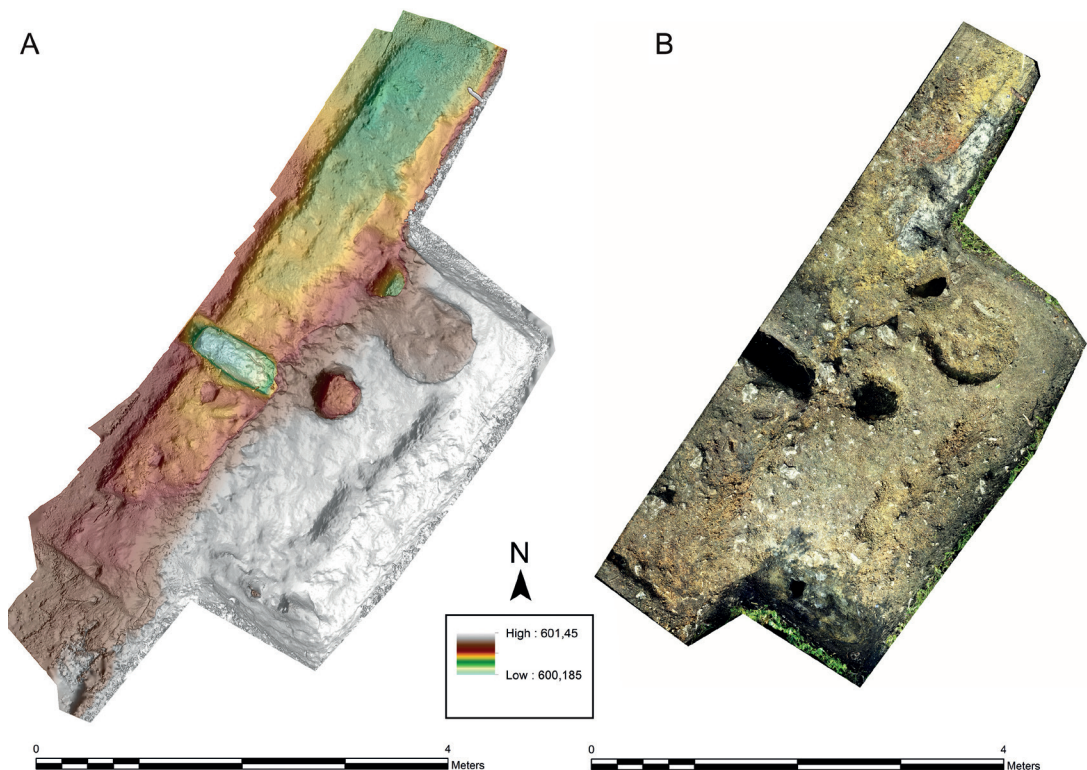


Figure 19. Mošovce (Slovakia). Remains of an Early Roman industrial area. An example of 2D documentation. A: DEM, B: georeferenced orthophoto plan derived from the 3D model.

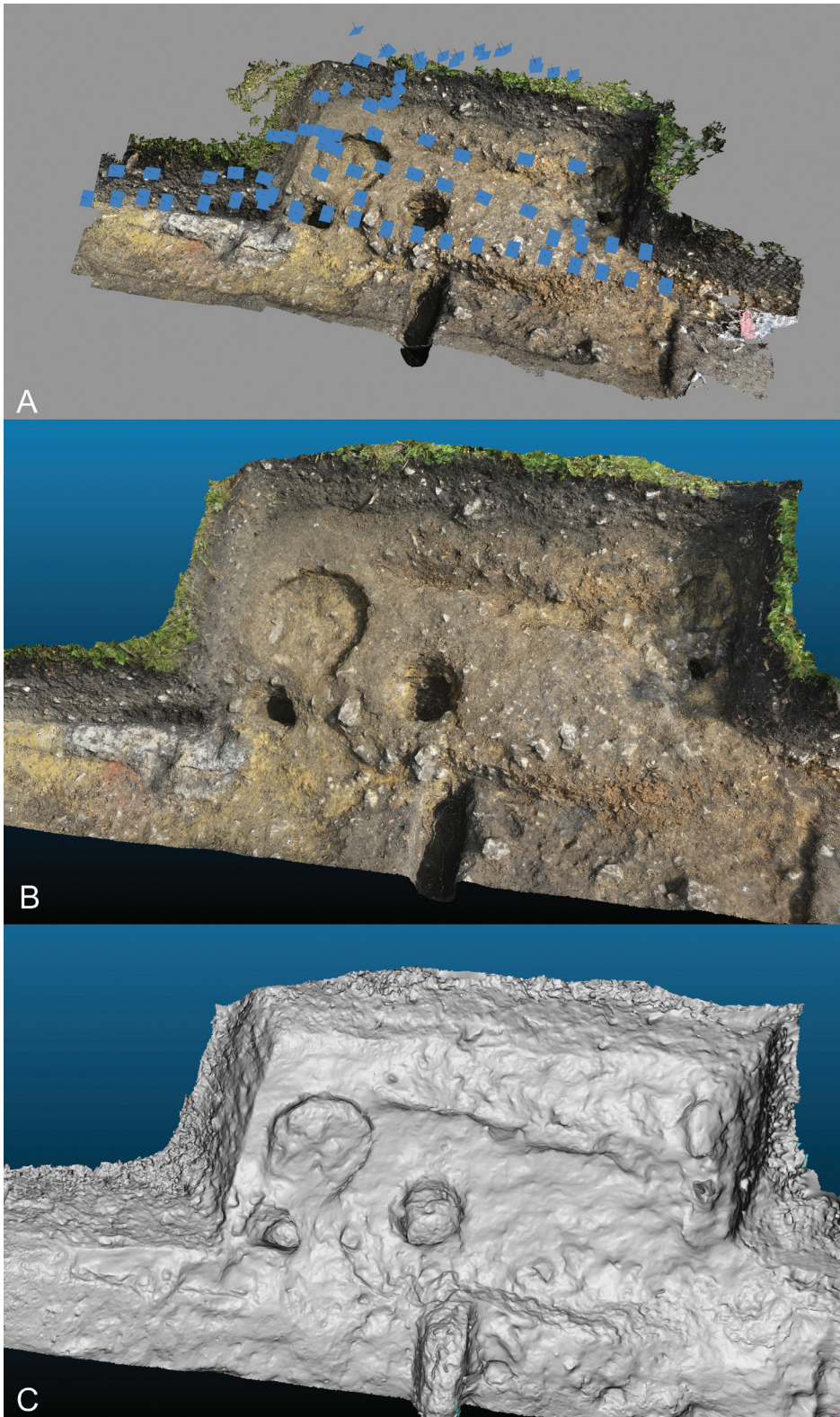


Figure 20A-C. Mošovce (Slovakia). Remains of an industrial zone, early Roman period. lBM (78 photos, 12Mpx). A: position of the cameras, B: textured 3D model, C: shaded 3D model.

Bratislava, Castle

Site type:	Castle and settlement area
Location:	Northern terrace of the Bratislava Castle, SW Slovakia
Dating:	10 th -12 th century A.D.
Research type:	Preventive excavation
Recording technology:	IbM
Recording equipment:	Camera Sony Nex 7, unmanned aerial vehicle (UAV), TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan 1.0.0, CloudCompare, AutoCAD Civil 3D 2016 student version.
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figure 21).
Short description:	Bratislava castle was subject of preventive excavations between 2008 and 2014. In the years 2013 and 2014, 3D recording of the excavated areas was the main method of recording the general and partial ground plans and sections. The area of the northern terrace contained several significant architectural remains. The site contained abundant anthropogenic evidences also in the soil which were also investigated. They consisted of a sequence of cultural layers and imprints of structures, indicating an open settlement dated to the 10 th -12 th century AD. The recording was performed by IbM. An UAV was used for collecting the raw data (vertical low-flight level photos). Due to flat terrain morphology the vertical images were not complemented by oblique photos.

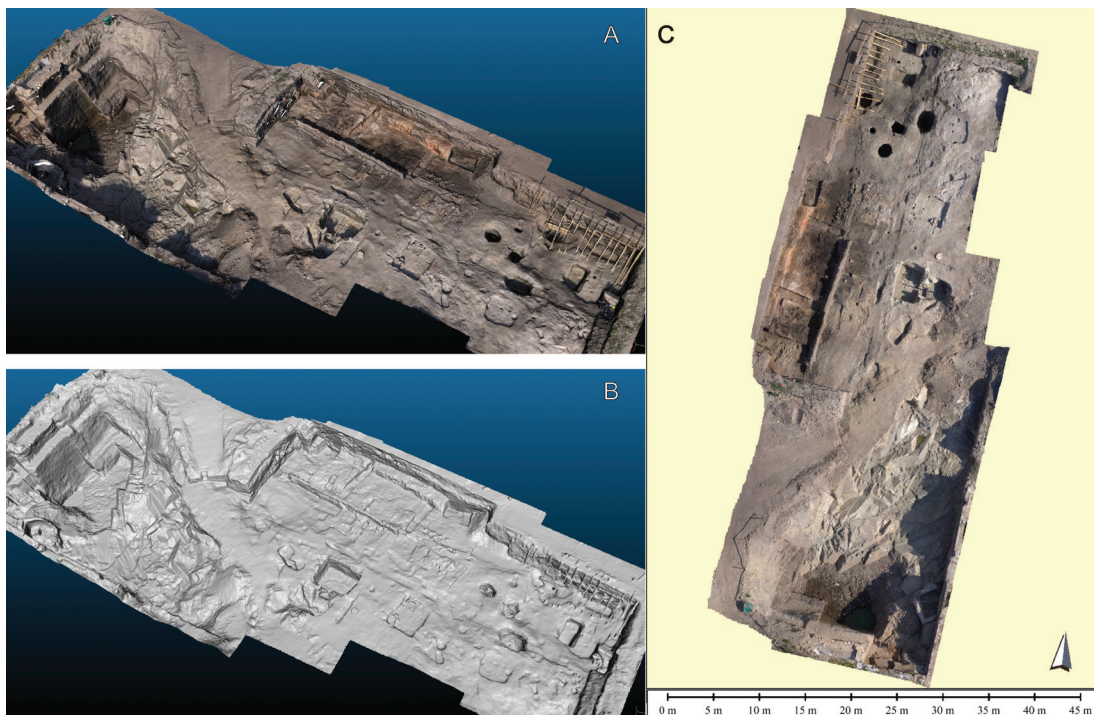


Figure 21. Bratislava, Castle, northern terrace. Remains of the open settlement, partly destroyed by a later quarry, 10-12th century. 3D model. IbM (352 photos, 12Mpx). A: textured 3D model, B: shaded 3D model, C: georeferenced orthophoto plan.

SITES WITH ARCHITECTURAL REMAINS

Archaeological sites with significant architectural remains are typical for urban areas, where they represent the product of urbanisation process. They are characterised by a high level of local micro-elevation, the degree of which is determined by the level of preservation of the masonry. Some specific examples of these are castles, where significant quantities of debris occur, in addition to the compact components of the masonry.

Archaeological research of the sites of this type is usually performed in close cooperation with the research on the history of construction. Particular attention is paid to capturing mutual relationships of the masonry and the anthropogenic soil deposits (designated backfill areas, walking surfaces, cultural layers, etc.), which should reveal general aspects of the historical development of the construction. Previously, a frequently used method of documentation of this type of sites was 2D photogrammetry, which enabled capturing the complex structure of the surface with individual details of the architecture. However, its substantial disadvantage is the radial and tangential distortion of the 2D orthophoto plans, especially in the case of a significant elevation of masonry constructions compared to the level of the surrounding ground; this can markedly reduce the accuracy of the geodetic plan of the site.

Senec, Synagogue

Site type:	Synagogue and its immediate surroundings
Location:	Senec town, District of Senec, SW Slovakia
Dating:	19 th century
Research type:	Research for scientific and documentation purposes
Recording technology:	IbM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan 1.2.6, AutoCad Civil 3D 2016 student version, CloudCompare 2.8
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans and cross-section views (Figs. 22-24).
Short description:	<p>The production-related part of the synagogue was seen in a significantly destroyed architecture consisting of brick walls with cladding, a preserved furnace and a ritual bath (mikveh). IbM was used for documenting the process of research by recording the individual stages of cleaning of different spatial segments. The overall model was created by joining models of the parts using referential GCP. Since high monopod stand or drone were not used for the collection of the data, the crowns of higher walls have, in some places, digitisation shadows. However, the rate of coverage and capturing with the 3D model is relatively high with regard to the tools used (a simple ladder). Moreover, special attention was paid to the 3D documentation of the furnace, which was planned for dismantling and relocating. Cross- and longitudinal sections were made for this purpose, which subsequently served as an input for the creation of paper models at 1:1 scale used for the reconstruction of furnace at the original scale. Exterior and interior of the furnace were separately recorded (IbM). A torch was used for the collection of raw data of the interior.⁵¹ The use of torch was not a markedly limiting factor in the processing of data, and the resulting 3D model did not show any significant deviation in terms of clarity of the surface geometry. In terms of the texture, it is understandable that the colour scale of the input data (i.e. photos) shifted chromatically (torch light), which also rendered the colour texture of the 3D model of the furnace interior artificial. The use of torch can thus be considered as a partially limiting factor. The 3D model of the furnace exterior was connected with the 3D model of its interior (common reference points defined arbitrarily in Agisoft Photoscan). The sections were made in CloudCompare and were subsequently saved for further processing of the architectural model in native CAD format (dwg).</p>

2 The use of torch is generally not recommended in photo-shooting for the image based modelling, but given the absence of any other light source, this was the only possible solution in this case. Moreover, it provided an opportunity for testing the flash usage and its effect in the subsequent data processing.

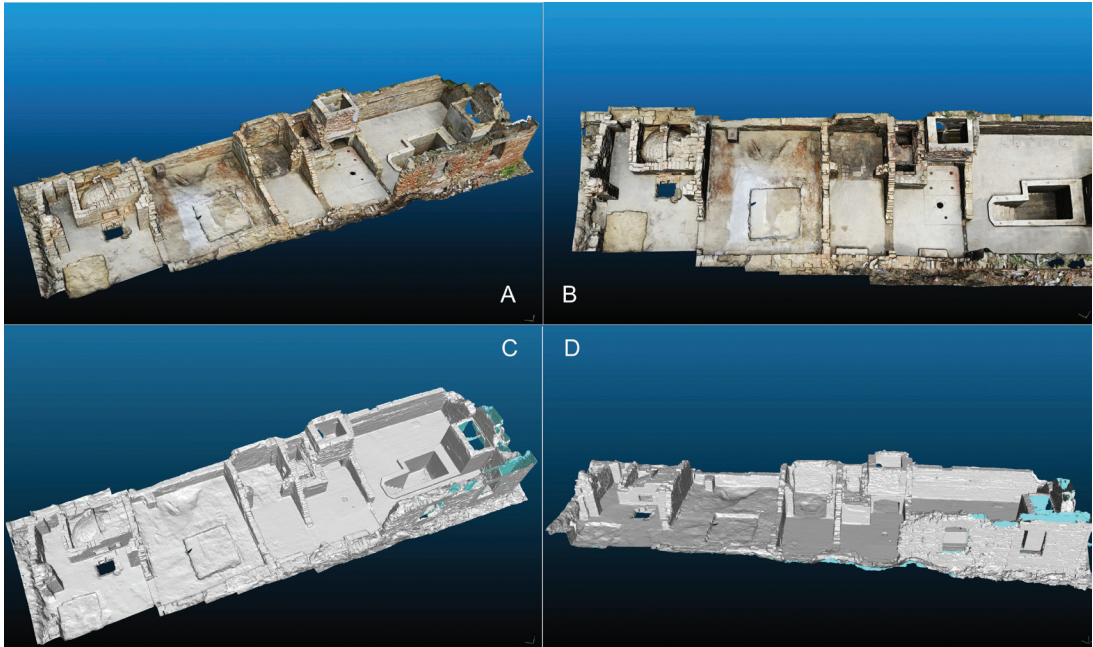


Figure 22. Senec, Synagogue (Slovakia). Remains of the economic section of the synagogue, with an oven and a mikveh, 19th century. lBM (1452 photos, 24 Mpx).
A, B: textured 3D model, C, D: shaded 3D model.



Figure 23. Senec, Synagogue (Slovakia). Remains of the economic section of the synagogue. Cross-section documentation derived from the 3D model.

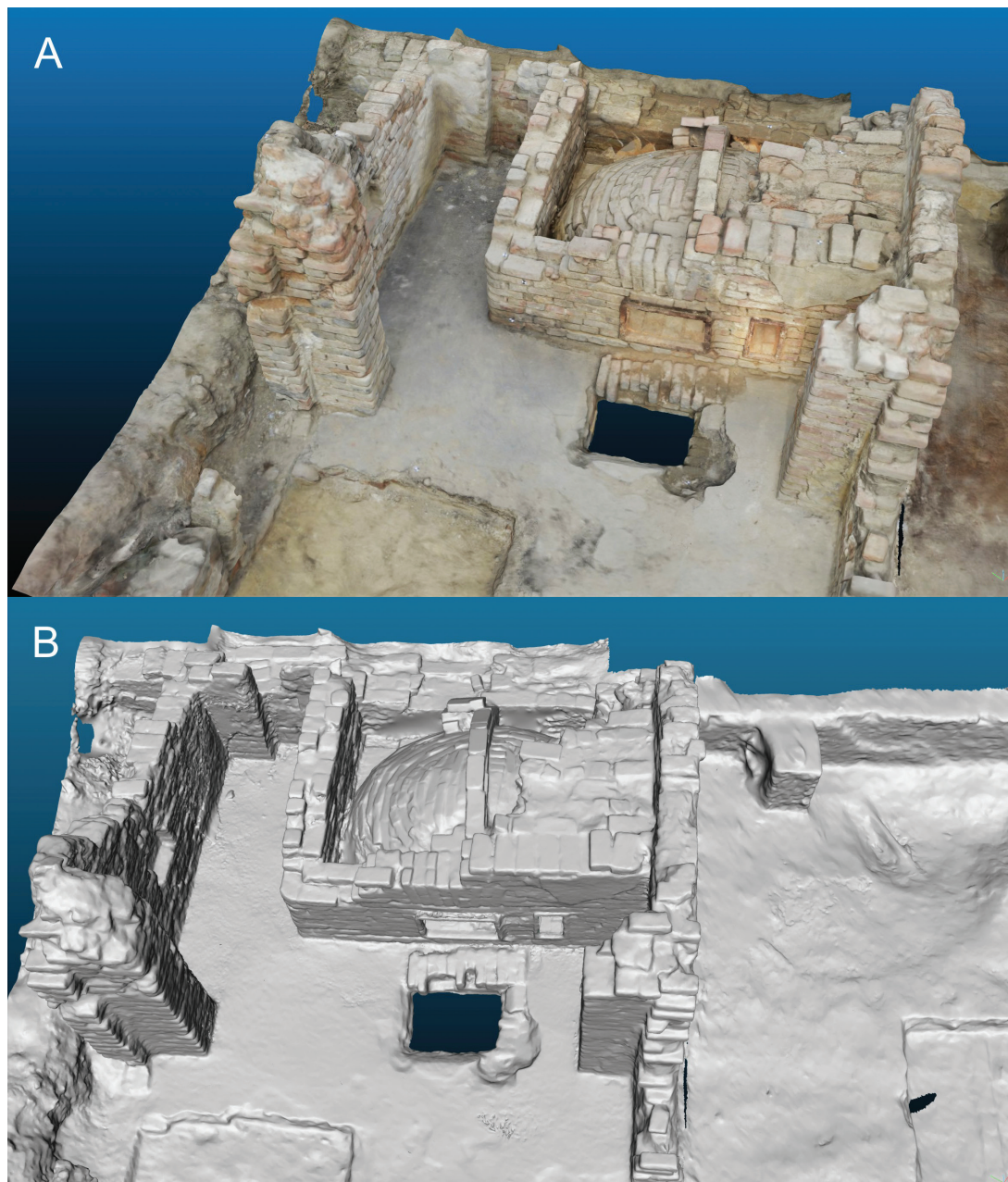


Figure 24. Senec, Synagogue (Slovakia). Remains of the economic section of the synagogue – detail of the oven, 19th century. IbM. A: textured 3D model, B: shaded 3D model.

Skalka nad Váhom, Monastery

Site type:	Monastery complex (Benedictines; Jesuits from the 17th century)
Location:	Skalka nad Váhom (district Trenčín), location – outside municipal/residential area
Dating:	14 th -18 th century
Research type:	Preventive research
Recording technology:	IbM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan, AutoCad Civil 3D 2016 student version, CloudCompare 2.8
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figs. 25, 26).
Short description:	The premises of the Benedictine (later Jesuit) monastery are situated under a high rocky overhang. The research was focused on the significantly destroyed area of the western part of the former convent, whose one side leaned against the rock whereas the other side was open to the area of viridarium. The convent area is significantly affected by destruction of the masonry and the debris infills. The 3D documentation was performed in a sequence that followed the stages of research. The complete 3D model was created by connecting individual parts of the models, according to their georeferences, within a single coordinate system based on the GCP. Special attention was paid to the medieval hypocaust (underfloor heating). A drone or monopod stand was not used for the collection of the data.

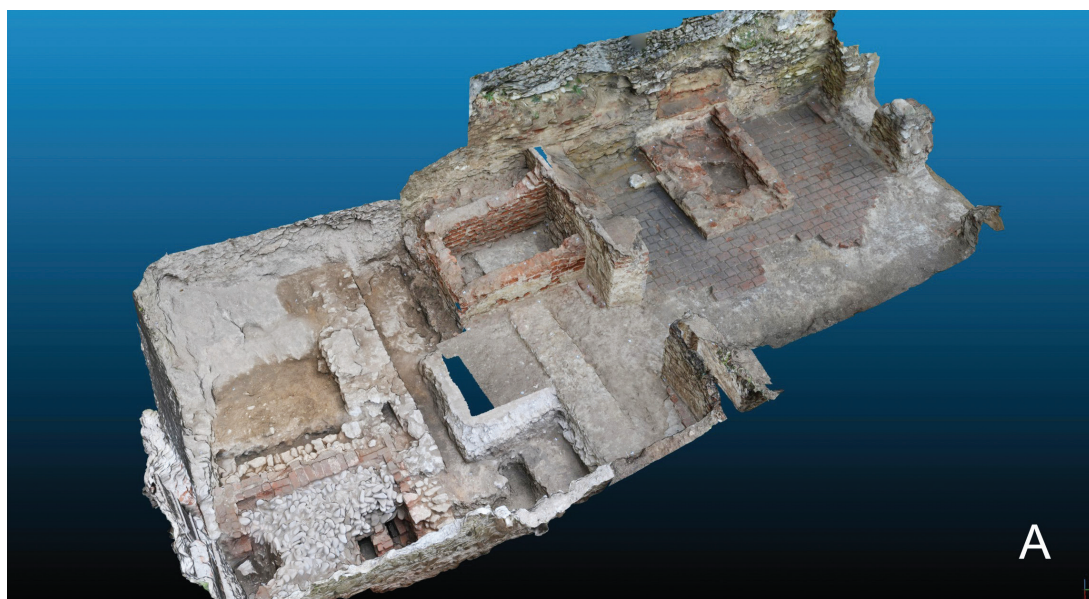


Figure 25A. Skalka nad Váhom (Slovakia). Remains of a medieval monastery, 14th-17th century. Textured 3D model combining the results from two archaeological seasons (see also Figure 25B) that focused on uncovering the west wing of the clausura. IbM (425 photos, 12+24Mpx).



Figure 25B. Skalka nad Váhom (Slovakia). Remains of a medieval monastery, 14th-17th century. Textured 3D model combining the results from two archaeological seasons (see also Figure 25A) that focused on uncovering the west wing of the clausura. IbM (425 photos, 12+24Mpx).

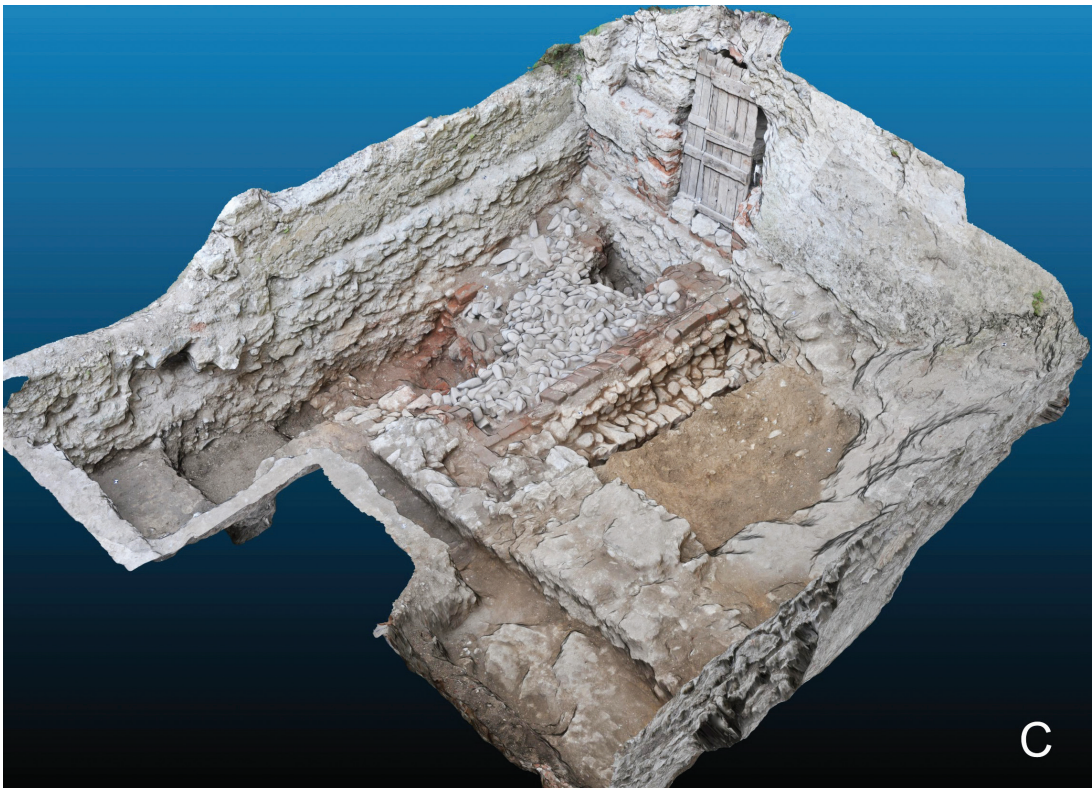


Figure 25C. Skalka nad Váhom (Slovakia). Remains of a medieval monastery, 14th-17th century. Textured 3D model – detail of medieval hypocaust.

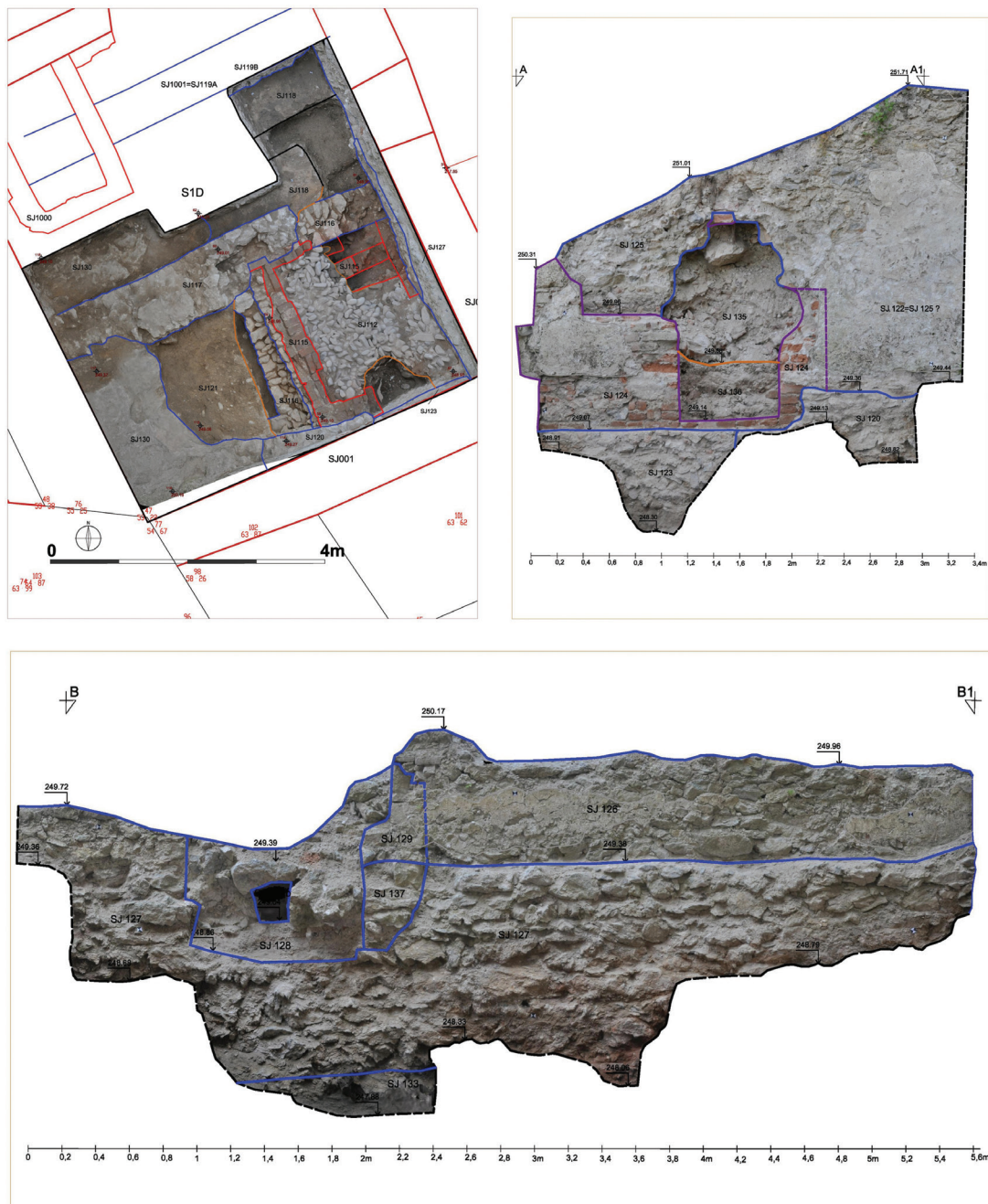


Figure 26. Skalka nad Váhom (Slovakia). Remains of a medieval monastery, 14th -17th century. Examples of 2D documentation derived from the 3D model.

Čachtice, Castle

Site type:	Castle
Location:	Čachtice, Nové Mesto nad Váhom District, W Slovakia
Dating:	13 th -16 th century
Research type:	Preventive research
Recording technology:	lBM
Recording equipment:	Camera Nikon D90 and Sony Nex 7, UAV (drone), TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan 1.0.0, AutoCad Civil 3D 2016 student version, ArcGIS 10.0
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans. Georeferenced DEM, cross-section views (Figs. 27 - 29).
Short description:	The excavation at Čachtice Castle was conducted in 2012 and 2013 and was primarily focused on the north castle wing, which was planned for structural reinforcement. Many elements of the former historical structures were revealed, such as the partly destroyed residential area and the basement area with partially preserved vaulted roof. The 3D documentation was performed with a high monopod stand and an UAV. Individual parts of the uncovered architecture were documented and processed as linked spatial segments.

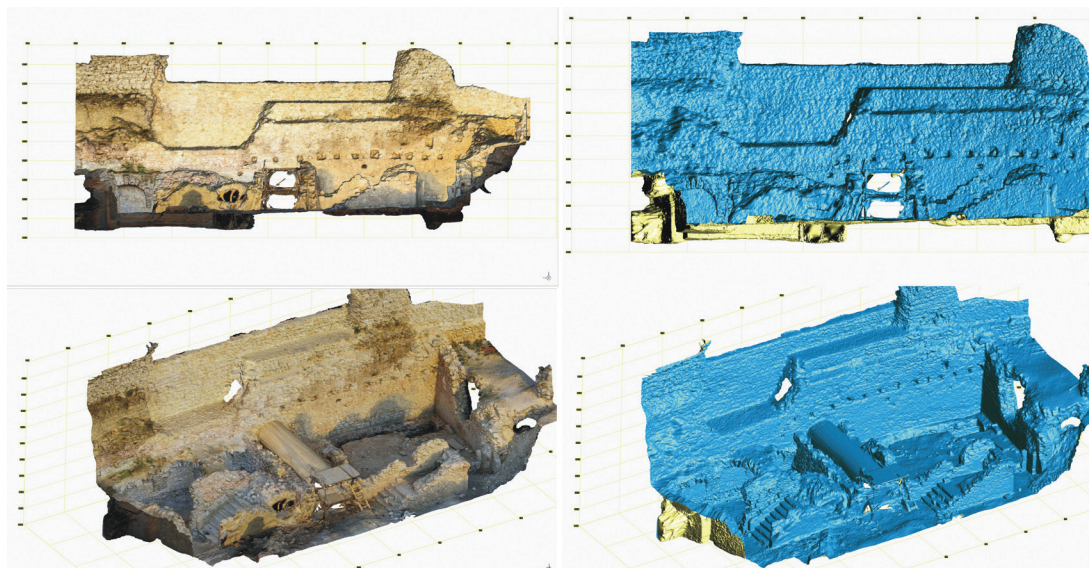


Figure 27. Čachtice (Slovakia). Medieval castle, 13th-16th century. 3D model of the eastern palace during the restoration process. lBM (250 photos, 12Mpx). Top – section through the interior of the eastern portion of the structure, bottom – isometric view of the same area.

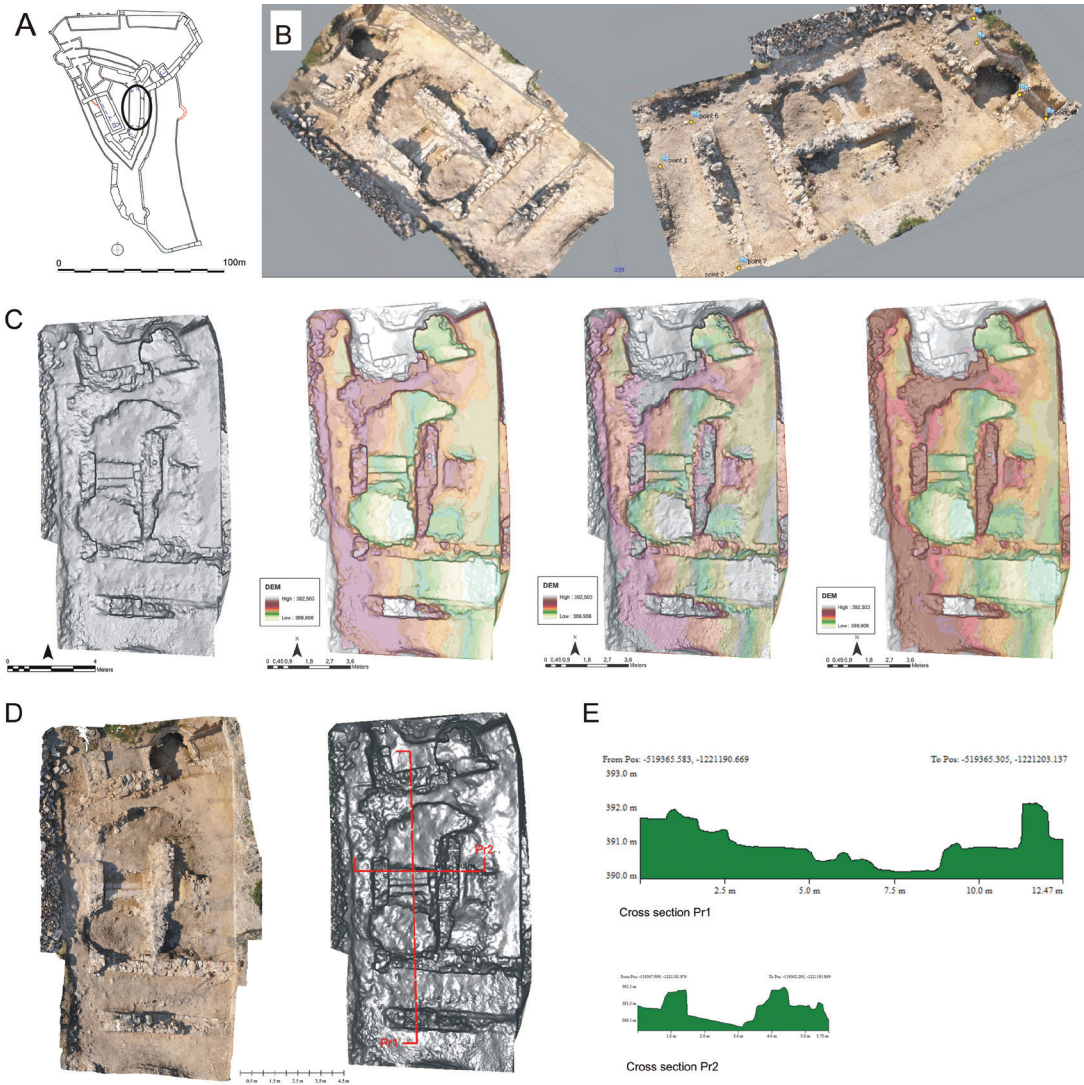


Figure 28. Čachtice (Slovakia). Medieval castle, 13th-16th century. Archaeological trench K25 in the eastern palace. IbM (65 photos, 12Mpx). A: ground plan of the castle with indicated location of the documented trench, B: solid 3D model of the trench with the texture map, C: DEM with different forms of visualisation (analytical hillshading and hypsometry), D: orthophoto plan, E: cross-sections.

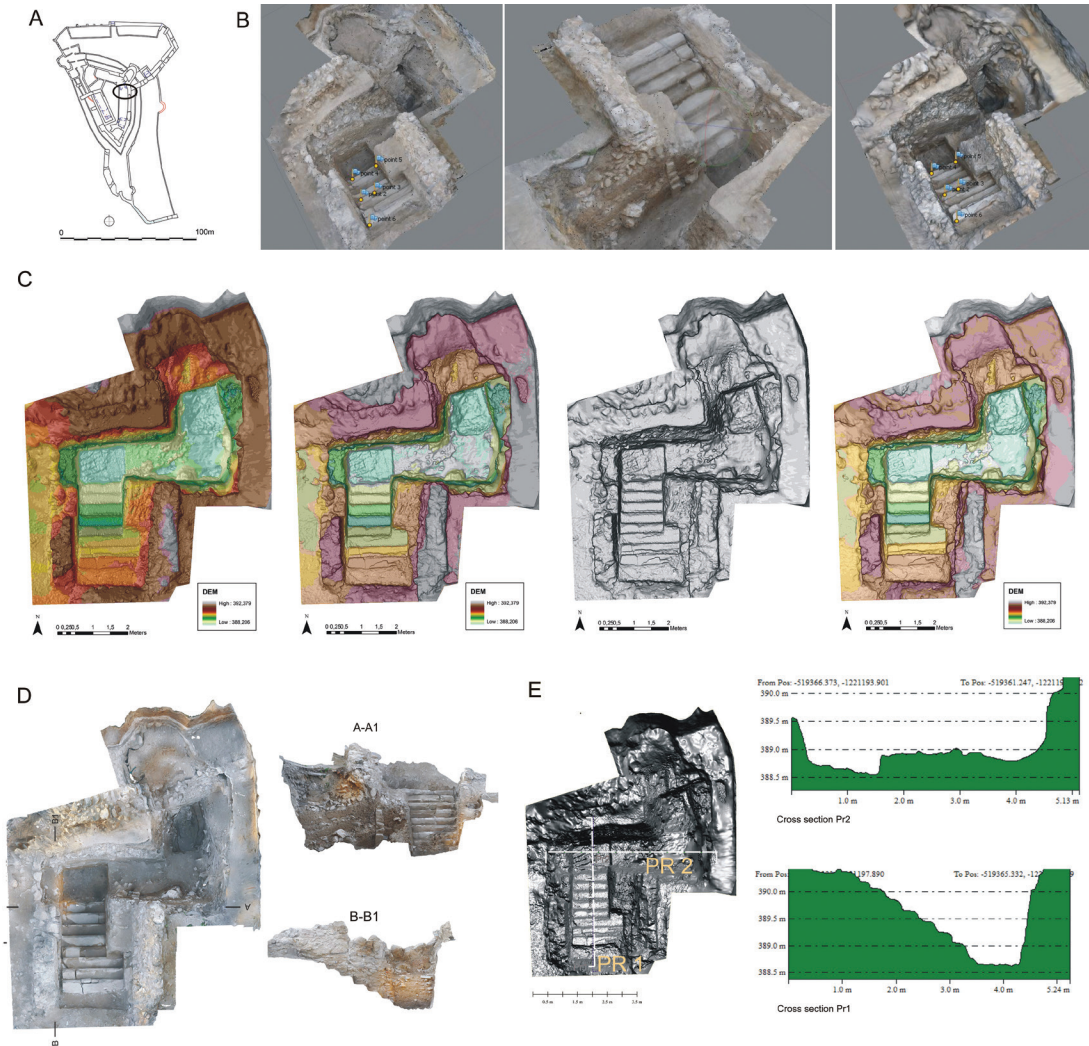


Figure 29. Čachtice (Slovakia). Medieval castle, 13th-16th century. Archaeological trench S3 in the eastern palace. IbM (30 photos, 12Mpx) A: location of the trench within the castle, B: solid 3D model of the trench with the texture map, C: DEM with different forms of visualisation (analytical hillshading and hypsometry), D: orthophoto plan of the layout and the profiles, E: cross-sections.

Brazda, Ancient sepulchral architecture

Site type:	Tomb
Location:	Brazda, Republic of Macedonia
Dating:	5 th -3 rd centuries BC
Research type:	Documentation of an archaeopark
Recording technology:	IbM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan 1.0.0, AutoCad Civil 3D 2016 student version, ArcGIS 10.0
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans. Georeferenced DEM, cross-sectional views (Figs. 30-32).
Short description:	The 5 th century BC tomb is situated at the foot of a fortified hillfort Brazda, some 15 km to the north from Skopje. The overall structure of this probable princely tomb represents a unique example of its kind in the wider Balkan area. It contains a rectangular chamber (9.8 x 6.6 m) with a long dromos, which slopes steeply for 20 m towards the chamber entrance. The walls of the underground chamber were built of massive travertine blocks of an average weight of 500-1500 kg. The site was investigated in the 1990s and is nowadays part of a small archaeological park. The 3D documentation was prepared without a drone or a monopod stand. The elevation of the structure is small in relation to the ground on which it was erected, and the majority of photos were taken at a relatively acute angle. The absence of images taken perpendicularly to the structure subsequently caused a high level of noise in the software processing. The level of noise was also increased by the dense vegetation growing on the tomb.

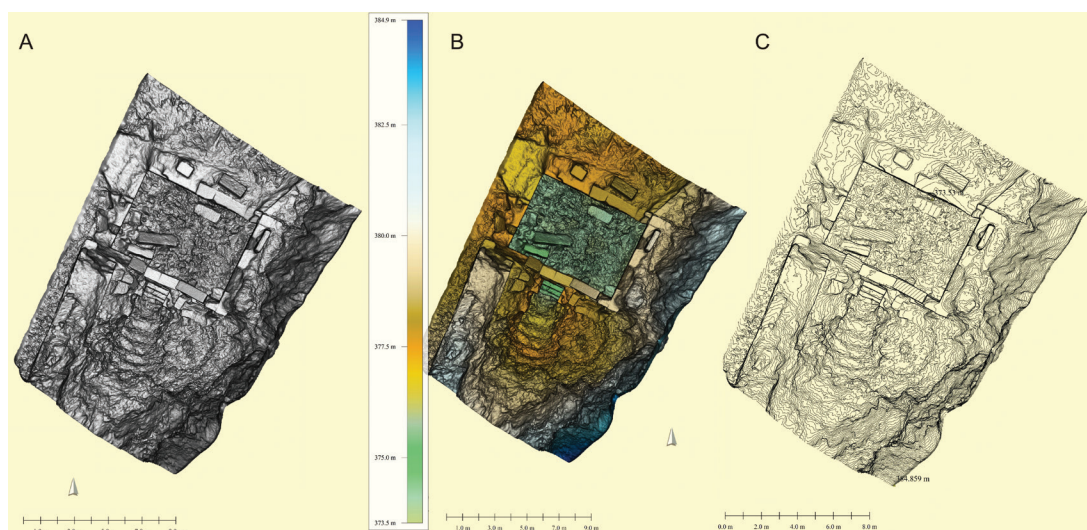


Figure 30. Brazda, Archaeopark (Macedonia). Remains of the stone-built tomb, 5th century BC. DEM derived from the 3D model. A: analytical hillshading, B: hypsometry, C: contours.

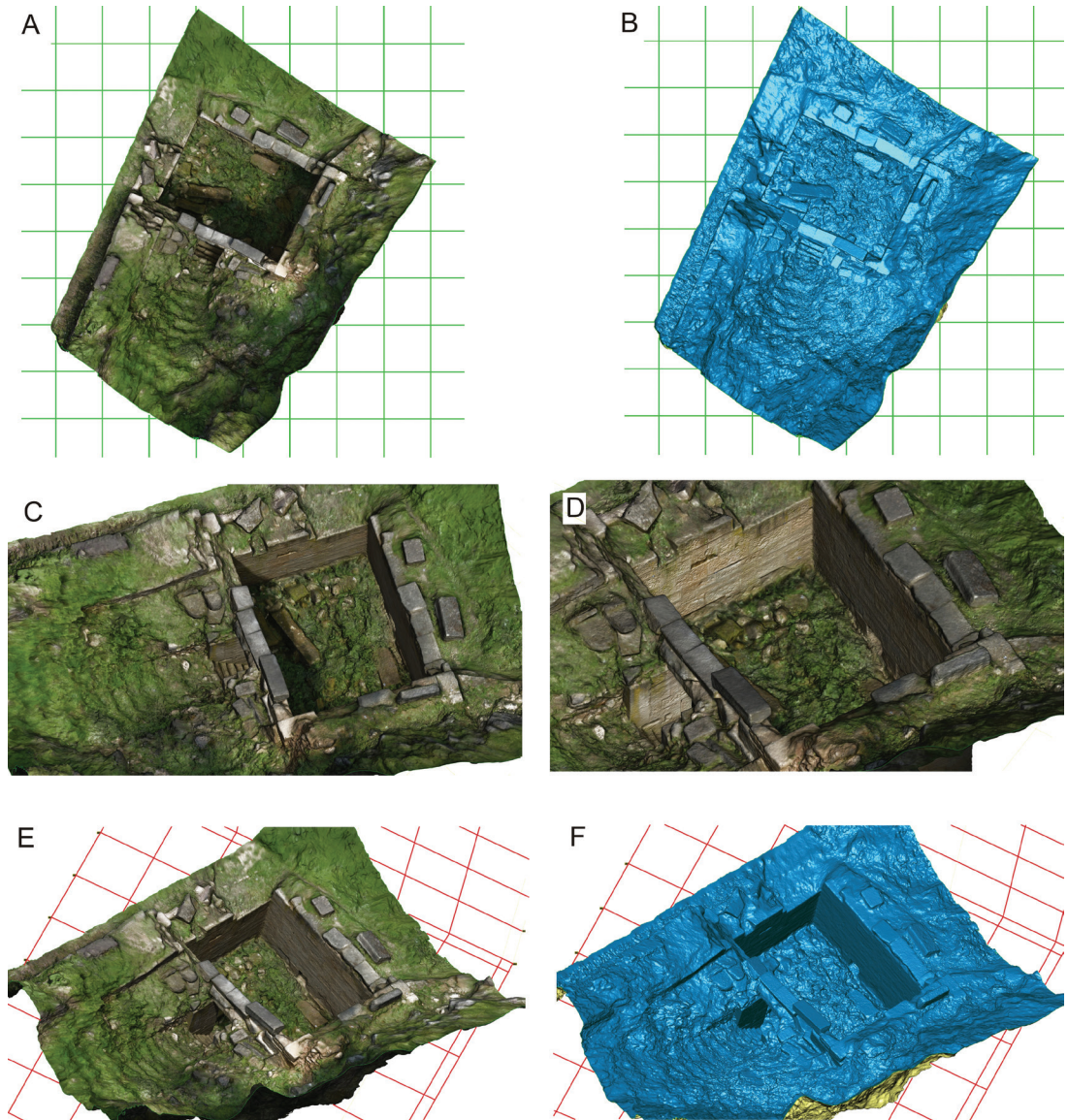


Figure 31. Brazda, Archaeopark (Macedonia). Remains of the stone-built tomb, 5th century BC. 3D model. lBM (476 photos, 24 Mpx). A,B: nadir view, C-F: isometric views.

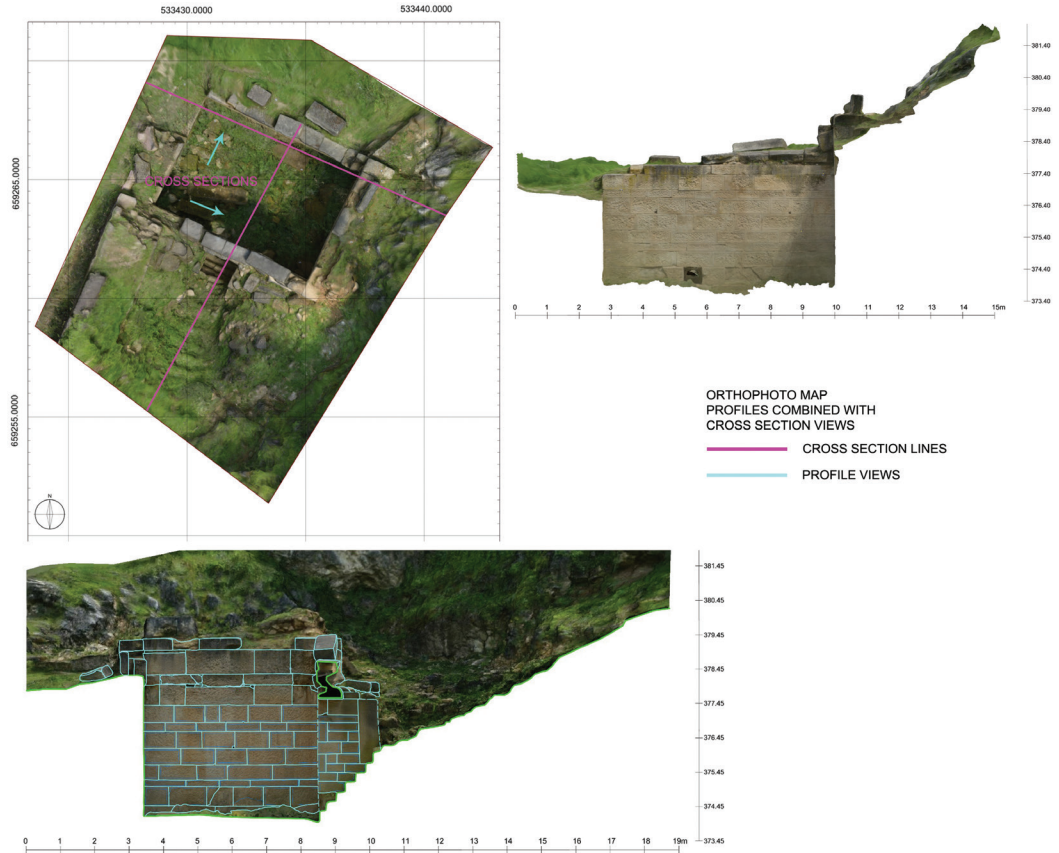


Figure 32. Brazda, Archaeopark (Macedonia). Remains of the stone-built tomb, 5th century BC. Examples of 2D documentation derived from the 3D model.

Bratislava, Castle

Site type:	Castle area, settlement area from the 1 st century B.C., built-up area from the 16 th century
Location:	Bratislava Castle, northern terrace, SW Slovakia
Dating:	Late La Tène period (1 st century BC), 13 th -17 th century AD
Research type:	Preventive excavation
Recording technology:	IbM, TLS
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), TLS Faro Focus X130, TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan 1.0.0, Faro Scene, CapturingReality RC, CloudCompare, AutoCad Civil 3D 2016 student version, ArcGIS 10.0 trial version
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans. Georeferenced DEM, cross-section views (Figs. 33-36).
Short description:	<p>The investigations in the area of the castle were carried out periodically between 2008 and 2014. The 3D documentation of archaeological situations was used as the basic recording type in the period 2013-2014 and as a sole method for creating plans and profiles of the entire site. Special attention was paid to the architectural remains discovered in the northern courtyard. These included foundations of two buildings constructed in the Roman style and dated to the 1st century BC. The main structural axis of the Building 1 formed two parallel masonry components, which, at their south end, were subsequently damaged by digging the moat for the medieval castle. The main axis was completed with two pillars with well-preserved elements of the above-ground structure and of the foundations. In the Building 2, cladding over the foundation walls, the cast mortar floor and two lines of four pillars along the main longitudinal axis were partially preserved.</p> <p>Some architectural remains related to the utilisation of the area in the 16th-18th century were also revealed. Especially remarkable was a 16th-century built-up area, located in place of an infilled medieval quarry. It consisted of structures made of stones bound by clay mortar. Here, a relatively well-preserved bread (?) oven was discovered. Remains of the 18th century Baroque garden were also discovered.</p> <p>All discovered structures were documented by IbM and using an UAV. However, the UAV was not used for recording of the 16th century built-up area and the remains of the medieval quarry. In these two cases, only oblique photographs were made. Terrestrial 3D scanning was used for the Roman-style buildings (TLS Faro Focus X130). Data from TLS documentation as well as from IbM were merged in the processing phase in CloudCompare and CapturingReality RC.</p>

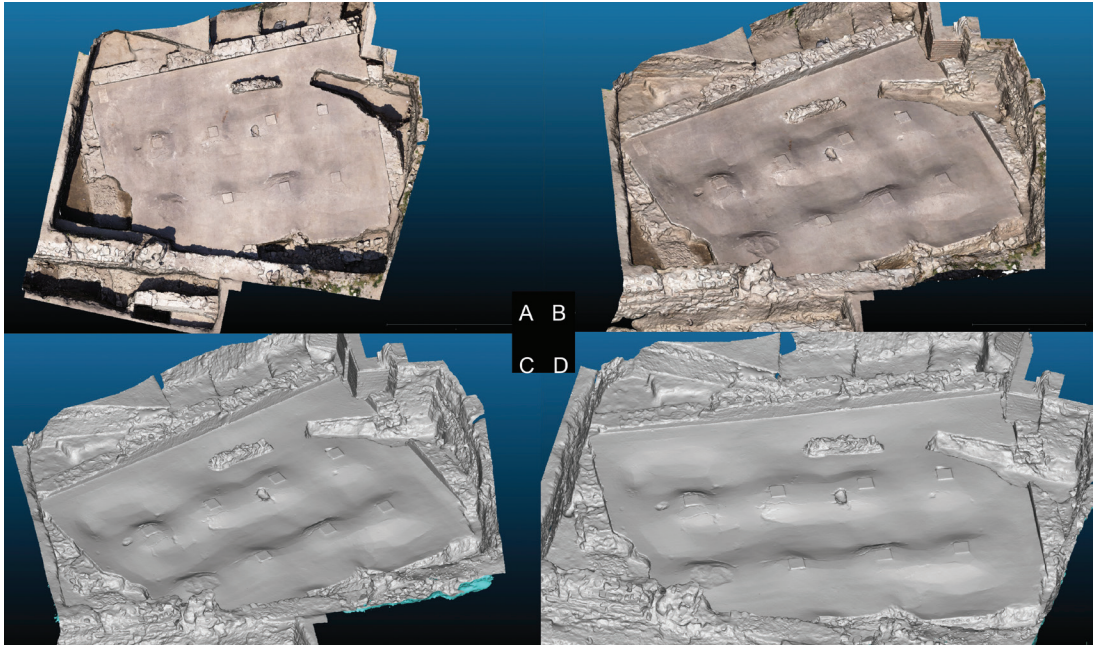


Figure 33. Bratislava, Castle, northern terrace. Roman-style Building 2, 1st century BC. 3D model. Terrestrial laser scanning (TLS) in combination with lBM. A, B: textured 3D model, C, D: shaded 3D model.

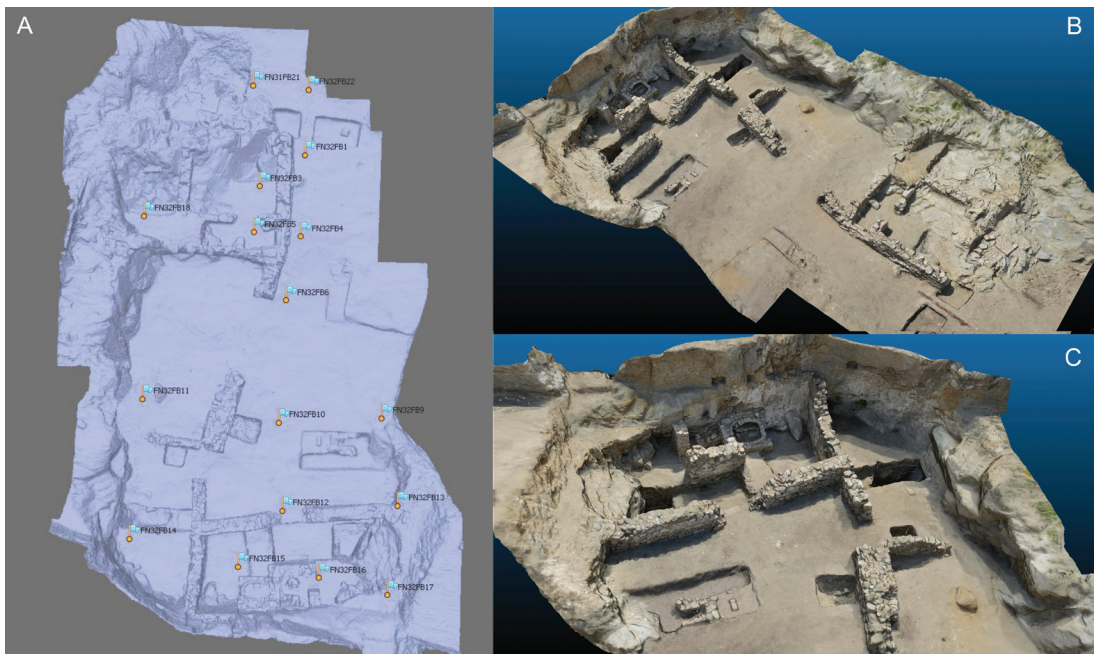


Figure 34. Bratislava, Castle, northern terrace. Remains of a residential structure, 16th century. 3D model. lBM (534 photos, 12Mpx). A: distribution of measured ground control points (GCP), B, C: textured 3D model.

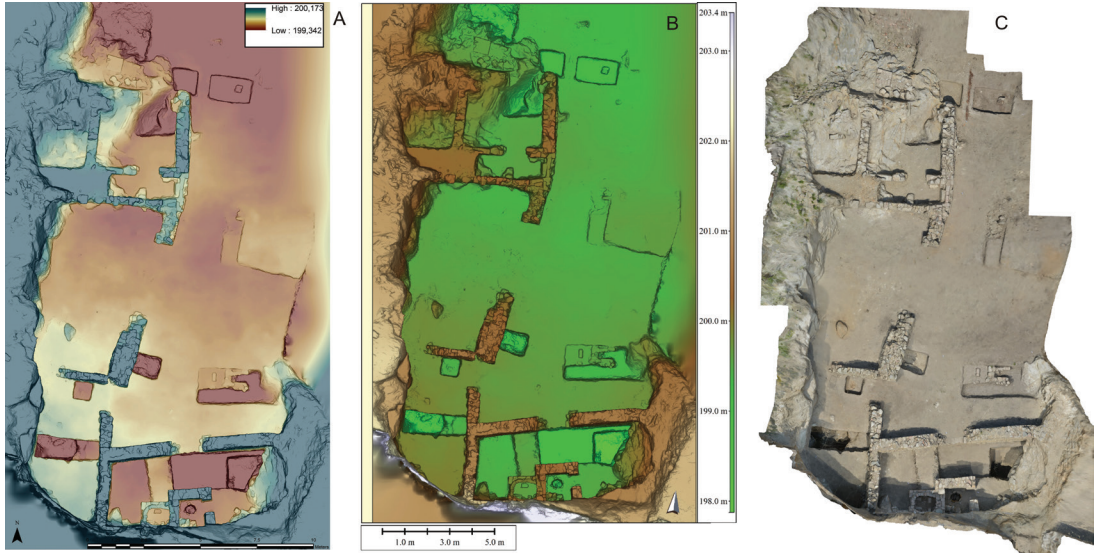


Figure 35. Bratislava, Castle, north terrace. Remains of a residential structure, 16th century. A, B: DEM derived from the 3D model, C: Georeferenced orthophoto plan derived from the 3D model.

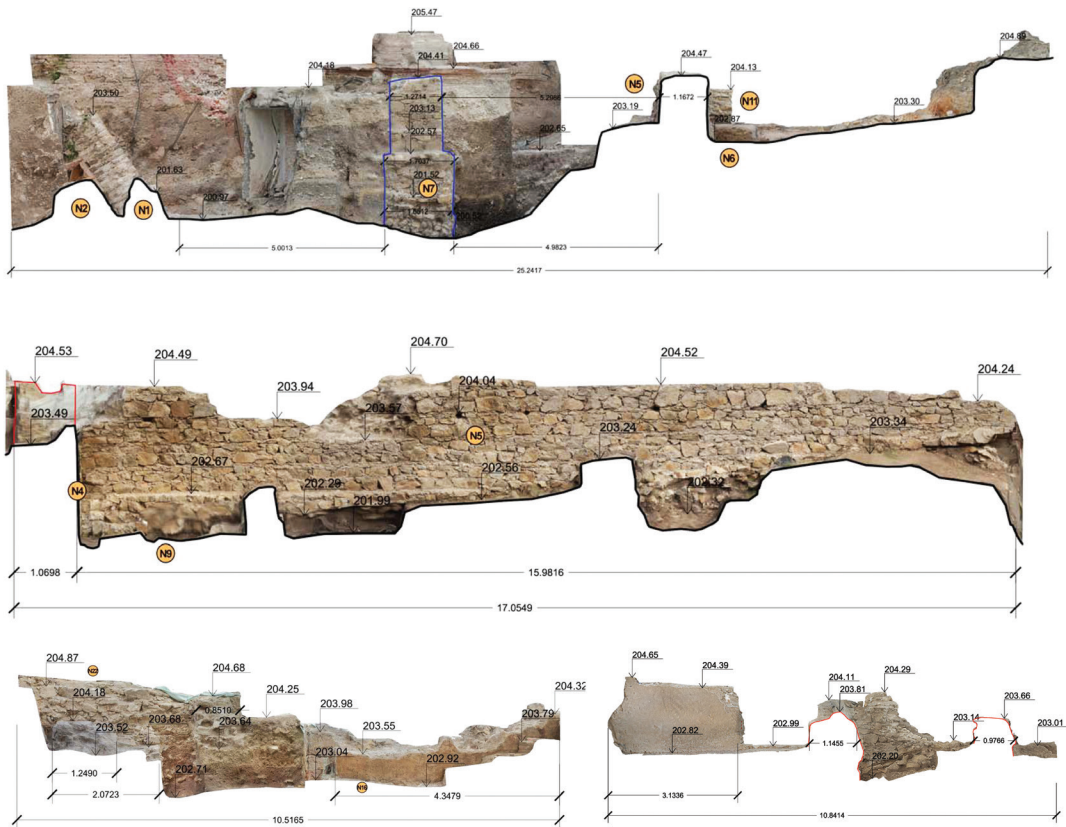


Figure 36. Bratislava, Castle, northern terrace. Roman-style Building, 1st century BC. Examples of 2D documentation deliverables derived from the 3D model. View of the cross-section.

Považská Teplá, Castle

Site type:	Castle
Location:	Považská Teplá - Považský castle (district Považská Bystrica), W Slovakia
Dating:	16 th -17 th century
Research type:	Preventive research
Recording technology:	lBM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan 1.2.0, CloudCompare, AutoCad Civil 3D 2016 student version
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans, cross-section views (Figs. 37, 38).

Short description: The subject of 3D documentation was the northern wing, revealed during the excavations in 2016. This was a rectangular structure with four columns in the corners placed on stone bases probably built from the secondarily used stone blocks. Effective collection of the data was hindered by the fact that the interior space did not allow to always obtain sufficient distance for taking the photos. Moreover, given the significant local elevation defined by the capitals, it was very difficult to capture the upper part of the structure from a sufficient number of sides. As the surrounding walls were considerably destroyed, they could not be used as an elevated platform. The top of the structure was possible to capture only by oblique photos taken from the west side. The absence of vertical photos of the top part of the structure resulted in a smeared colour of the texture in this part of the 3D model.

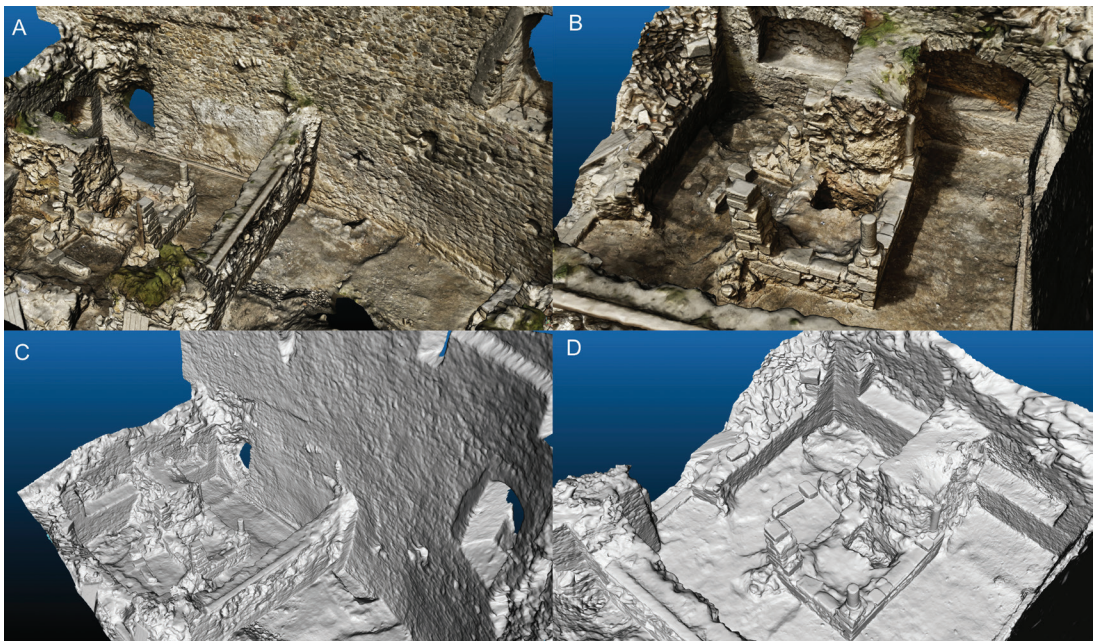


Figure 37. Považský Castle (Slovakia). North palace structure, 16th century. lBM (366 photos, 24Mpx). A, B: textured 3D model, C, D: shaded 3D model.

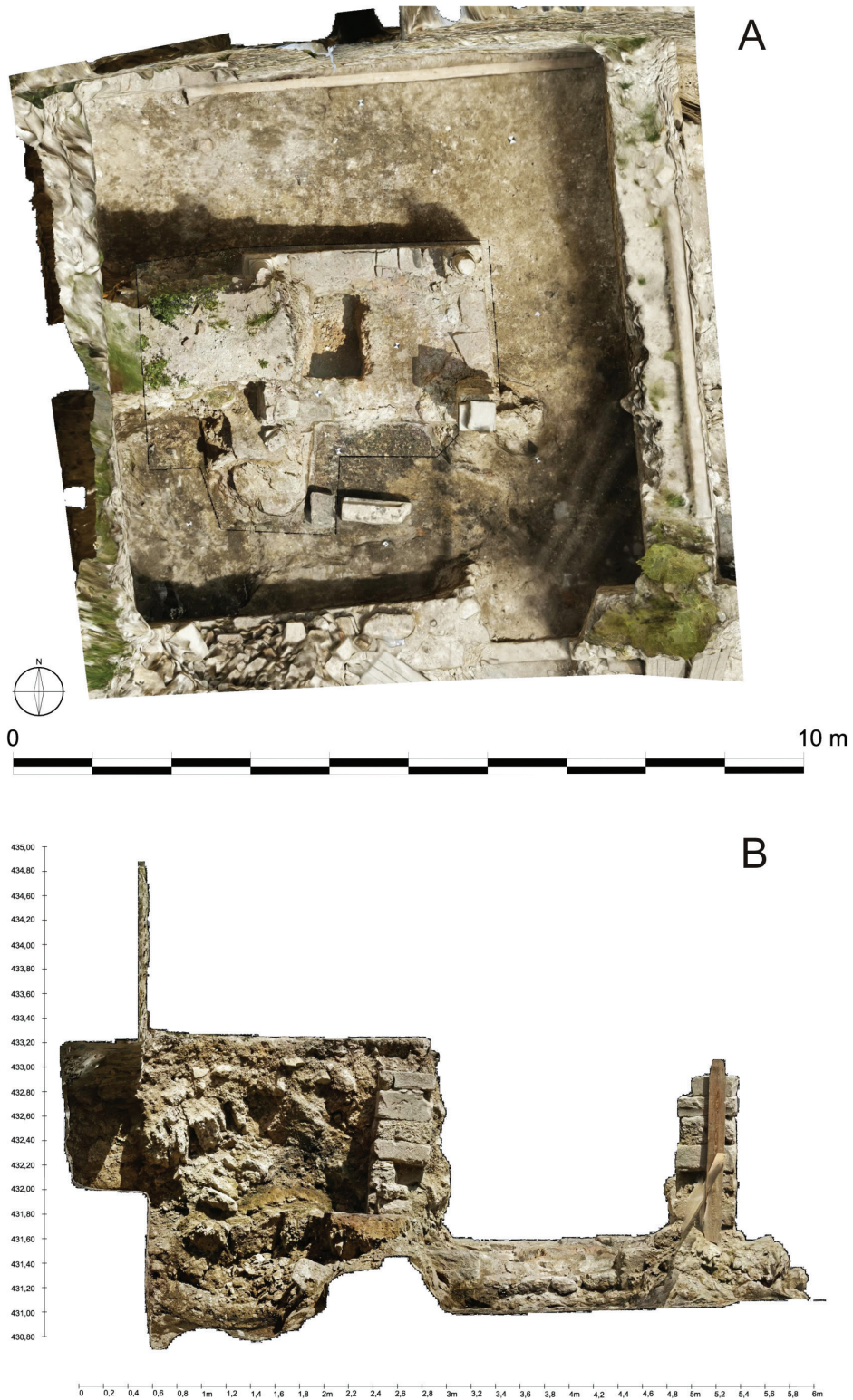


Figure 38. Považský Castle (Slovakia). North palace structure, 16th century. Examples of 2D documentation deliverables derived from the 3D model. A: groundplan orthophoto, B: profile orthophoto.

DISCUSSION

The experience from the presented case studies shows that lBM is the most suitable method for 3D digitisation of archaeological cultural heritage. Its advantage lies in the speed of the data collection, which is highly important in the rescue research. Moreover, compared to TLS, lBM represents a better alternative in terms of the total cost, because the only costly items are the camera and the high-performance computer. In the case of archaeological situations in which the largest part of the documented area is situated at the level of the surrounding terrain, and where vertical structures are represented only by sporadic and largely destroyed architectural elements, the application of TLS is significantly limited. This is because TLS scanners usually have limited manoeuvring ability of the sensor when placed vertically in relation to the terrain.

When photographing extensive flat areas of archaeological sites for the lBM documentation, it is suitable to use an UAV (drone) or a high monopod stand, which enable taking photos from above and from an adequate distance. In case a drone is used, it is recommended to limit the flight distance (flight level) in order to maintain the sufficient image resolution. In the case of structures with parts preserved up to a certain height (e.g. masonry preserved to a height exceeding 1 m), it is necessary to complete the vertical photography with oblique photo documentation. In many cases, it is required to combine aerial documentation with terrestrial photography, whereby the scanning circuits must be merged in a respective software using GCP.

For georeferencing a 3D model and the creation of basic 2D and 2.5D documentation products (georeferenced orthophoto plan and DEM), it is necessary to distribute, and subsequently measure, GCP in space. Depending on the size of the area documented, and the planned distance of the camera from the photographed space (especially as regards the expected flight level), GCP should be sufficiently large to be visible on individual images. The distribution of points should include the whole area. Although it is not required to distribute GCP over a grid, certain regularity is welcome (Figure 34: A). If calibrated coded reference markers are used, some software packages (e.g. Agisoft Photoscan and Pix 4D) have the option of automatically conducting their identification (Figure 40). In addition to calibrated coded markers, standardised markers can be also used, such as bicolour squares placed diagonally or with overlapping angles; they can, depending on the software used, also be identified on the images using a semi-automatic method.

Given that archaeological sites usually have significantly structured geometry of the surface, as well as rich texture, the SfM algorithm has no problem to detect a sufficient number of SIFT points on the input photos without a significant 'dead zone'. The resulting 3D model is thus clean and sharp. A problem can occur if the structure is also captured by vertical photography and if its surface is documented only with oblique photos made at an acute angle (see the case study of Brazda) from various sides. In such a case, a high re-projection error can occur in the process of 'bundle adjustment'; this can result in high noise as well as in the occurrence of ghosting effect in the process of creation of a dense point cloud. If this cannot be prevented by using a drone or a high monopod, the re-projection error must be thoroughly and precisely reduced in the given software environment (ideally, to below 1px) (Figure 39).

In addition to the digitisation of ground plans, the concept of IBM is also suitable for documenting complex profiles, especially those of large length or composed of several layers created by diverse architectonic elements. In addition to the creation of a 3D information database, the main significance of 3D digitisation of archaeological finds, especially in the case of rescue archaeological research, lies in the fact that it represents extraordinarily effective method of generating 2D documentation in the form of georeferenced ortho-photo plans and digital elevation models (DEM). These are necessary elements of the research documentation. From the perspective of practical utilisation of 3D digitisation by professional archaeologists, 2D documentation still prevails. Nevertheless, a tendency has appeared towards the application of 3D mesh for the purpose of 3D vectorisation, subsequently interconnected with the database model in 3D GIS solution. However, it characterises mainly long-term research projects that hire professional research teams.

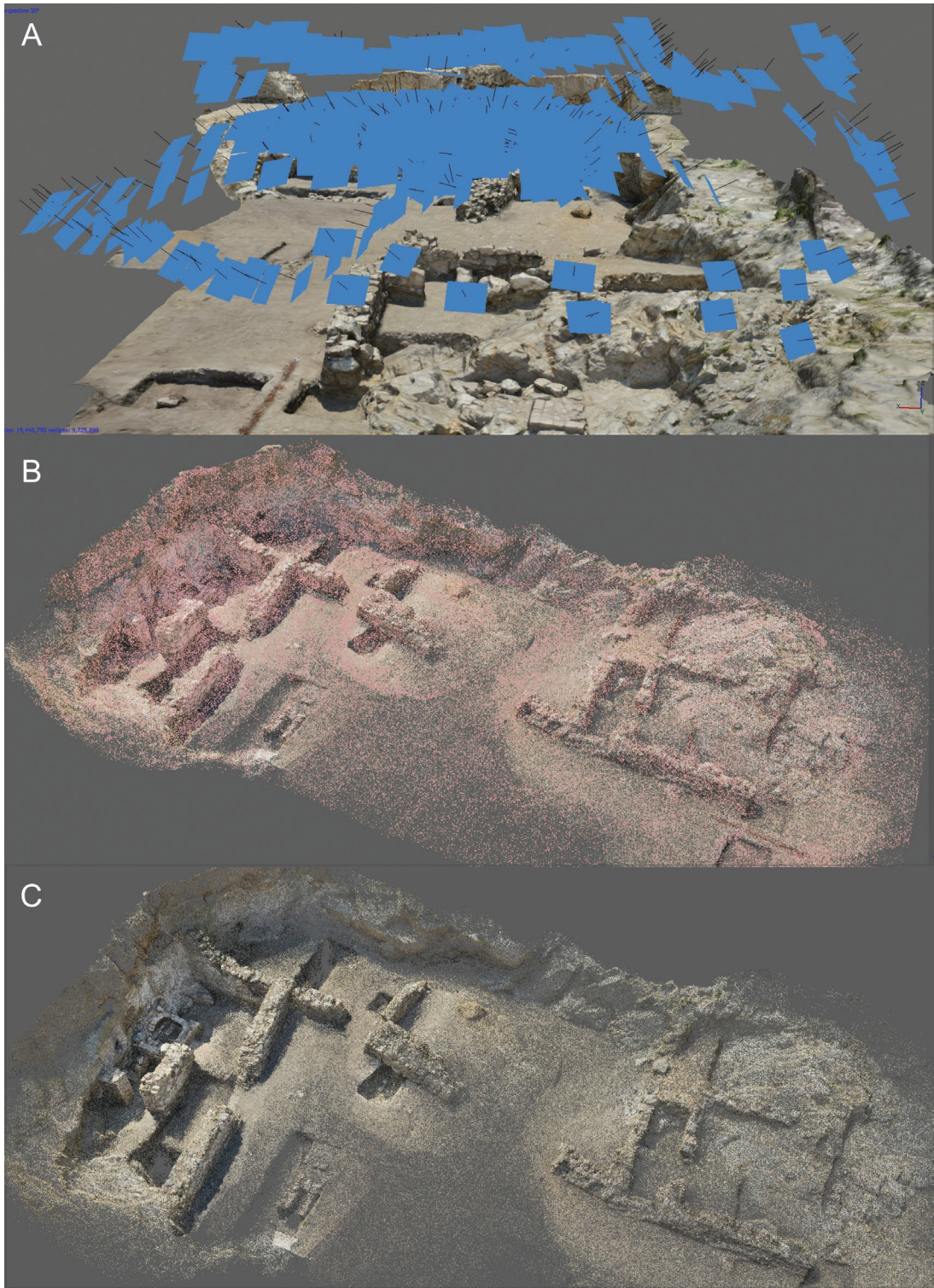


Figure 39. Bratislava Castle. A: broader area documented only with oblique photos, B: without verticals, resulting in a noisy sparse cloud, C: with large number of points with a high re-projection error that needs refinement in the iterative process.

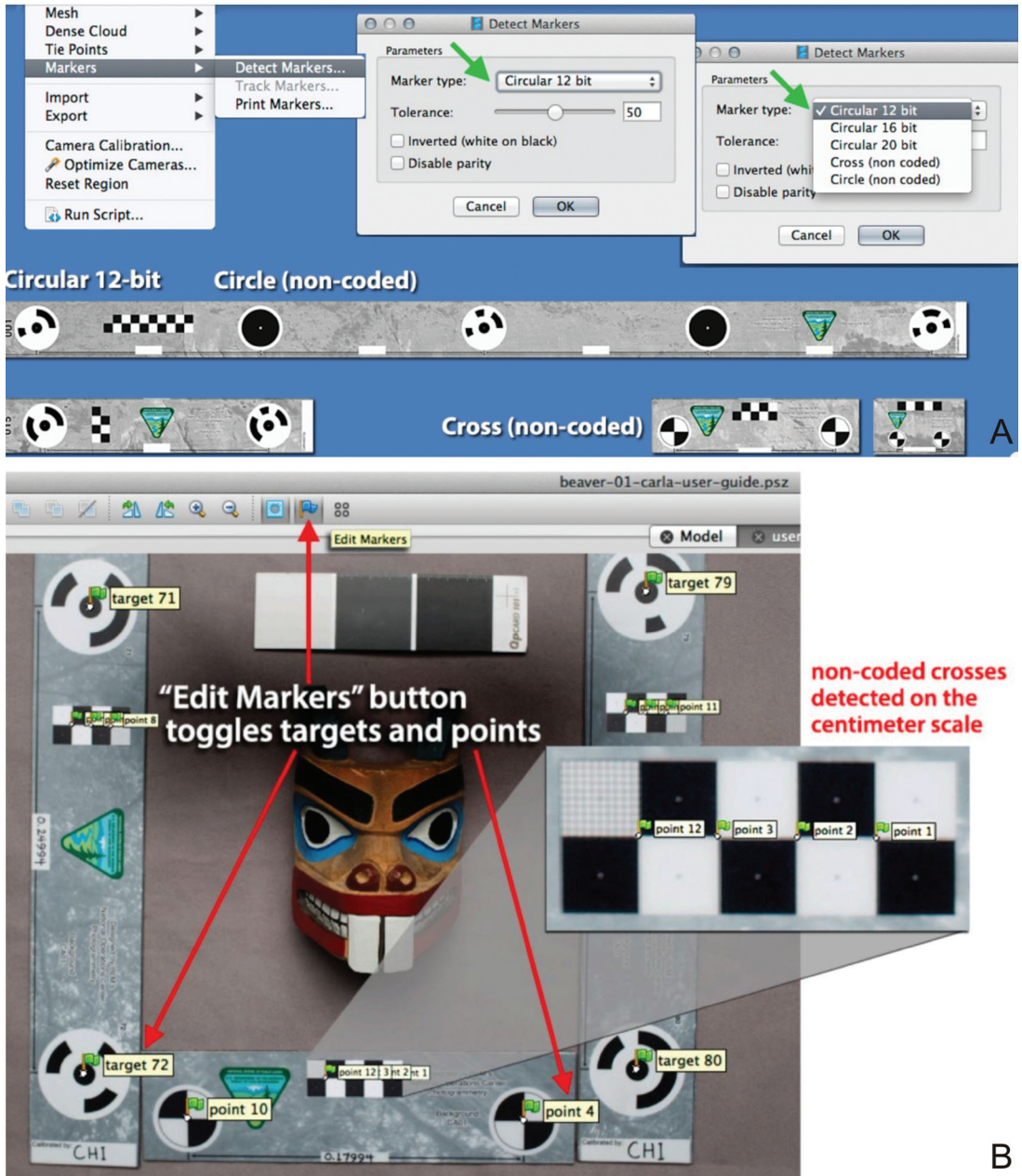


Figure 40. A: Types of calibrated coded and non-coded targets, B: the process of automatic recognition of coded and non-coded targets in Agisoft Photoscan. (Available at: http://www.agisoft.com/pdf/tips_and_tricks/CHI_Calibrated_Scale_Bar_Placement_and_Processing.pdf).

3D RECORDING OF ARCHITECTURE

Ján Zachar (Via Magna) & Perica Špehar (University of Belgrade)

Comprehensive digitisation of complex architectural forms usually represents the most demanding tasks within the framework of documentation of cultural heritage. Spatial and elevation variations, together with often very hard-to-access elements, require thorough planning of the data collection, as well as their systematisation and the nomenclature, for the purpose of smooth processing. Various lighting and spatial conditions offered by exterior and interior of the context in many cases require the application of different techniques of data collection, and the subsequent effective merging of the results.

Architectural structures of different sizes and different levels of complexity of exterior and interior elements were selected as the case studies within the framework of the CONPRA project. TLS and lBM methods were tested by using UAVs or monopod stands in order to assess the usefulness and effectiveness of the technological solutions in these particular cases.

The case studies were selected with a view of demonstrating possibilities and limits of 3D documentation in the context of various types of architecture. All case studies were processed in a workstation with the following parameters: Intel Xeon CPU E5-2620 v2@ 2,10 GHz, RAM 128 GB, GPU NVIDIA GeForce GTX 780 3GB, OS W7. In the case of TLS application, the resolution was always set to 6 mm per 10 meters. For lBM, two types of software were used: Agisoft Photoscan and CapturingReality RC (the latter was chosen based on the licence availability). In Photoscan, the following parameters were set for the batch processing workflow: step – align photos (high accuracy with the key point limit of 80,000 and the tie point limit of 40,000 points); step – refinement of alignment (decreasing of global re-projection error to max. 1px); step – build dense point cloud (medium quality, aggressive depth filtering); step – build mesh (arbitrary surface type, dense

point cloud as source data, interpolation enabled, custom face count: various values); and step – build texture (generic mapping mode, texture from all cameras, blending mode Mosaic, texture size 8192, texture count 1, and no colour correction). In the application of CapturingReality RC software, the parameters were as follows: step – align photos (+ laser scans) (max. feature per image 120,000, pre-selector feature 60,000, image overlap medium, detector sensitivity medium, max. re-projection error 2px); step – re-construction (normal detail); step – build texture (Guter 3, texture resolution 8192, large triangle removal threshold 10, maximal texture count style, visibility based texture style).

Jazernica, Medieval church

Site type:	Church
Location:	Jazernica, Turčianske Teplice District, NW Slovakia
Dating:	15 th century
Recorded parts:	Exterior, roof
Recording technology:	lBM
Recording equipment:	Cameras Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX) and Sony Nex7, UAV
Software:	DxO Optics Pro 10.0, Agisoft Photoscan 1.1.0, CloudCompare 2.7, AutoCAD Civil 3D 2016 student version
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figure 41)
Short description:	<p>The structure is situated within the residential area, in the area modified into a provisional park. It represents a single-aisle Gothic building with a semi-circular plan of the shrine and the sacristy in the north. On the outside, the shrine gradually extends into to the aisle, without any offset in the wall alignment. Three windows with simple tracery are installed on the south side of the aisle and the semi-circular shrine. The roof is covered with metal sheets. The church is a simple building without much diversity in the spatial configuration or the height. These are favourable conditions for the collection of raw data. The collection was also facilitated by the placement of the church in a relatively open space of the park. However, the accessibility for documenting was limited on the northern side of the sacristy, which is partially covered with a low shrubbery and is located in proximity of the fence that separates plots of land. Documentation of the facades was performed by a handheld camera. For collection of the data of the roof, an UAV was used. Navigation of the drone was complicated on the northern side of the building due to the high poles carrying high voltage lines. The data was collected in sunny weather with a high index of sunlight. The absence of diffuse lighting conditions caused significant contamination of the resulting texture with shadows of trees. Intensive sunlight also complicated documentation of the roof covering whose surface was very shiny (metal sheets).</p>

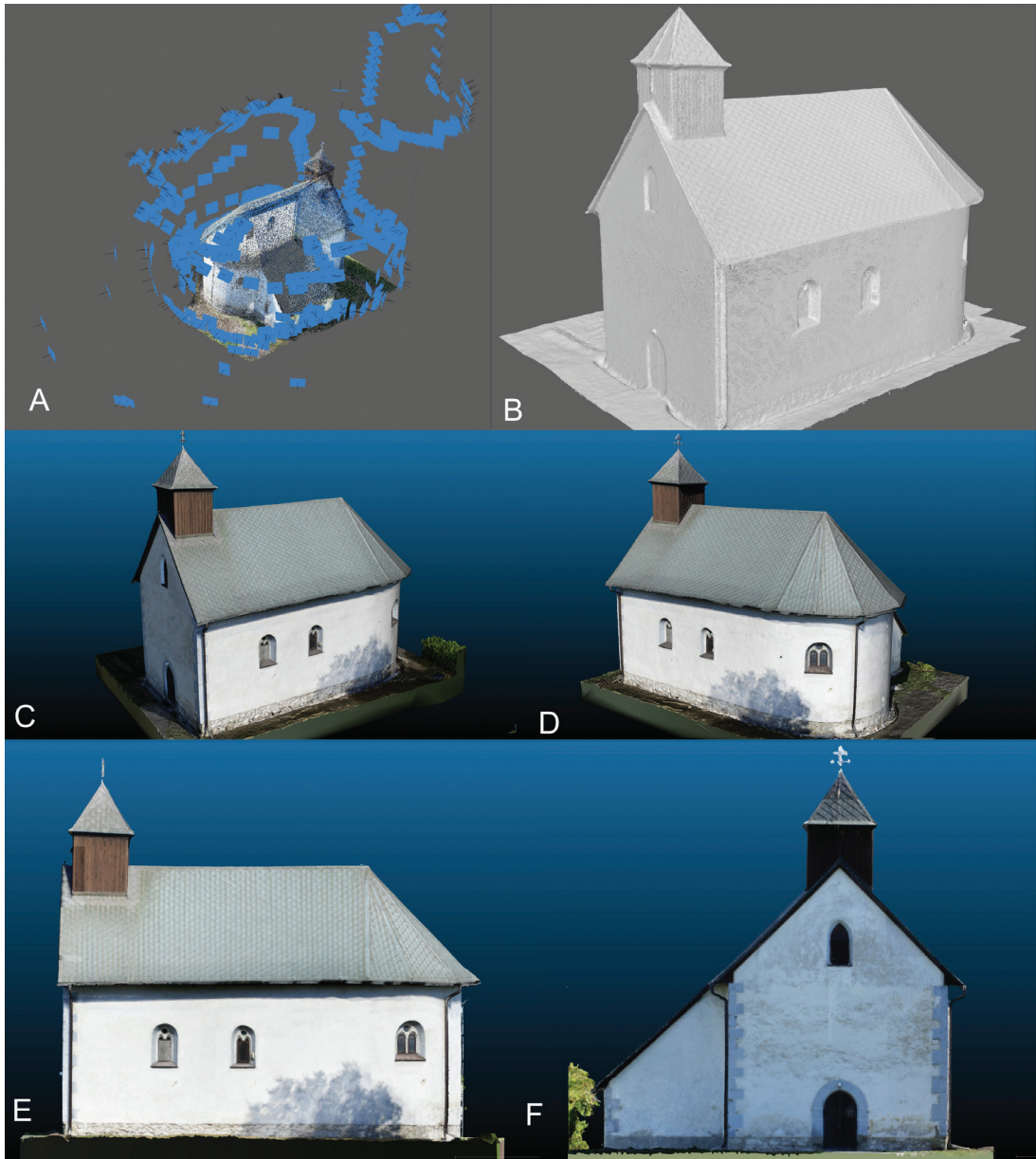


Figure 41. Jazernica, Medieval church, 15th century. IbM (586 photos, 12+24 Mpx).
 A: distribution of cameras, B: dense point cloud, C,D: textured 3D model – isometric view,
 E and F: textured 3D model – ortho-view of the facades.

Rajec, Historical Town Hall

Site type:	Architecture
Location:	Rajec, Rajec District, NW Slovakia
Dating:	16 th -17 th century
Recorded parts:	Exterior, roof
Recording technology:	lBM
Recording equipment:	Camera Nikon D 90
Software:	DxO Optics Pro 10.0, Agisoft Photoscan 1.2.0, CapturingReality RC, CloudCompare 2.7, AutoCAD Civil 3D 2016 student version
Record:	Scaled 3D model (mesh), scaled orthophoto plans (Figs. 42, 43)
Short description:	The Renaissance town hall in Rajec is a two-floor block building in the central part of a rectangular square. The ground floor is lined with an arcade. The high hip roof is covered with roof shingles. At the time of the recording, smooth white plastering covered the exterior facades. The walls and roof were not visually obstructed by other structures. The walls were photographed by a handheld camera. Photographs of the roof were taken from a larger distance using zooming of transfocal lens to capture the majority of its surface features with sufficient resolution. Certain problems appeared in processing of the raw data due to the glass inserts in the arches on the ground floor whose surface could not be captured with sufficient accuracy due to the transparency, reflectivity and shininess. Data processing proved problematic also for some parts of the monochromatic smooth facade plaster. The absence of plasticity as well as texture did not create good conditions for generating a sufficient number of SIFT points, consequently causing a higher level of noise with sparse and dense point cloud and surface deformations in the 3D mesh. Input photos needed to be edited prior to processing in order to optically highlight the surface structure as well as the colouring (DxO Optics Pro).

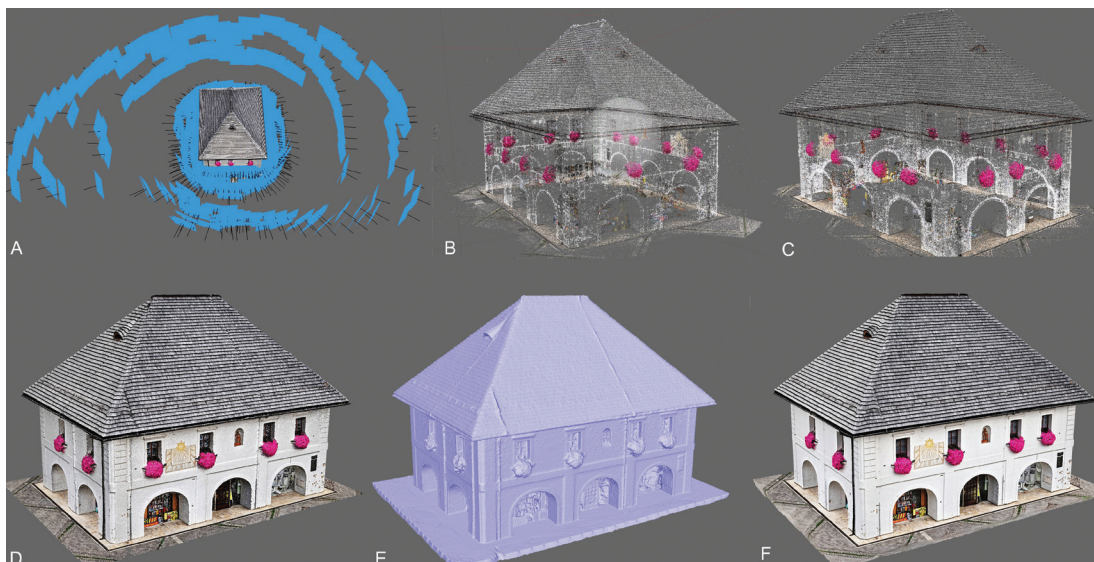


Figure 42. Renaissance Town Hall in Rajec, Slovakia. lBM (576 photos, 12Mpx).
A: camera positions, B: sparse point cloud before reprojection C: sparse point cloud after the reprojection, D: dense point cloud, E: meshed 3D model, F: textured 3D model.

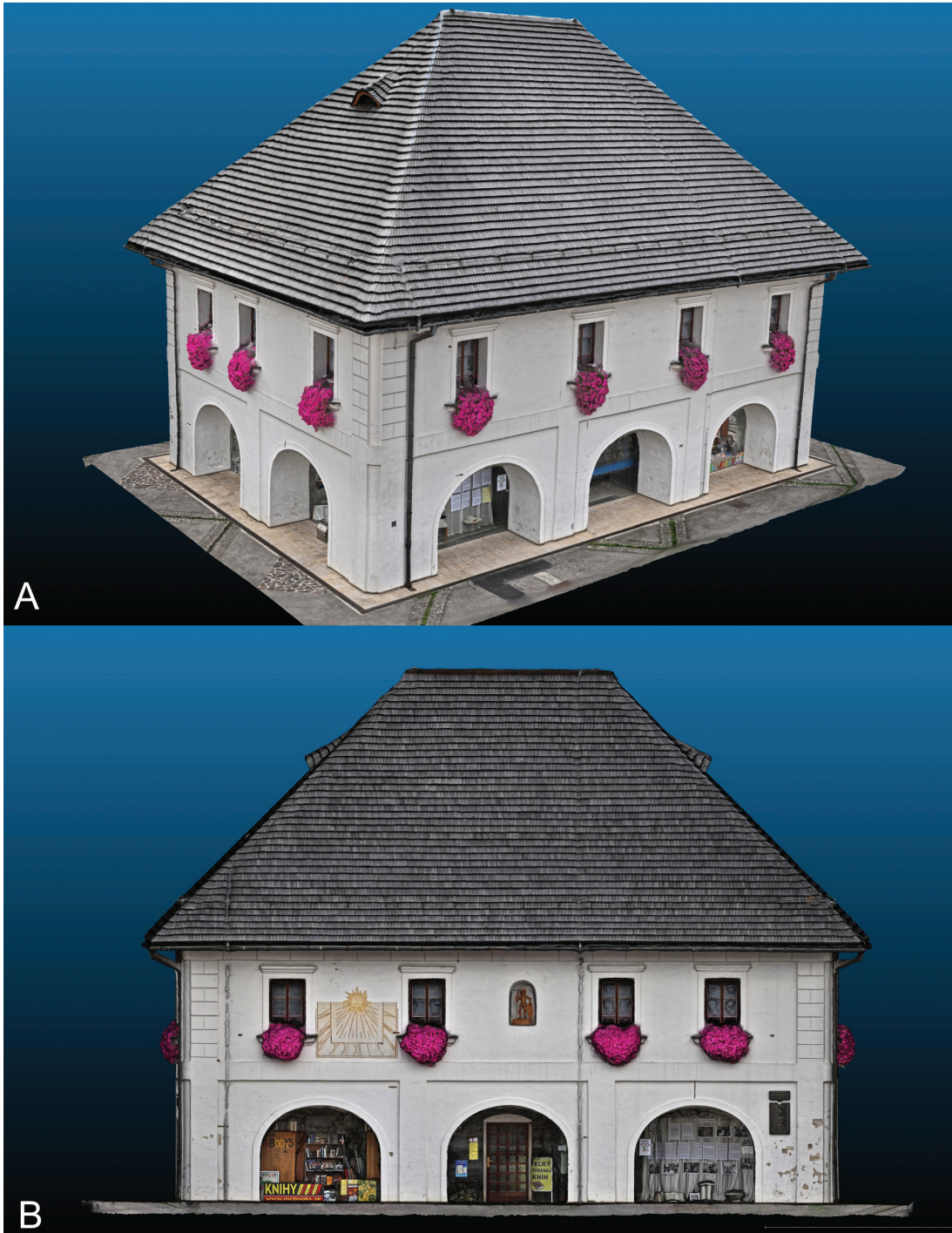


Figure 43. Rajec, Renaissance Town Hall, 16th century. IBM.
A: textured 3D model – isometric view, B: textured 3D model – ortho-view of the facade.

Sazdice, medieval church

Site type:	Church
Location:	Sazdice (district Levice), south-central Slovakia
Dating:	14 th -15 th century
Recorded parts:	External walls (facades)
Recording technology:	lBM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX)
Software:	DxO Optics Pro 10.0, Agisoft Photoscan 1.2.0, CapturingReality RC, CloudCompare 2.7, AutoCAD Civil 3D 2016 student version
Record:	Scaled 3D model, scaled orthophoto plans (Figs. 44-46)
Short description:	The church is situated in the central part of the village located on a sloping terrain. Spacious but compact, the church was built in the Early Gothic style (ca. 1330) as a single-aisle building with the square-in-plan presbytery, to which the sacristy was added on the northern side. The structure was modified according to the Late Gothic style (end of the 15 th c.) and was later subject to Baroque modifications (mainly of the interior) at the turn of the 17 th to the 18 th c.. The building was partially repaired in 1932 when an anteroom was added to the western facade. The recording was focused on the facades, which were subject to the reconstruction and required orthophoto plans to a specific scale in order to capture the condition of the brickwork. A scaled complete 3D model of the church exterior was used for making orthophoto plans to the required scale. The recording was performed with a handheld camera.

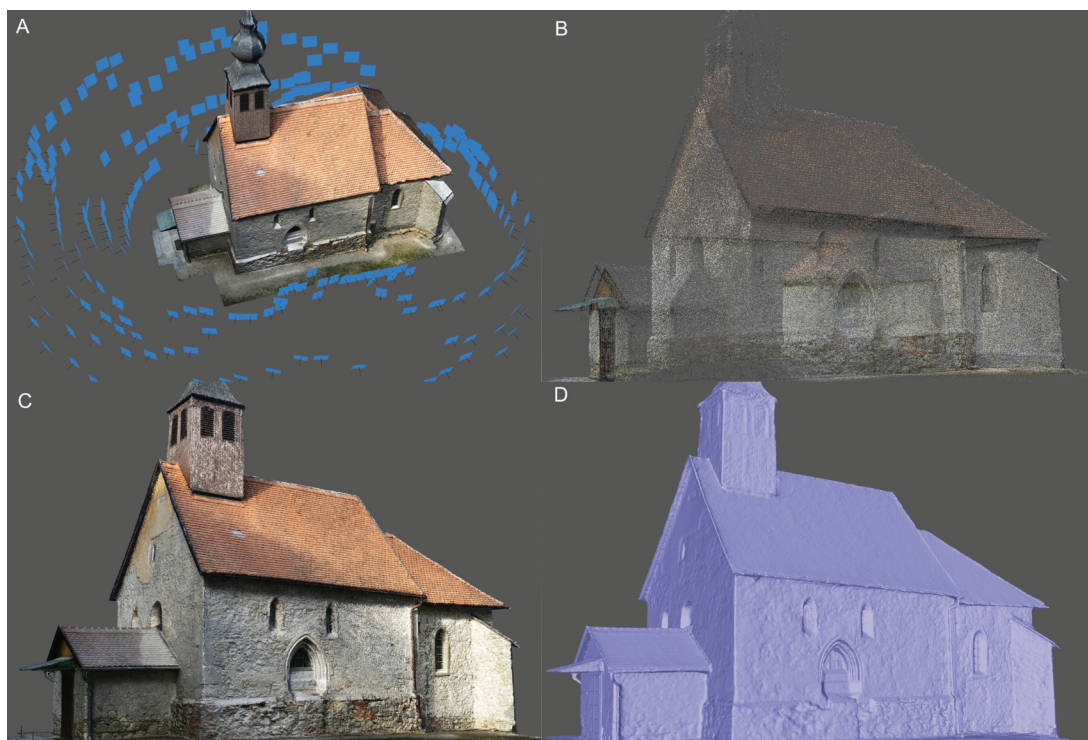


Figure 44. Sazdice (Slovakia). Medieval church, 14th century. lBM (249 photos, 24Mpx).
A: distribution of cameras, B: sparse point cloud, C: sense point cloud, D: meshed 3D model.



Figure 45. Sazdice (Slovakia). Medieval church, 14th century. IBM.
Textured 3D model – isometric view.

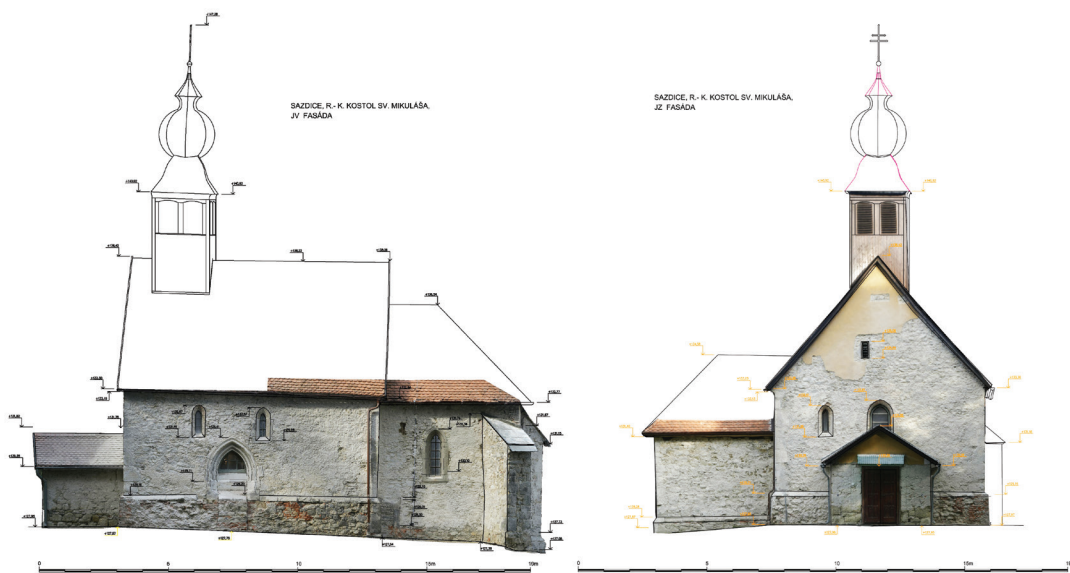


Figure 46. Sazdice (Slovakia). Medieval church, 14th century. IbM. Textured 3D model – isometric view. Examples of 2D documentation deliverables derived from the 3D model – ortho-view of the facades.

Žehra, Hodkovce, Manor house

Site type:	Manor house
Location:	Žehra, Hodkovce, Spišská Nová Ves District, E Slovakia
Dating:	18 th -19 th century
Recorded parts:	exterior (facades), roof, interior
Recording technology:	IbM, TLS
Recording equipment:	Cameras Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX) and Sony Nex7, TLS Leica C10, UAV, TS, GNSS Rtk Rover (differential GPS)
Software:	DxO Optics Pro 10.0, Agisoft Photoscan 1.1.0, CapturingReality RC, CloudCompare 2.7, Microstation V8i trial version, Cyclone
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans and cross-section views (Figs. 47-52).
Short description:	<p>3D recording of the manor complex in Žehra, Hodkovce was completed in 2014. The recording included the manor house, adjacent park with a garden, a farm building and 2 other structures (church and garden architecture) situated in the forested part of the park. The whole complex is situated on a slope descending in W-E direction. The manor house is a four-wing single-floor building with internal courtyard/garden. The ground floor has the entrance side facing the park; the facade is divided by elongated windows lined with bands organised into lesene (pilastre-strip) frames. There are two windows in the centre of the east wing facade that has pilasters on the sides and a cornice on the wall; stucco ornaments were moulded in a semi-circular pediment above the windows. There is a large gable above them, originally with vases on the sides. The elevated terrace in front of the facade is accessed by two staircases with conical railing. In the east wing corners there are towers with elevated storied pavilions with garrets. The west wing was added in the 19th c. The central part of the west wing consists of an open arcade set with Prussian arches and with strips in between the arches; it enabled access from the west part of the park to the manor's internal courtyard. The arcade is flanked (the north and south) with stylised square bastions, which are elevated one floor up and topped with stylised crenellation. The ground floors of individual wings are covered with saddle roof made of an artificial material. The open area of the garden in the park extends along the west and south sides of the manor. A pathway runs directly in front of the east facade. To the north, fence delimits the park area. The exterior of the manor was recorded with TLS (Leica C10), IbM methods, and using an UAV. The recording for IbM was difficult due to unfavourable weather with bad lighting conditions and occasional rainfall. Since the roof was not recorded with TLS, the only source of data was IbM. TLS data were processed in the Cyclone and IbM data in Agisoft Photoscan and Capturing Reality RC. Data from both digitising technologies were merged by registration in CloudCompare. The interior of the manor was documented solely with TLS. With regard to the elaborate interior structuring, a large number of camera positions was required. The digitisation of narrow and spatially complex rooms was very difficult because the scanner had to be moved many times and thus the number of positions grew. Registration of the data was carried out by the total station used for measuring the GCP.</p>

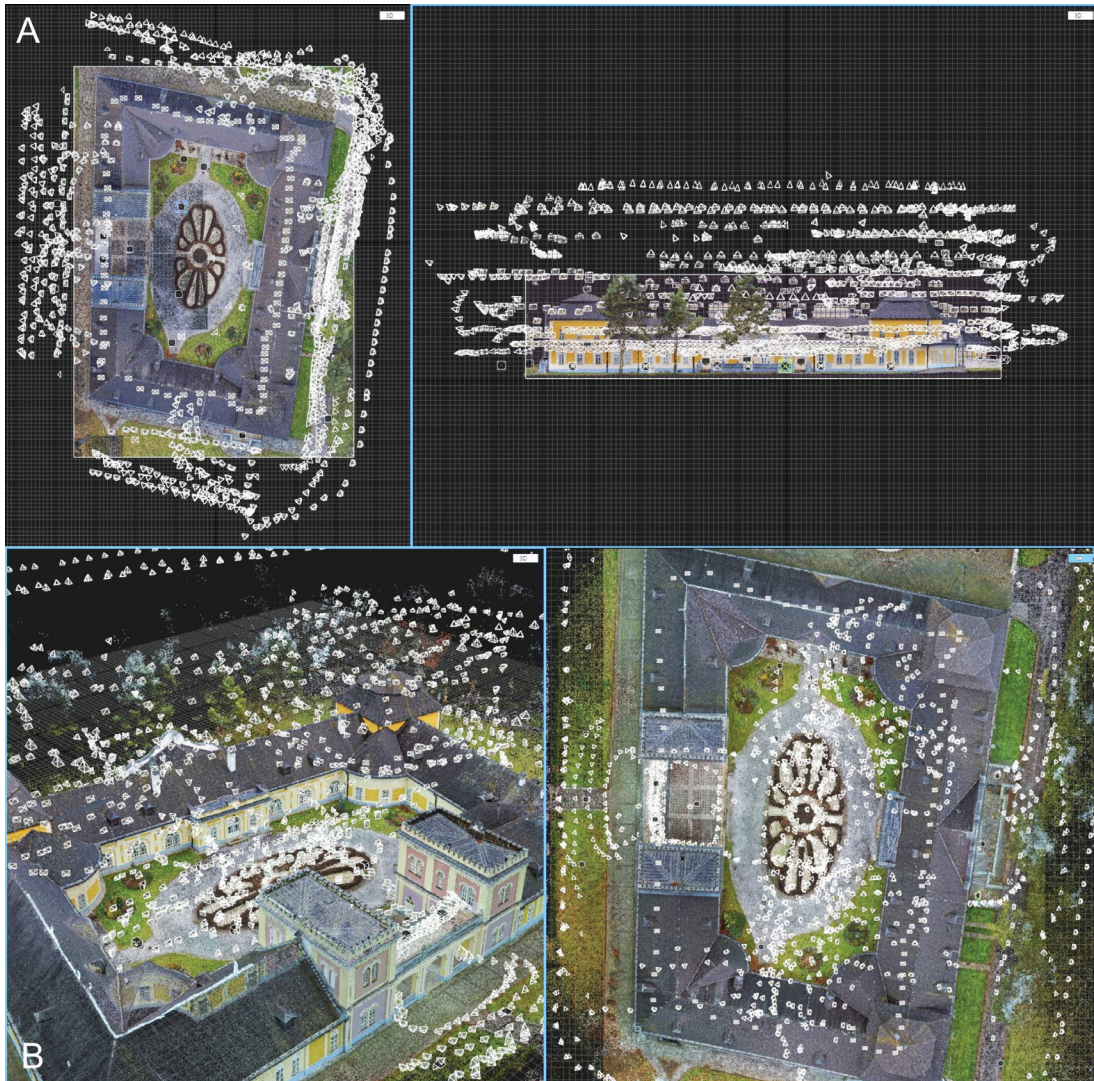


Figure 47. Žehra, Hodkovce (Slovakia). Manor house (18-19th century), exterior. lBM in combination with TLS (1520 photos 24Mpx, 41 TLS stations). Distribution of cameras and stations. A: outer facades, B: inner courtyard.

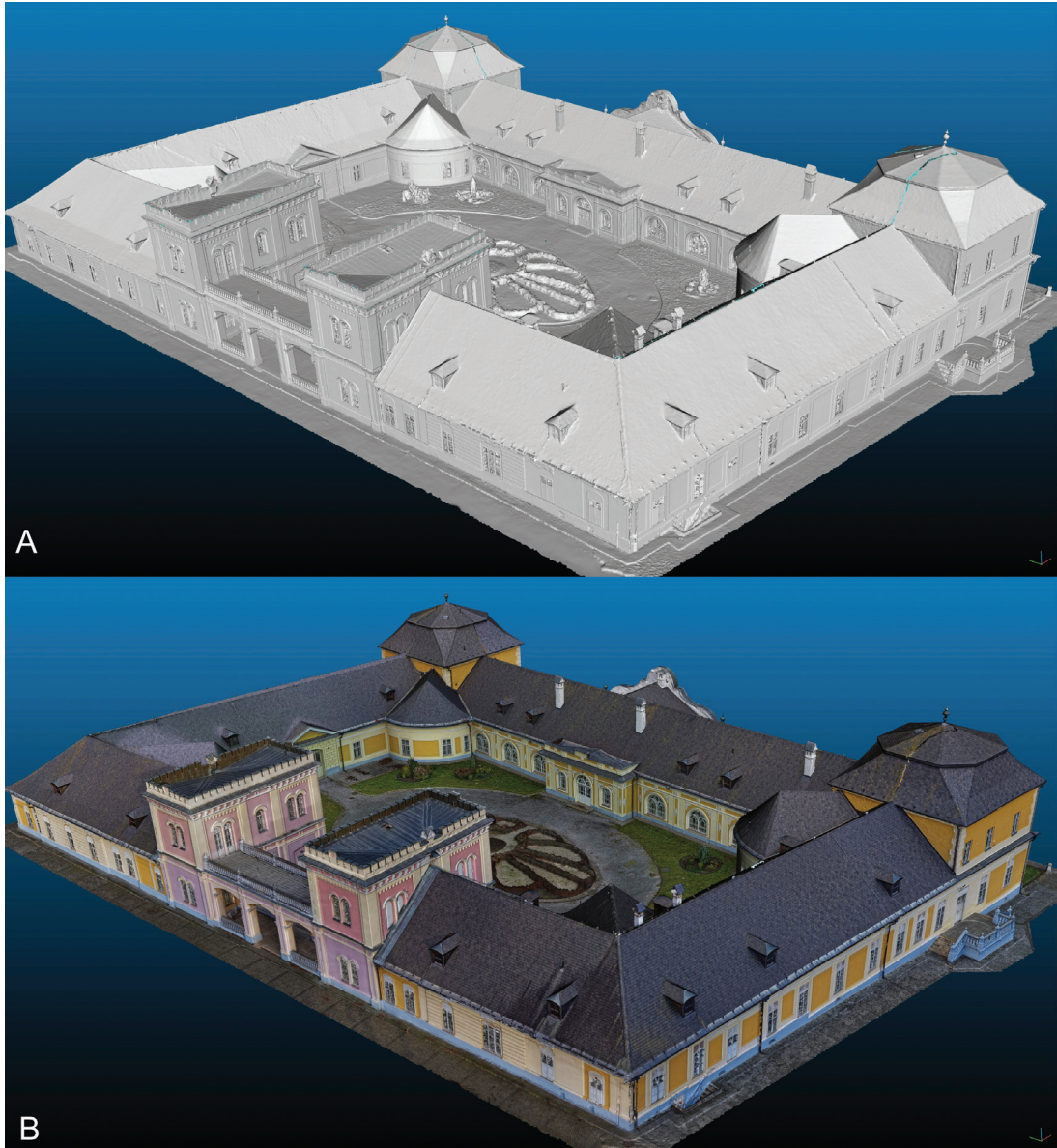


Figure 48. Žehra, Hodkovce (Slovakia). Manor house (18-19th century), exterior. lBM in combination with TLS. Isometric views. A: shaded 3D model, B: textured 3D model.

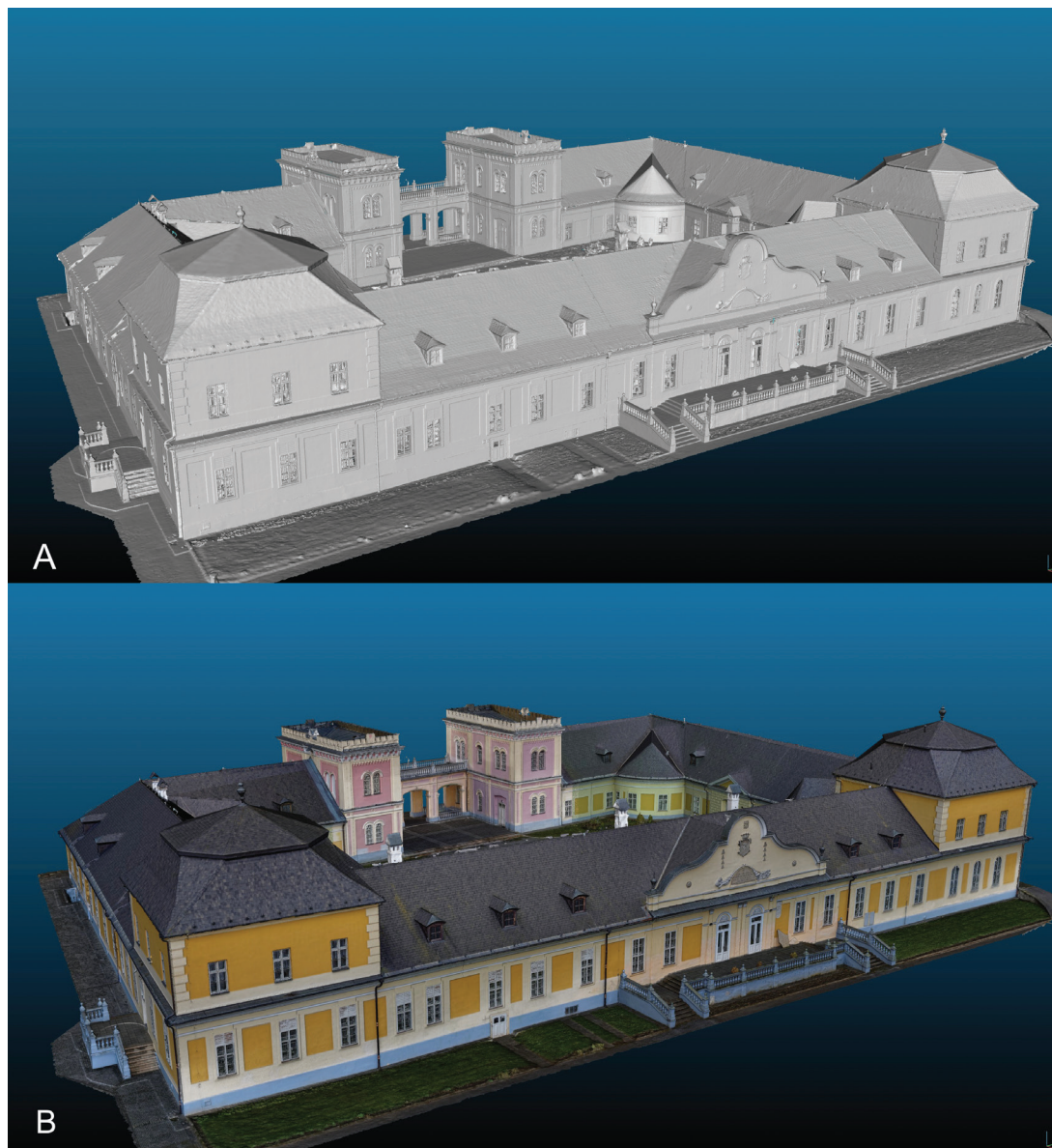


Figure 49. Žehra, Hodkovce (Slovakia). Manor house (18-19th century), exterior. lBM in combination with TLS. Isometric views. A: shaded 3D model, B: textured 3D model.



Figure 50. Žehra, Hodkovce (Slovakia). Manor house (18-19th century), exterior. lBM in combination with TLS. Ortho-views of the facades.

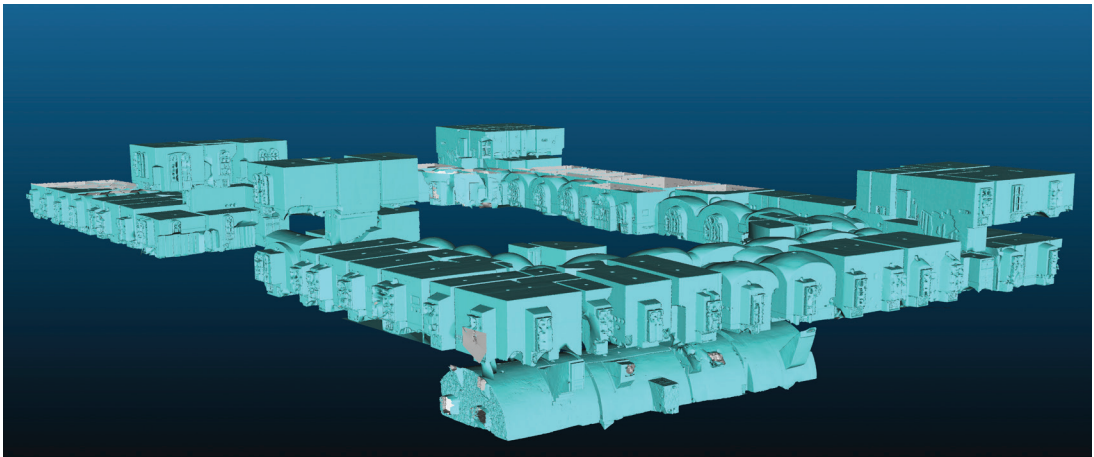


Figure 51. Žehra, Hodkovce (Slovakia). Manor house (18-19th century), interior – 3 levels. TLS (168 TLS stations). Shaded 3D model.

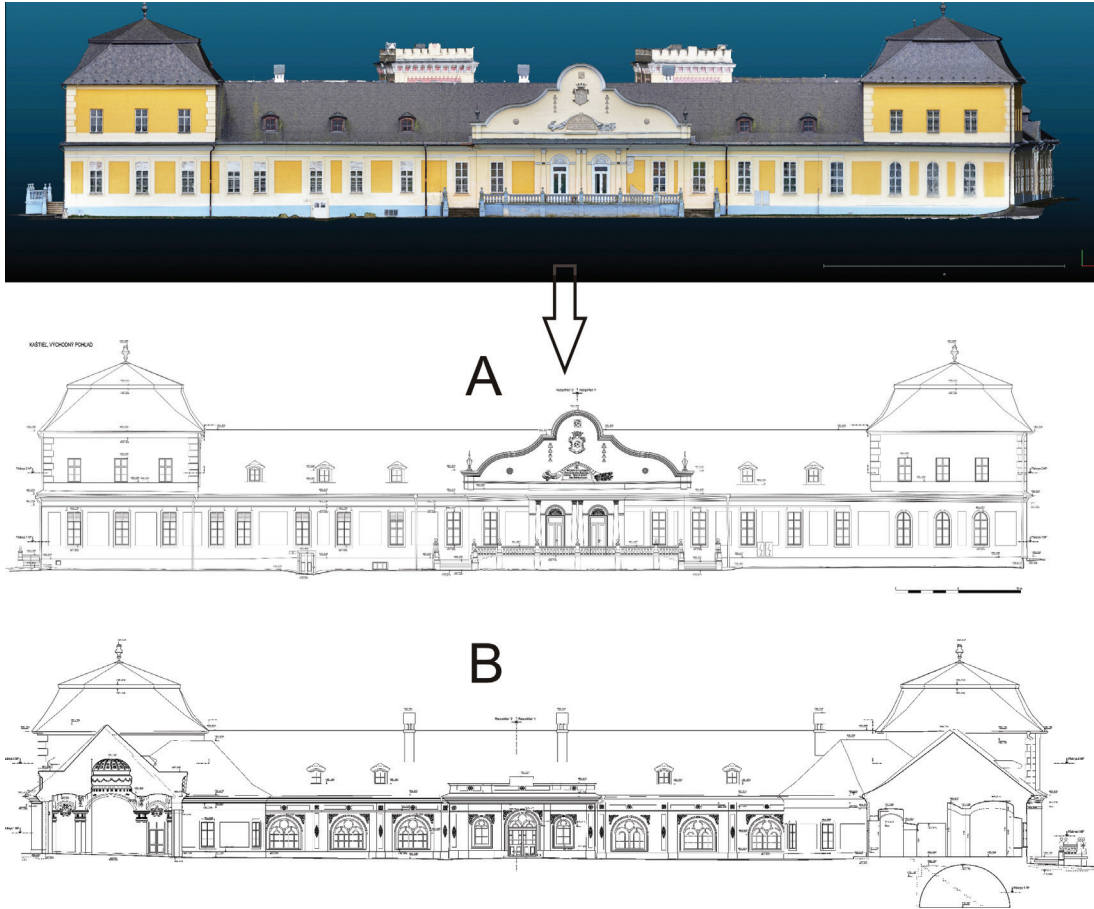


Figure 52. Žehra, Hodkovce (Slovakia). Manor house (18-19th century), exterior.
A: example of 2D vectorisation of ortho-rectified east facade, B: example of 2D documentation derived from the 3D model – cross-section.

Žehra, Hodkovce, Neo-Gothic church

Site type:	Church
Location:	Žehra, Hodkovce, Spišská Nová Ves District, E Slovakia
Dating:	19 th century
Recorded parts:	Exterior (facades), roof, interior
Recording technology:	IbM, TLS
Recording equipment:	Cameras Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX) and Sony Nex7, TLS Leica C10, UAV, TS, GNSS Rtk Rover (differential GPS)
Software:	DxO Optics Pro 10.0, Agisoft Photoscan 1.1.0, CapturingReality RC, CloudCompare 2.7, Microstation V8i trial version, Cyclone
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans and cross-section views (Figs. 53-59)
Short description:	<p>The neo-Gothic church building is located in a park, in a densely forested area on undulating terrain. The church is oriented in the E-W direction, with the west end sitting on significantly elevated terrain. The transition between the single-aisle building and the semi-circular sanctuary is smooth and without breaks in the facade. There is a marked neo-Gothic portal on the west side. The width of the aisle and the sanctuary is greater in the east section, which gives the building an asymmetrical ground plan, with extension in the east part. The narrow, polygonal tower is situated to the west from the aisle and its roof is covered with sheet metal; the tower significantly exceeds the height of the saddle roof over the church aisle, also covered with sheet metal. The west part of the structure consists of a funeral chapel with neo-Gothic portal at the west end and a saddle roof covered with sheet metal. The external facades were documented by TLS (Leica C10) and IbM. The roofs were documented by IbM using an UAV. The usage of the drone was considerably complicated by the dense trees. The relatively low amount of light during the documentation process required subsequent detailed editing of the photos prior to their processing in the selected software environment. The absence of plasticity and texture of the smooth, monochromatic plastering of external facades caused a low number of SIFT points in the bundle adjustment in the software processing of IbM data and, consequently, high level of noise in the creation of the point cloud. This could be partially improved by HDR filtration of the photos in the phase of editing of the raw photographic material. The church interior was documented solely by TLS. The TLS data were registered in Cyclone. IbM data were processed in Agisoft Photoscan and CapturingReality RC. The DxO Optics Pro was used for basic editing of the photographic material. The processed and TS-georeferenced TLS data and outputs from IbM were merged in CloudCompare.</p>

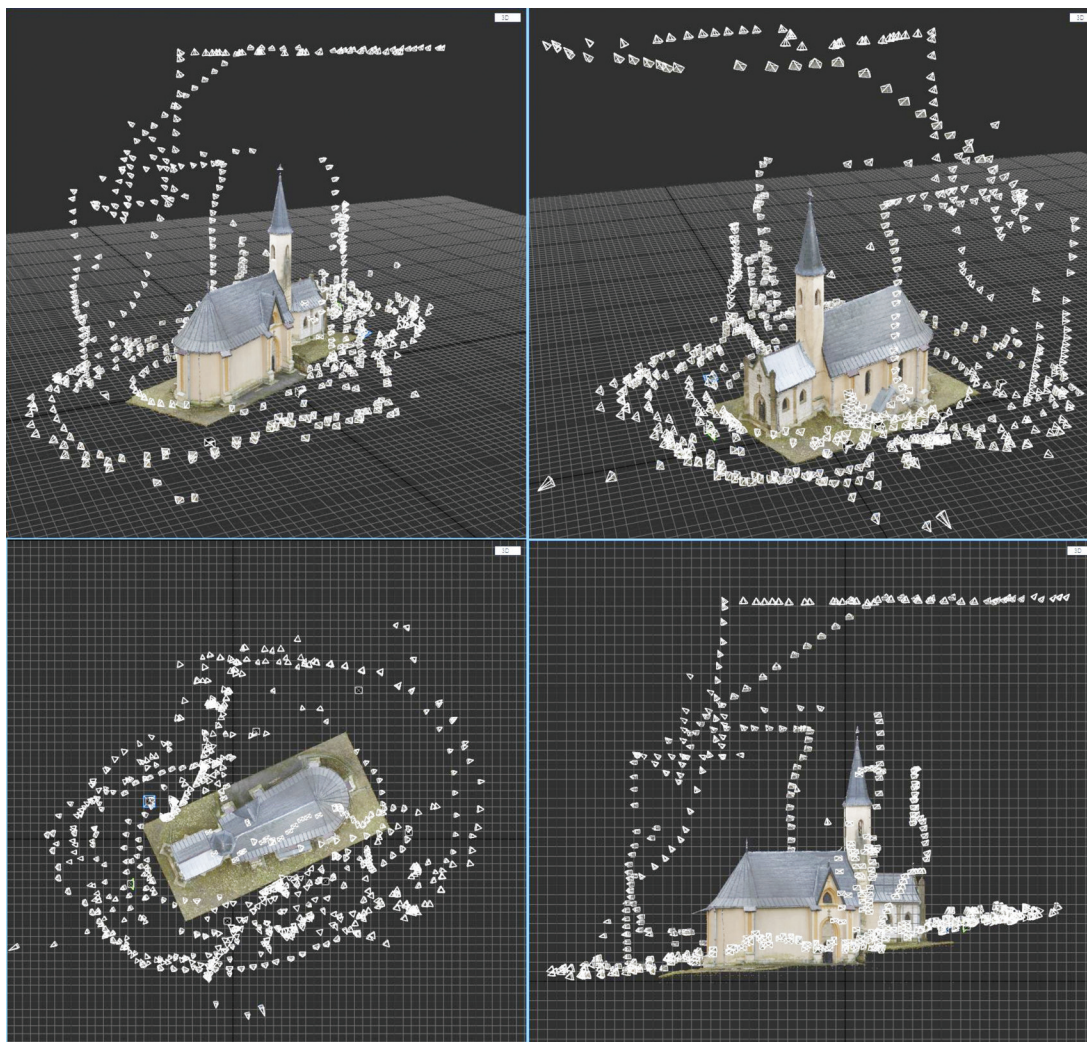


Figure 53. Žehra, Hodkovce (Slovakia). Neo-Gothic church (19th century), exterior. lBM in combination with TLS (713 photos 24Mpx, 10 TLS stations). Distribution of cameras and stations.

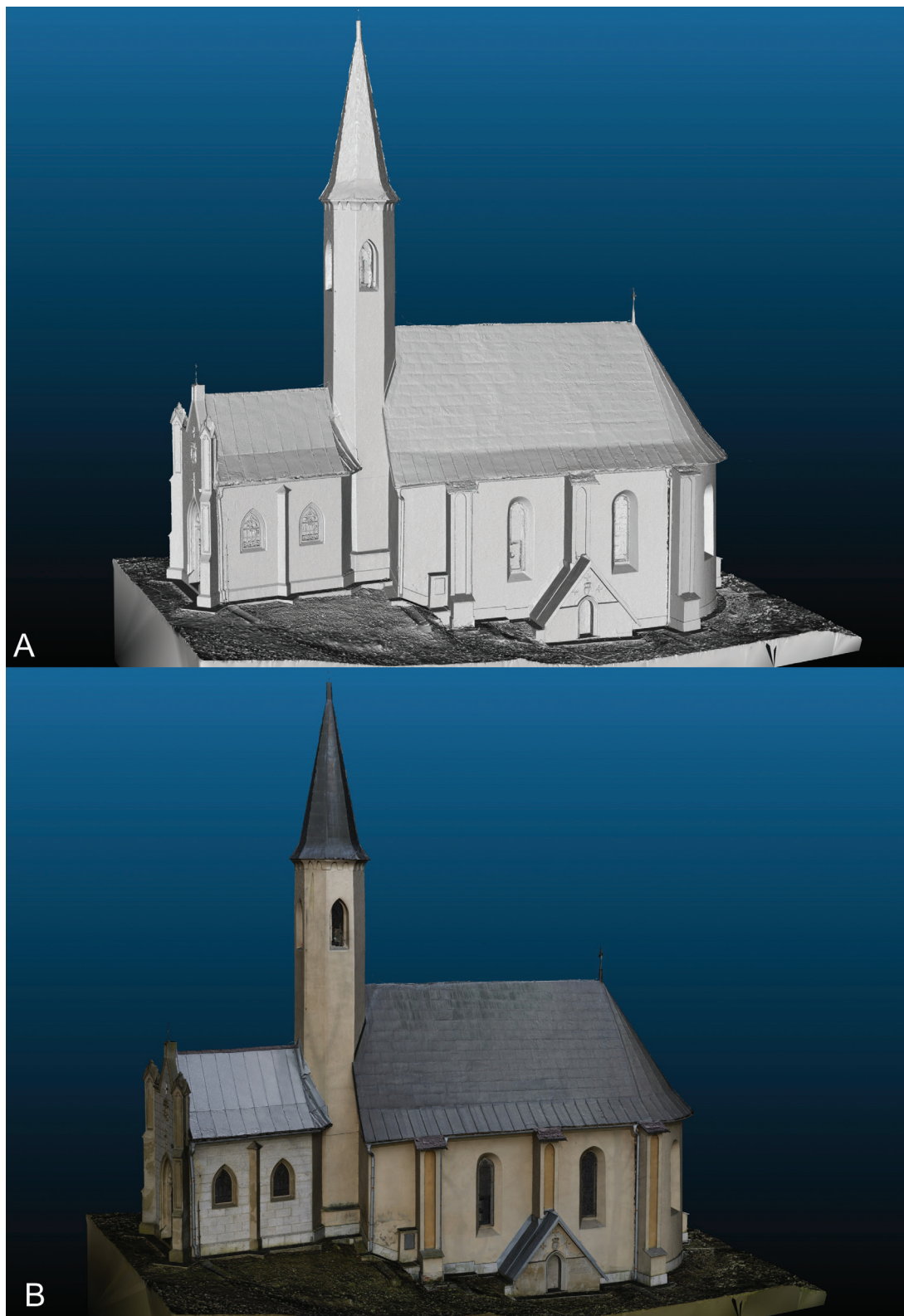


Figure 54. Žehra, Hodkovce (Slovakia). Neo-Gothic church (19th century), exterior. lBM in combination with TLS. Isometric views. A: shaded 3D model, B: textured 3D model.

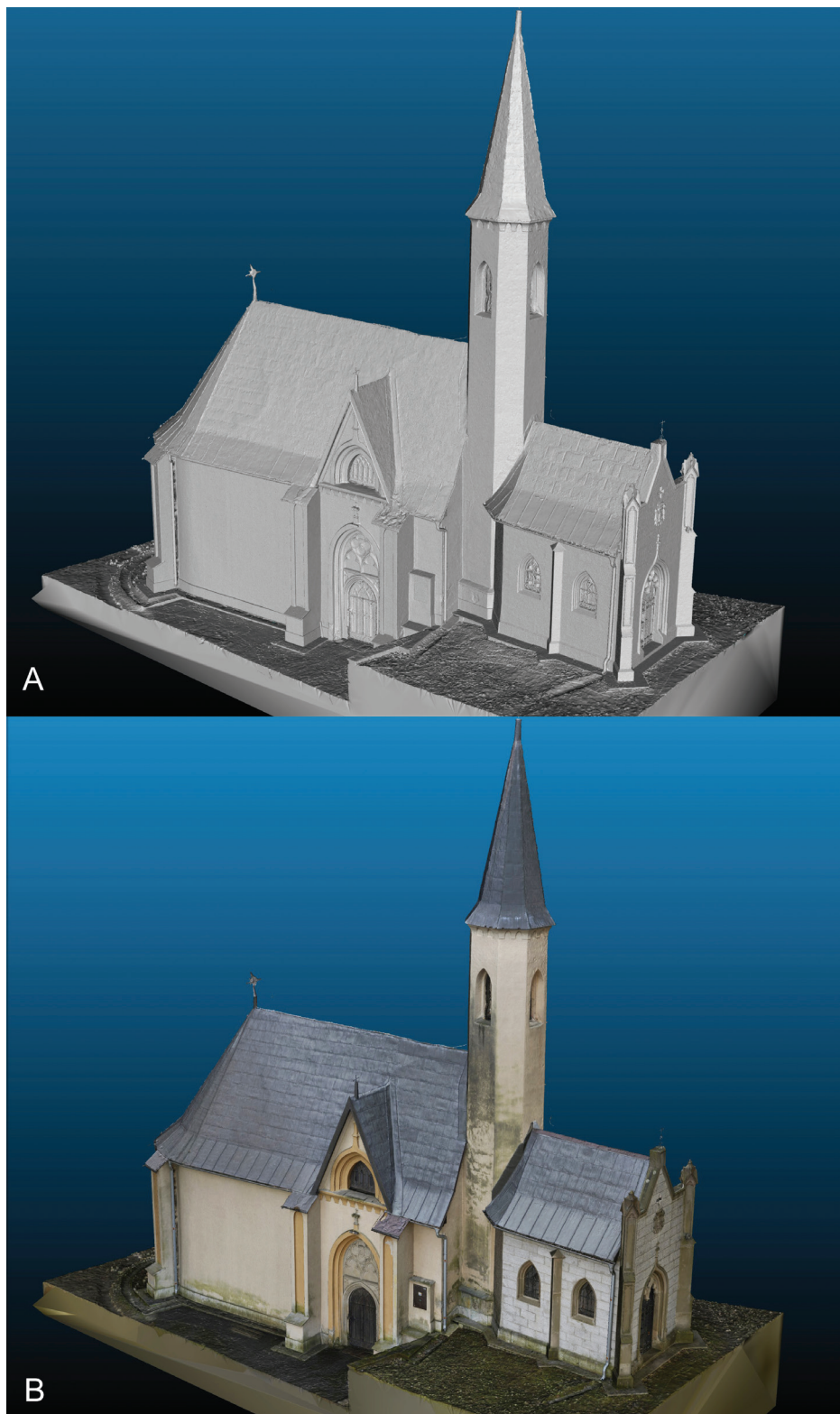


Figure 55. Žehra, Hodkovce (Slovakia). Neo-Gothic church (19th century), exterior. lBm in combination with TLS. Isometric views. A: shaded 3D model, B: textured 3D model.



Figure 56. Žehra, Hodkovce (Slovakia). Neo-Gothic church (19th century), exterior. lBM in combination with TLS. Ortho-views of the facades.

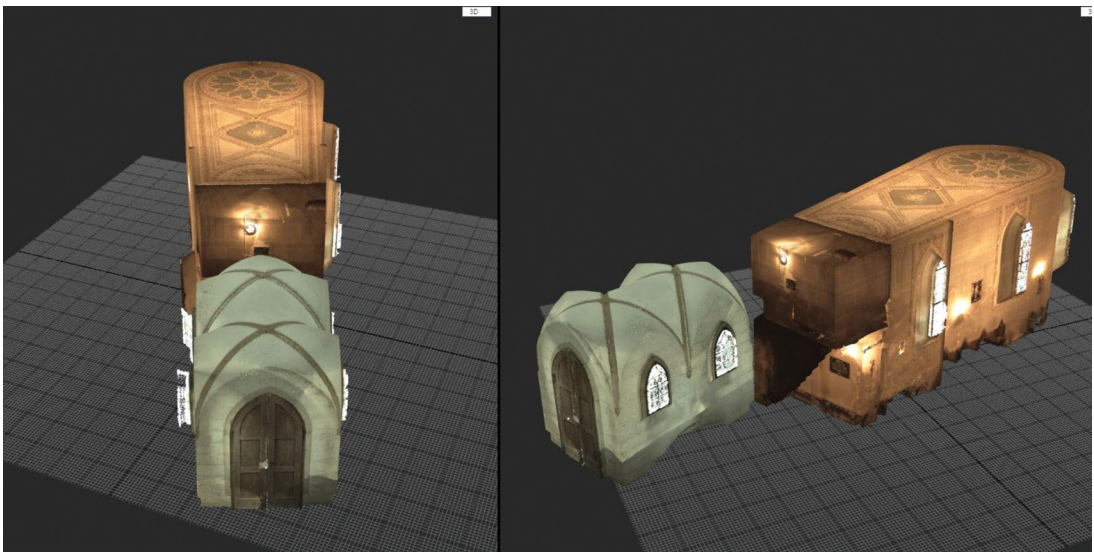


Figure 57. Žehra, Hodkovce (Slovakia). Neo-Gothic church (19th century), interior. TLS (9 TLS stations). Dense point cloud.

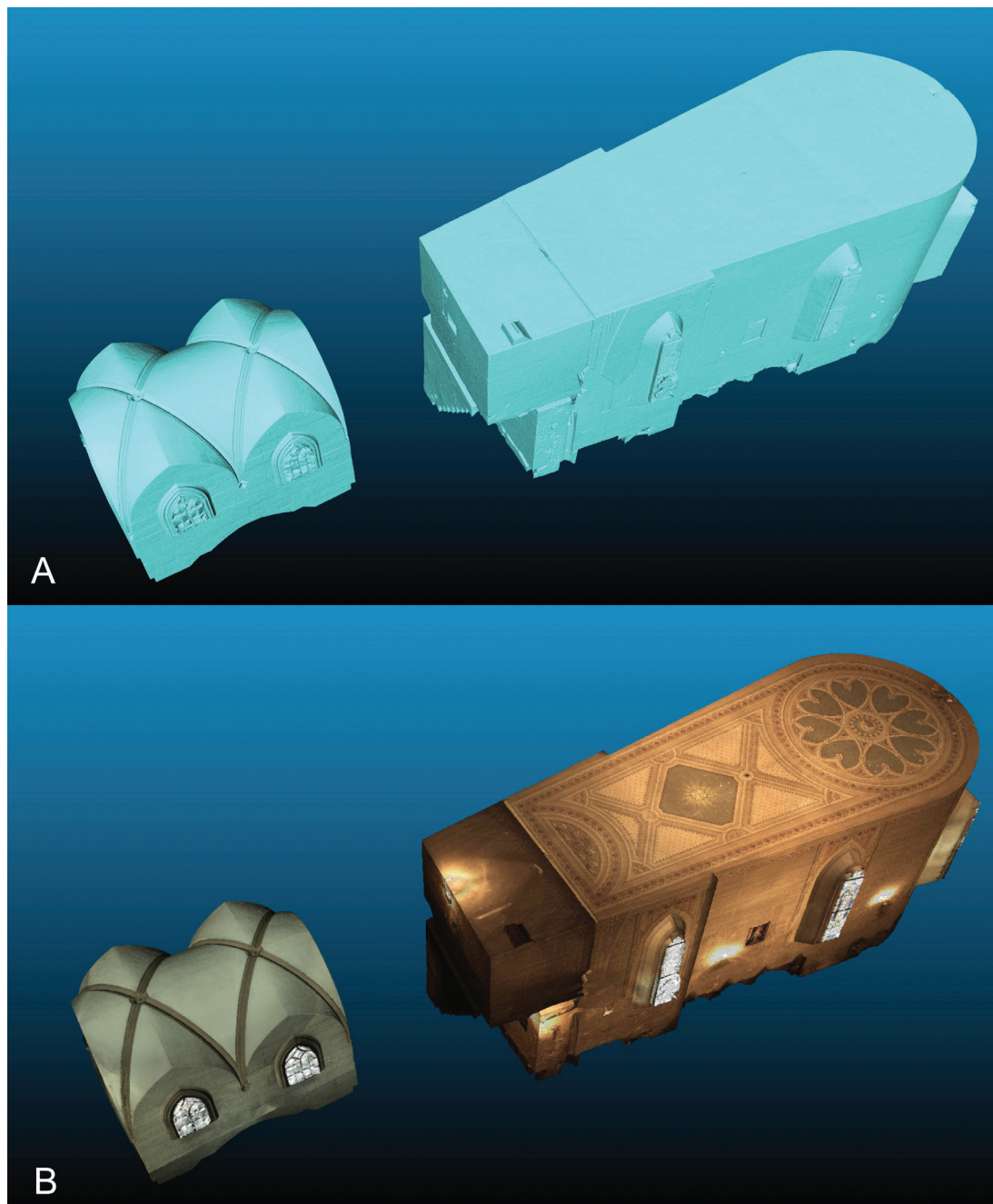


Figure 58. Žehra, Hodkovce (Slovakia). Neo-Gothic church (19th century), interior. Isometric views. A: shaded 3D model, B: textured 3D model.

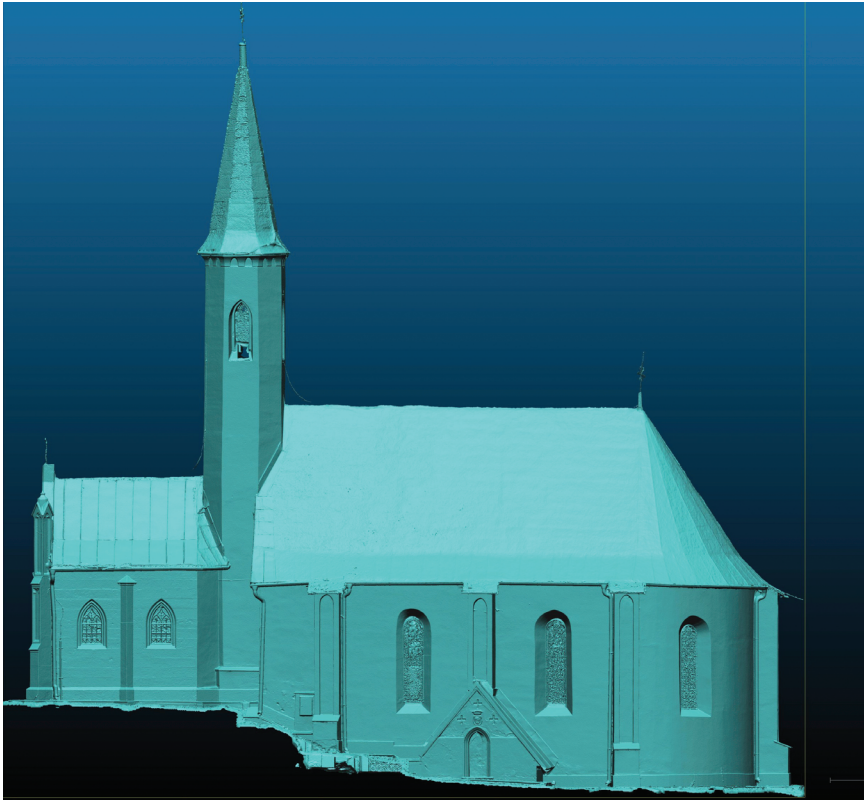


Figure 59. Žehra, Hodkovce (Slovakia). Neo-Gothic church (19th century), exterior. Example of 2D vectorisation of ortho-rectified south facade.

Žehra, Hodkovce, Neo-Gothic architecture

Site type:	Park architecture
Location:	Žehra, Hodkovce, Spišská Nová Ves District, E Slovakia
Dating:	19 th century
Recorded parts:	Exterior (facades), roof, interior
Recording technology:	IbM
Recording equipment:	Cameras Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX) and Sony Nex7, UAV, TS, GNSS Rtk Rover (differential GPS)
Software:	Adobe Photoshop CC, Agisoft Photoscan 1.1.0, CloudCompare 2.7
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans and cross-section views (Figure 60)
Short description:	A fine piece of neo-Gothic park architecture is situated on the south-west end of the green area of the park. It is a block building open on all four sides, with openings topped with pointed arches. It has a simple saddle roof with front (east) and rear (west) gable bearing stucco neo-Gothic ornaments. The structure is visually partially obstructed by trees and low plants growing along the west and the south side. The method of IbM was solely used for the digitisation of the building, whereas the roof area was documented by UAV. The data processing was complicated since smooth, white plastering that did not create sufficiently marked texturing elements. Thorough editing of the raw photos was necessary prior to their final processing (application of HDR filter in Adobe Photoshop CC).



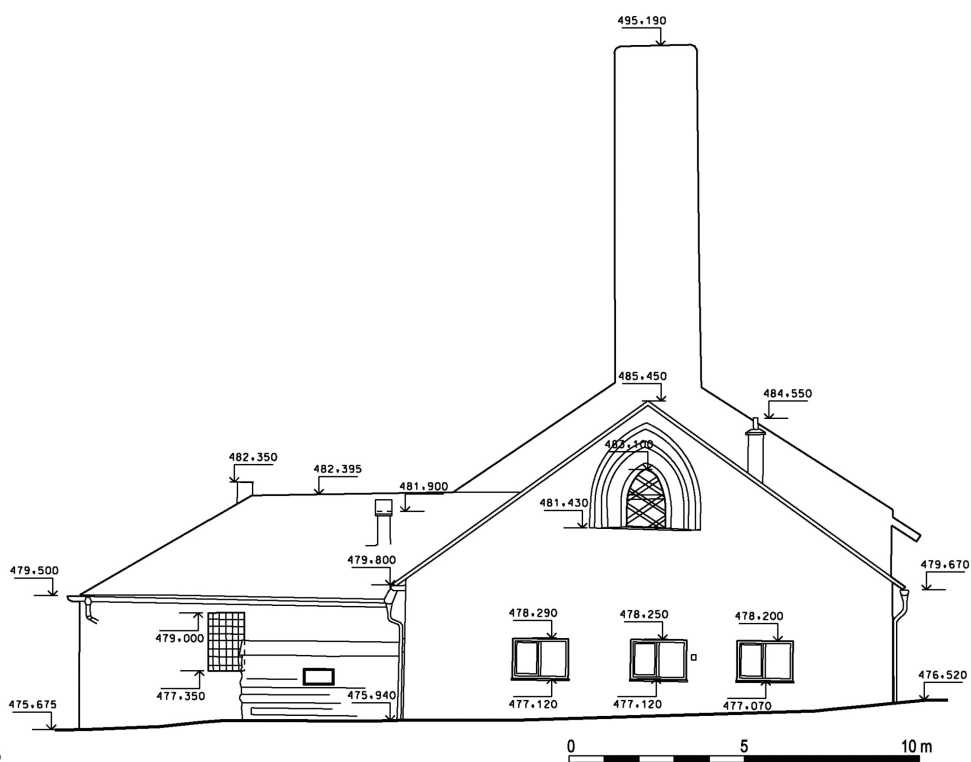
Figure 60. Žehra, Hodkovce (Slovakia). Neo-Gothic park architecture (19th century), exterior. lBM (325 photos 24Mpx). Isometric views of the textured 3D model.
A: visualisation with normals, B: visualisation without normals.

Žehra, Hodkovce, Farm building

Site type:	Farmhouse and auxiliary buildings
Location:	Žehra, Hodkovce, Spišská Nová Ves District, E Slovakia
Dating:	19 th century
Recorded parts:	Exterior (facades), roof
Recording technology:	IbM
Recording equipment:	Cameras Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX) and Sony Nex7, UAV, TS, GNSS Rtk Rover (differential GPS)
Software:	Adobe Photoshop CC, Agisoft Photoscan 1.1.0, CloudCompare 2.7
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figure 61)
Short description:	<p>The farm building is located on the eastern side of the park. It is a block single-floor building, with the longer axis orientated in the east-west direction. It is located on a slope gradually rising to the west. A high chimney rises from the central part. The structure has a saddle roof covered with sheet metal. The eastern and western walls are shorter and topped with gables. The western gable masonry is interrupted with a neo-Gothic pointed arch. Both longitudinal facades are completed with a row of rectangular glazed windows. The structure was documented by the method of IbM with the application of an UAV. The photos were shot under unfavourable lighting conditions (low luminosity), as a result of which the photo documentation from the UAV also contained insufficiently sharp images due to the low value of aperture (the f-number). The low level of luminosity required setting of the aperture value of the camera to below F 5.6; otherwise, the high f-number could result in the longer time of exposure and this would produce highly blurred photos due to the drone movement. Increasing the ISO value was not a solution in this case, as it would mean additional layering of the noise level. Recording of the longitudinal facades from the level of the surrounding terrain was complicated due to fenced areas for animals in the close proximity. The problems with detection of the sufficient number of SIFT points on the images of the facades, which are flat and covered with smooth white plastering, again appeared. Photo editing was, therefore, necessary (Adobe Photoshop CC by applying the HDR filter).</p>



A



B

Figure 61. Žehra, Hodkovce (Slovakia). Farm building (19th century), exterior. *IbM* (472 photos, 24Mpx). A: dense point cloud, B: Example of 2D documentation derived from the 3D model – view of the facade.

Žehra, Hodkovce, Park

Site type:	Park with garden
Location:	Žehra, Hodkovce, Spišská Nová Ves District, E Slovakia
Dating:	19 th century
Recorded parts:	Ground plan
Recording technology:	IbM
Recording equipment:	Camera Sony Nex7, UAV, TS, GNSS Rtk Rover (differential GPS)
Software:	Adobe Photoshop CC, Agisoft Photoscan 1.1.0, CloudCompare 2.7
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figure 62)
Short description:	<p>The park has an elongated shape and stretches in the east-west direction. It is divided into two approximately equally large parts, with the centrally placed manor house. The area adjacent to the western wing of the manor house represents a French garden with a central fountain and pathways covered with gravel. Other parts of the park are of a more 'casual' nature, including areas occupied by deciduous and coniferous trees. A large part of the eastern half of the park is currently used as an open space for keeping horses and other farm animals. The part under trees, to the west, is on a considerably undulating terrain, upwardly sloping towards the west. The 3D digitisation was conducted by IbM with an UAV. Vertical images of the whole park area were made from a relatively constant height. The garden area with fountain was recorded from a much smaller flight height (to capture a higher level of details). The flight sequences were processed separately and were later merged. The GCP, measured with TS, were printed in A2 format in order to be visible from the greater flight height. In the meshing stage of the data processing, it became obvious that, in the case of data collected from a greater height, branches of smaller trees could not be captured with sufficient resolution. Thus, although the point cloud captured the majority of trees in a compact manner, it was not dense enough to allow creating of a compact mesh of branches of smaller trees. In such a case, it is necessary to complete the data with images made from lower heights in order to capture individual branches as well.</p>

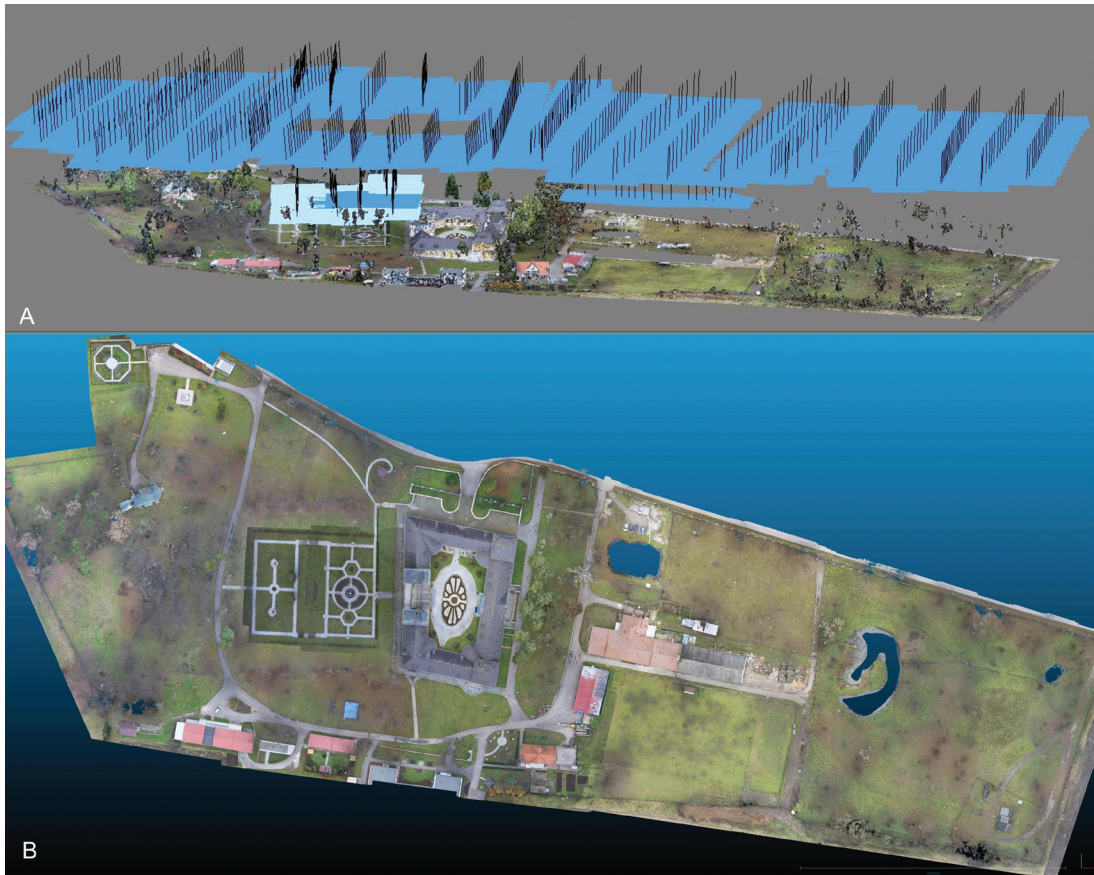


Figure 62. Žehra, Hodkovce (Slovakia). Park, 19th century. IBM (800 photos 24Mpx).
A: distribution of cameras, B: nadir view of the textured D model.

Banská Belá, mine

Site type:	Mining tunnels
Location:	Banská Belá, Banská Štiavnica District, Central Slovakia
Dating:	15 th century
Recorded parts:	Interior of mining tunnels
Recording technology:	IbM
Recording equipment:	Camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX),
Software:	DxO Optics Pro 10, Agisoft Photoscan 1.1.0, CloudCompare 2.7, AutoCAD Civil
Record:	Scaled 3D model (mesh), scaled orthophoto plans (Figs. 63-65)
Short description:	<p>The unfinished mining structure (a two-arm mining tunnel) is situated near the former town hall (?) building. The opening is in the area of the first above-ground floor; the tunnel extends perpendicularly to the mass of the rock where it turns at makes an almost right angle and leads to the basement of a medieval burgess house. One part of the tunnel was cut off while another part was blown up by gunpowder. There are beam holes on the tunnel walls, probably remaining from the wooden formwork supporting the ceiling. The collection of data was done with a handheld camera. A camera stand could not be used due ti the limited space, and resetting of the camera and re-compositioning of the photos would be slow and would significantly increase the working time. The most important principle followed during the photographic recording was to take care of the lighting to avoid shadows, which would cause artificial shadows in digitising. In practice, the best method was to place a halogen lamp perpendicularly to the selected part of the wall and two lamps at a certain distance from it, at 45 degrees angle to the centre of the part of the wall documented. This prevented creation of shadows in the rock crevices and, at the same time, maintained the sense of plasticity. In this way, it was possible to obtain the relevant input data with sufficient light parameters, which, after the basic editing (DxO Optics Pro), could be processed in software for IbM with high-quality output and without a non-standard/high level of noise. In order to define the scale of the 3D model and of the output derived from the 3D documentation, maximum distances between ad-hoc indicated GCP (cross-shaped marks drawn by a chalk because standard markers could not be fixed properly on damp walls) were measured by means of a laser meter. The measurements were entered manually as distance parameters of manually defined markers in the relevant software during processing.</p>

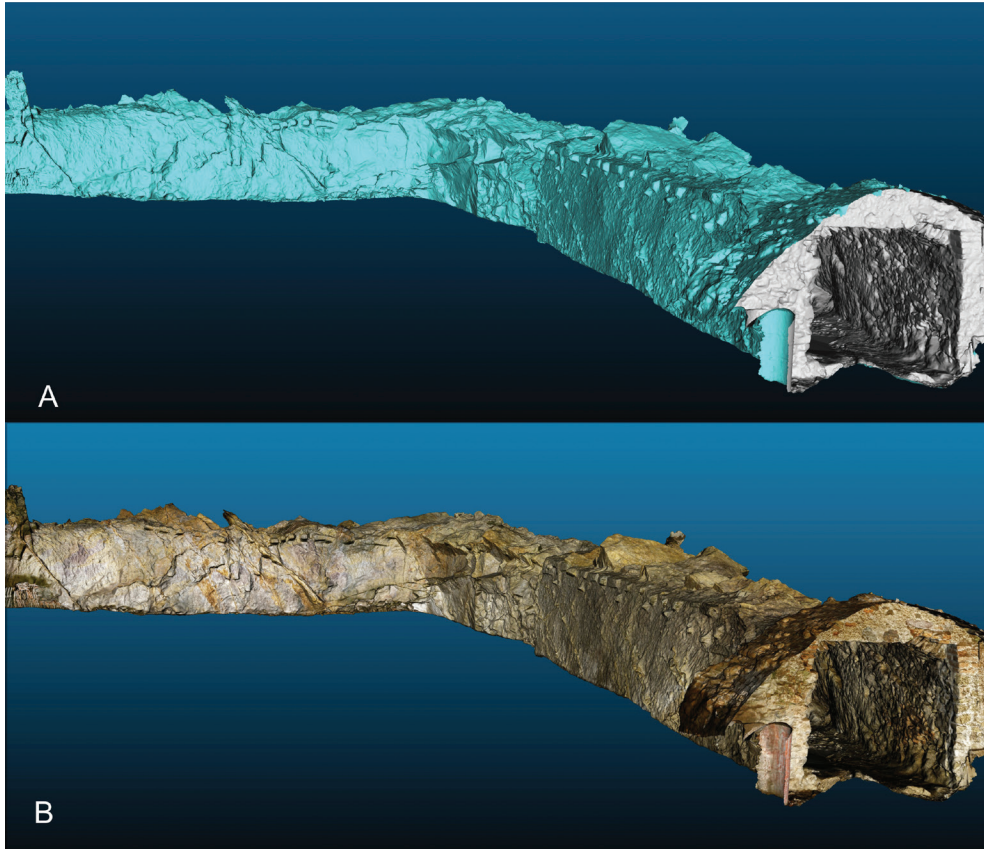


Figure 63. Banská Belá (Slovakia). Mining site, 15th century. IbM (691 photos 24Mpx). Isometric views. A: shaded 3D model, B: textured 3D model.



Figure 65. Banská Belá (Slovakia). Mining site, 15th century. Example of 2D documentation derived from the 3D model.

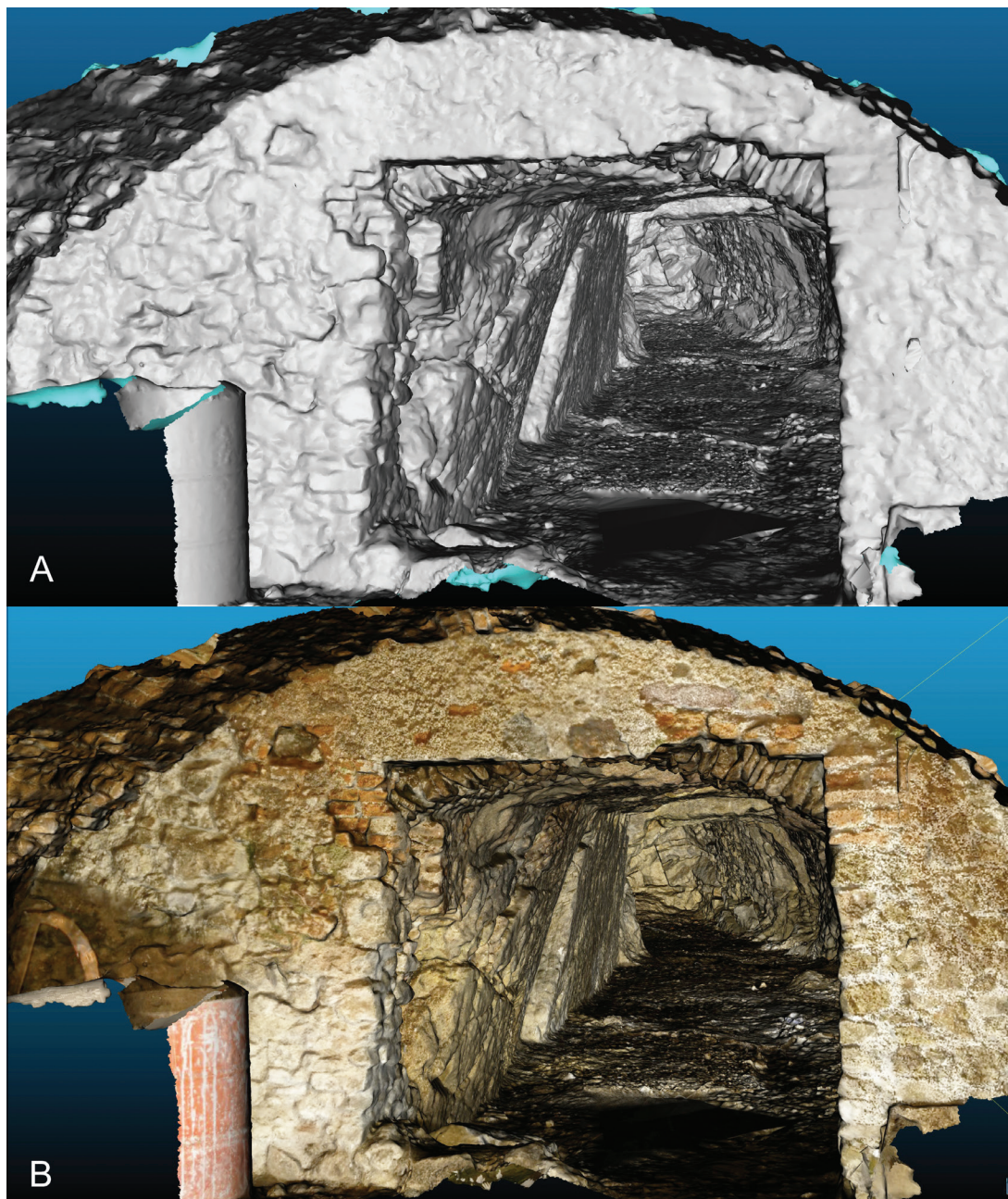


Figure 64. Banská Belá (Slovakia). Mining site, 15th century. lBM.
Isometric views A: shaded 3D model, B: textured 3D model.

Rajec, Burgess house

Site type:	Burgess house, basement
Location:	Rajec, Rajec District, N Slovakia
Dating:	17 th century
Research type:	Interior
Recording technology:	lbM
Recording equipment:	Camera Nikon D90 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX)
Software:	DxO Optics Pro 10, Agisoft Photoscan 1.1.0, CloudCompare 2.7
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans (Figs. 66-69)
Short description:	<p>The Burgess house (nowadays a museum) is situated in a row of buildings on the southern side of the central historical square. Its northern (front) side has an entrance recess area slightly inclining to the street demarcating this side of the square. The object of 3D documentation was the basement which is situated under the right/west section of the burgess house. The basement can be accessed by a staircase from the central corridor of the ground floor. The staircase leads to a small central room, from which entrances lead into the southern and northern room. The ceiling of the southern room is represented by a compressed barrel vault with two pairs (one on each long side) of parallel pentagonal lunettes intersecting the vault. There is a vent opening in the southern wall leading to the inner courtyard. The northern room has a simple compressed barrel vault. Two vent openings are situated in the northern wall of this room, leading to the street delimiting the square. The documentation was created by the lbM. Data collection was done with a handheld camera without the stand. The area was lighted with two halogen lamps. One of them had a fixed position at the level of the underlying terrain, the other one was manipulated by the supporting assistant and always lighted one specific area, with the beam directed perpendicularly to the centre of the area. The rooms were documented and processed separately and were later merged in the single coordinate system. Although the wall and vault surfaces are covered with monochromatic white plastering, thanks to the thorough editing of individual photos prior to their processing (DxO Optics Pro), a sufficient number of SIFT points was identified on the images. The resulting 3D model thus contains only a minimum level of noise.</p>



Figure 66. Rajec (Slovakia). Burgess house (16th century), cellar. lbM (217 photos 12Mpx).
A: example of raw photos with markers indicating control points, B: distribution of cameras.

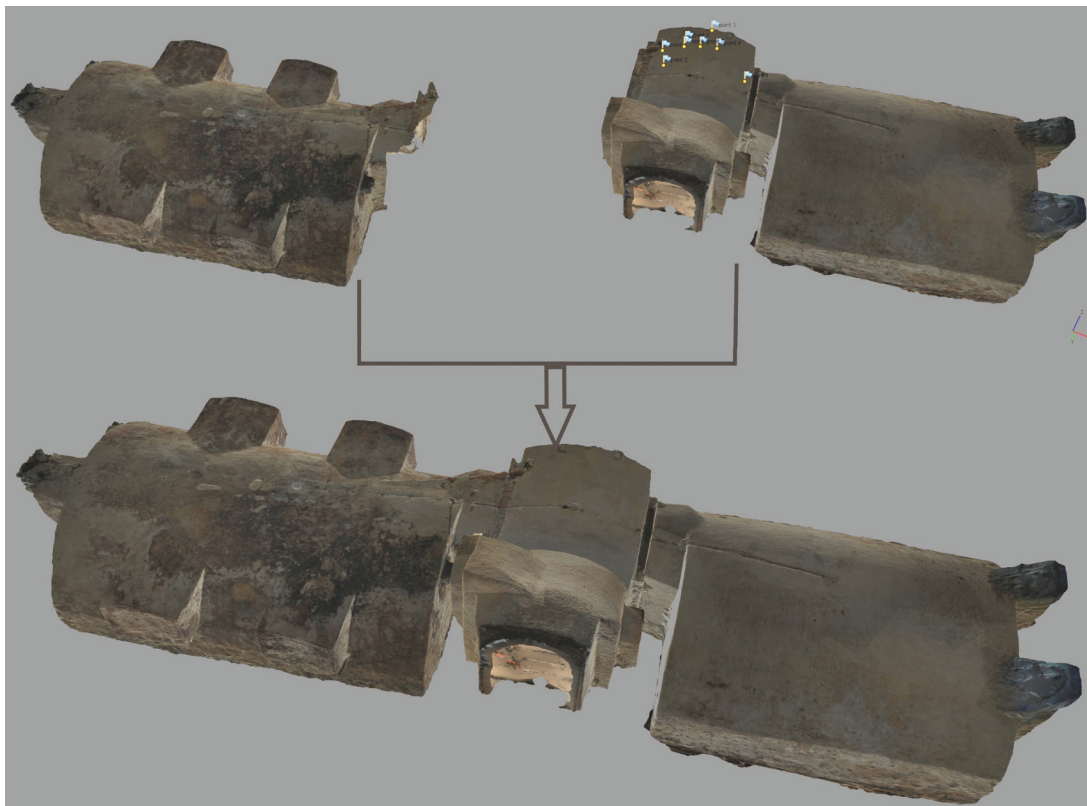


Figure 67. Rajec (Slovakia). Burgess house (16th century), cellar. IbM modeling. Depiction of the alignment of cellar rooms processed individually through the control points.



Figure 68. Rajec (Slovakia). Burgess house (16th c.). IbM, Isometric view of the cellar interior.



Figure 69. Rajec (Slovakia). Burgess house (16th century), cellar.
IBM. Isometric views of the exterior. A: shaded 3D model, B: textured 3D model.

DISCUSSION

Depending on the basic requirements of a digitisation project and the complexity and structuring of the architecture documented, it is necessary to define the strategy of 3D documentation, including the selection of digitising technologies and technical aids and tools. It is advisable to prepare a general digitisation scenario for more complex objects on the grounds of thorough reconnaissance of the area in question. Such scenario should determine the time schedule of tasks and the types of technology applied in relation to individual parts of the structure, as well as associated technical tools. In many cases, the project budget also needs to be prepared. It is recommended to make sketch drawings of the positions and the process of documentation and to mark GCP during data collection in the field. The obtained data should be saved in order to enable their simpler and clearer manipulation during the processing stage.¹

The experience from the presented case studies suggests that, in the case of 3D digitising of interiors, it is better (although more cost-demanding) to use TLS than lBM from the perspective of accuracy requirements. Securing appropriate lighting in interiors tends to be much more demanding (more unfavourable) than in open space. This does not cause problems in the case of TLS with priority regard to the accuracy of surface geometry and not to the texture, but causes substantial complications in the case of lBM.

The basic precondition for successful digitisation of interior by means of lBM is an emphasis on optimal lighting of the documented area and usage of camera stand in combination with adequate setting of the camera (low ISO value, high f-number value nearing the 'sweet spot', correct setting of white balance etc.), which should provide the largest possible depth of field. The whole procedure of data collection is thus very slow and logistically demanding operation. Understandably, demands grow with the growth of complexity and structuring of the documented interior. Moreover, if lBM is applied one must take into account the higher noise level in the data processing than in the case of TLS, and also that the level of noise grows significantly in interior spaces. Interior structuring can lead to problems with registration of the data and often causes significant digitisation shadows. Documentation of parts of a facade around window openings poses a large problem in lBM. These parts have a sharp border, i.e. a break between different lighting parameters; in the case of photo-documentation, this leads to a situation where one part of the image is in overly bright colour or strongly under-exposed in shades of black, whereas the other part of the same image is at the correct exposure. The source data obtained in this way tend to cause digitisation shadows or noise during processing. In such cases, it is necessary to apply HDR processing of images, where exposures of 3 (or more) images with various EV values are merged into one image.

A factor significantly limiting the application of TLS in interior space is the structuring of the area, which may require frequent shifting of the scanner and thus increases the number of positions. A complication is also encountered when measuring (G)CP used for the registration and georeferencing, as they must be interconnected with the points measured in the exterior. However, the greatest disadvantage of TLS is the weak optical

¹ Data should be saved with utmost transparency, especially in the case of multi-floor manor houses with many rooms, where both lBM and TLS methods are applied; otherwise, it can later be very difficult to associate individual datasets with specific spaces.

sensor for making composite images, which serve for the generation of RGB values of the point cloud and are often the only source for texturing the final 3D model. The lighting conditions of internal areas are inadequate and of poor quality and this significantly devalues the texture of the resulting model. The only effective solution is to texture the model, on the grounds of TLS data, in external software using the images made with DSLR.

lBM indisputably proved to be the effective method for 3D digitisation of external facades and roofs. A high monopod stand or an UAV are usually required for the documentation of roof areas and upper floors. The application of TLS is significantly limited in such cases.² The experience from the case studies shows that, the crucial advantage of applying lBM for documenting architectonic exterior (as well as interior) is, from the perspective of accuracy and quality of the resulting model, the quality and sufficient depth of field of the images. These aspects often depend considerably on the light parameters of the environment in which the documentation takes place. Although unfavourable weather conditions can partially be compensated by editing RAW files prior to their processing, sometimes the quality of final images cannot be improved sufficiently to create a 'clean' 3D model.

The structure of the documented surface can also represent a problem. The basis for a clean resulting 3D model with good resolution is the sufficient number of SIFT points³ detected on input images at the stage of bundle adjustment of the SfM process. Insufficient number of SIFT points (or else 'key points') has, as a consequence, noise of the dense point cloud and substantial errors in the resulting 3D model (Figs. 70, 71). The number of captured SIFT points is, to a significant degree, determined by geometry and texture of the surface of the structure documented (Figure 72). The experience from the case studies demonstrates that, flat facades with smooth, monochromatic plastering do not have sufficient amount of texture components and curvature of the surface for detecting the necessary number of SIFT points and the successful final product – the accurate and clean, high-resolution 3D model. As it turns out, standard editing of the input data – the individual images – solves the problem only partially (Figure 73). Apparently, the best solution is to apply strong HDR filtration, which will highlight on the images even very small colour hues as well as minimum irregularities of the surface; this will give texture and plasticity to individual images (Figure 74). However, the increase of plasticity and texture structuring of an image comes at the cost of authenticity of the colour spectrum.⁴ Thus, HDR-filtered images cannot be used for texturing of the resulting 3D model.⁵

The documentation of the premises of the manor house in Žehra, Hodkovce showed that, the combination of TLS and lBM is ideal from the perspective of achieving the highest possible accuracy. TLS guarantees calibrated accuracy of the data measured and, especially, a low level of noise, which is very important in the case of smooth surfaces (such as building walls). lBM enables capturing elevated parts of the structures (such as upper floors and roofs) through the use of an UAV and, at the same time, can be a source of quality texturing of the resulting 3D model.

2 Examples of connecting a TLS to a movable platform of an UAV have occurred recently, but this approach is still in its developmental stage and not common.

3 SIFT points can be identified with key points defined in Agisoft Photoscan,

4 HDR creates false colour spectrum of images.

5 The original images without HDR toning must be used for texturing. They should have the same name as the images used for creation of the model itself. It is sufficient to change the folder of source images in the stage of texturing.

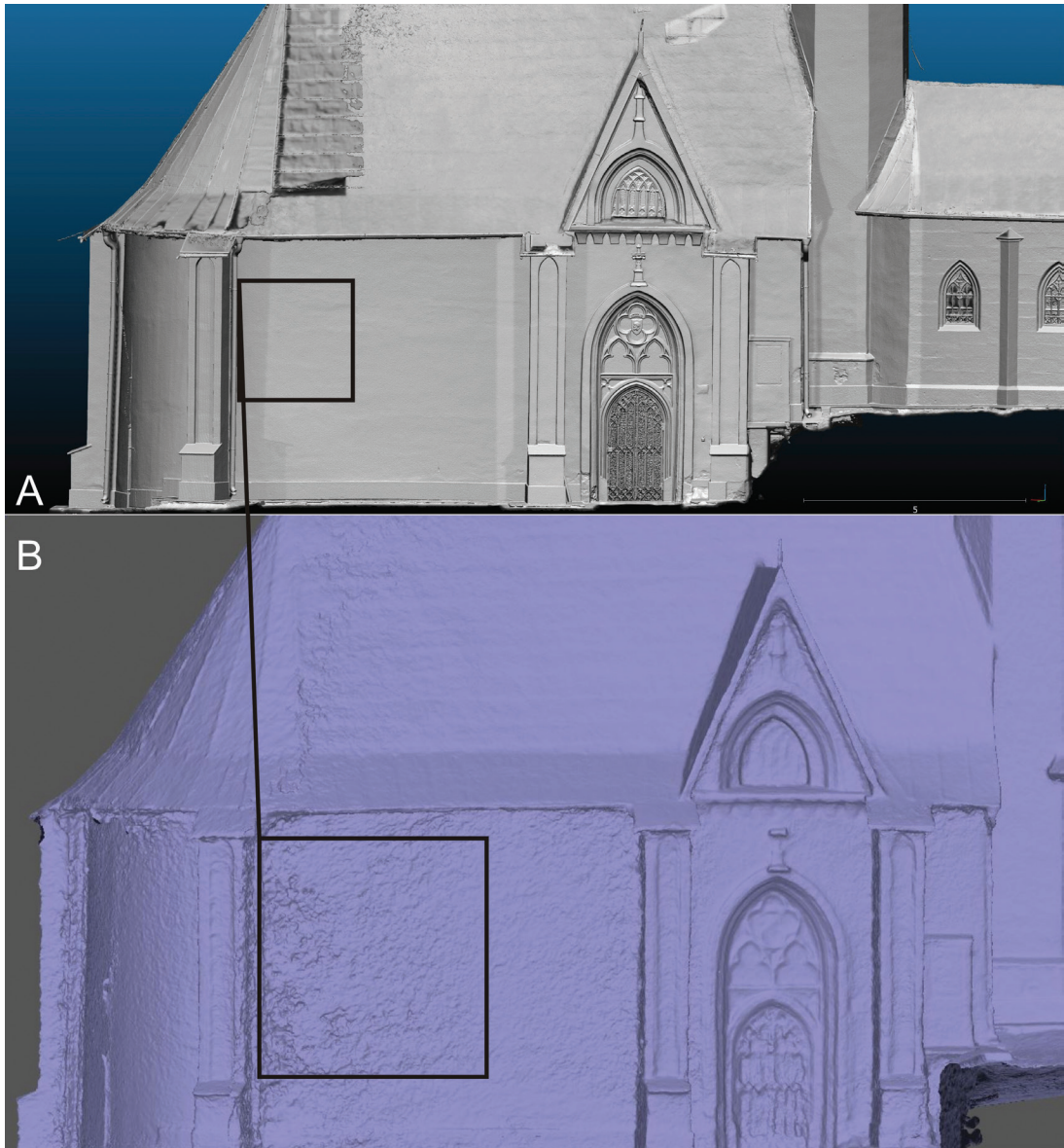


Figure 70. Žehra, Hodkovce (Slovakia). Neo-Gothic church, exterior. Example of a noisy mesh resulting from insufficient number of SIFT points detected on unedited photos. A: clean mesh derived from TLS data, B: noisy mesh resulting from lBM using unedited photos.

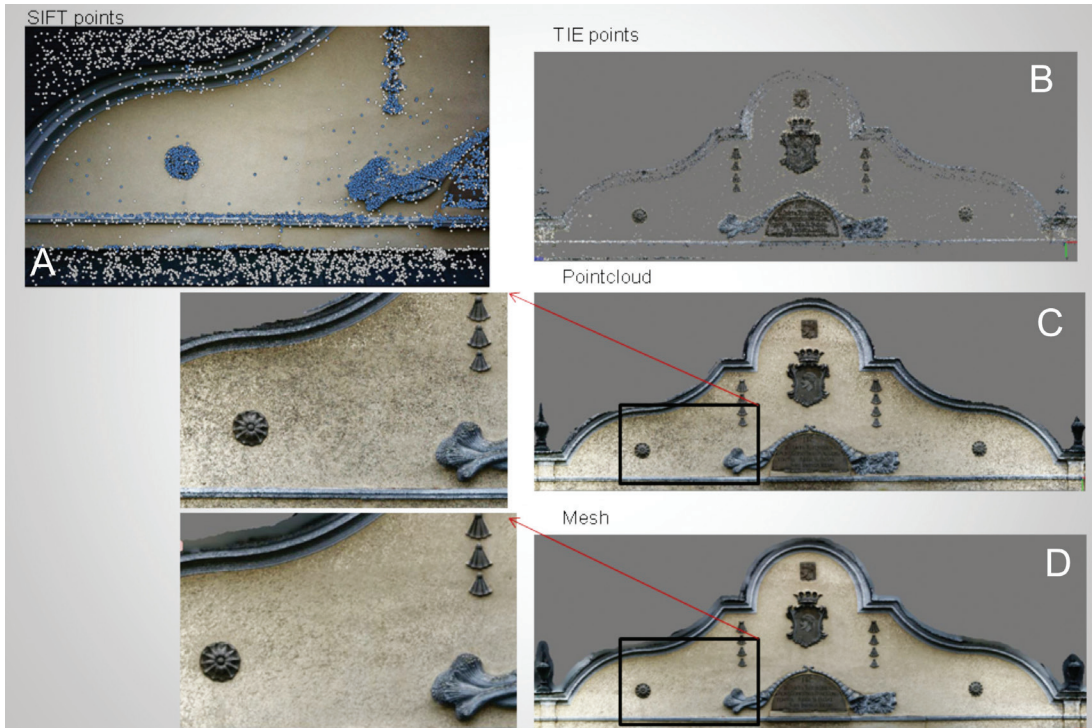


Figure 71. Žehra, Hodkovce (Slovakia). Manor house, exterior, tympanon. Example of noisy data resulting from insufficient number of SIFT points. A: insufficient number of SIFT points, B: sparse tie points with the lack of surface geometry, C: dense point cloud with the noisy part magnified, D: mesh with the distorted part of the surface magnified.



Figure 72. Distribution of SIFT points (key points) detected by bundle adjustment. A: raw stone structure, B: flat facade covered with single-colour fine plaster.

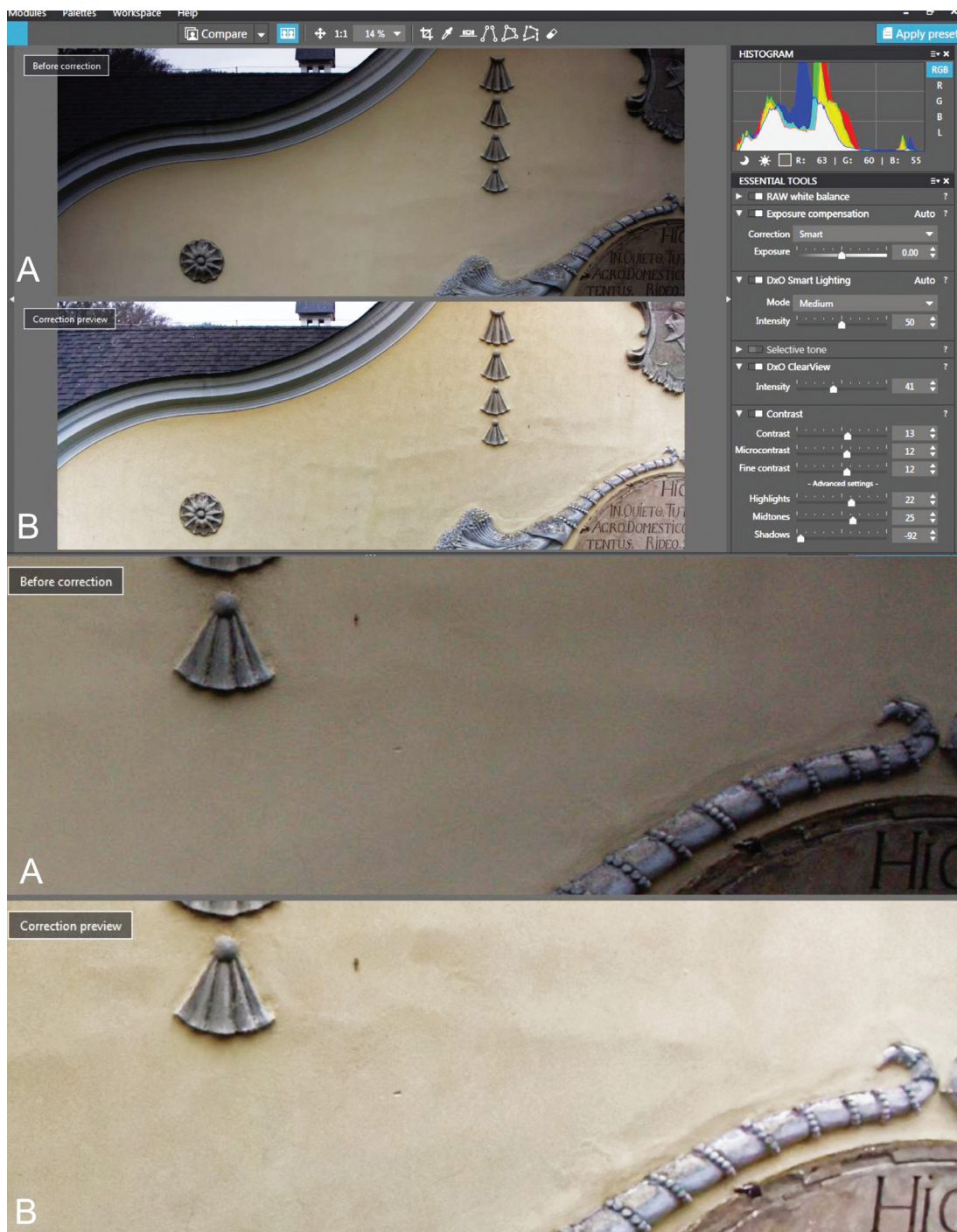


Figure 73. Examples of photo editing as a part of the pre-processing of raw data.
Software DxO Optics Pro. A: raw photo, B: edited photo.



Figure 74. Example of HDR filtering/toning of photos leading to better quality of the final 3D model (mesh) on one hand, and false colour information on the other. A: mesh built from photos with default settings, B: mesh built from HDR-toned photos.

3D RECORDING OF CASTLES

Ján Zachar (Via Magna) & Marko A. Janković (University of Belgrade)

Architectural remains of castles are quite distinctive compared to other types of buildings regarding the degree of preservation and the landscape in which they are located. Both factors significantly influence the digitisation strategy. As already stated in the case of 'standard' architecture, the spatial organisation and height considerably increase demands on the digitising techniques. This applies even more to castle architecture. The remains of castle buildings are often found in various stages of destruction and thus structures have complex forms. Given the predominantly vertical elements, the effective collection of data is even more complicated, especially in terms of recording upper floors. Moreover, the majority of castle ruins is situated in an environment characterised by irregular terrain and often with dense low or high vegetation. This creates natural obstacles and shadows in the photo-documentation and can be a highly limiting factor for the performance of techniques and tools used in the collection of data, such as an UAV.

Two castle complexes were selected as case studies within the framework of the CONPRA project. They are different, especially in terms of the natural landscape in which they are situated. The environment of Čachtice castle is composed of relatively open space with small areas under forest and a relatively regular terrain around the castle premises. On the contrary, Dobrá Voda castle is situated in a densely forested area with marked elevations of the terrain underlying different parts of the castle complex.

All case studies were processed in a workstation with the following parameters: Intel Xeon CPU E5-2620 v2@ 2,10 GHz, RAM 128 GB, GPU NVIDIA GeForce GTX 780 3GB, OS W8. In the case of TLS application, the resolution was always set to 6 mm per 10 meters. For lbM, Agisoft Photoscan software was used with the following parameters set for the batch processing workflow: step – align photos (high accuracy with the key point limit of 40,000

and the tie point limit of 20,000 points); step – refinement of alignment (decreasing of global re-projection error to max. 1px); step – build dense point cloud (medium quality, aggressive depth filtering); step – build mesh (arbitrary surface type, dense point cloud as source data, interpolation enabled, custom face count: various values); and step – build texture (generic mapping mode, texture from all cameras, blending mode Mosaic, texture size 4096, texture count 1, and no colour correction). In case of CapturingReality RC, the parameters were as follows: step – align photos (max. feature per image 80,000, pre-selector feature 40,000, image overlap medium, detector sensitivity medium, max. re-projection error 2px); step – reconstruction (normal detail); step – build texture (Gutter 3, texture resolution 8192, large triangle removal threshold 10, maximal texture count style, visibility based texture style).

Čachtice, Castle

Site type:	Castle
Location:	Čachtice, Nové Mesto nad Váhom District, W Slovakia
Dating:	13 th -16 th century
Recorded parts:	Complete castle area
Recording technology:	lbM
Recording equipment:	Camera Sony Nex 7, UAV
Software:	CapturingReality RC, CloudCompare 2.7
Record:	Scaled 3D model (mesh) (Figs. 75, 76)
Short description:	The Čachtice castle is situated on the top of a limestone peak in Malé Karpaty mountains. The former frontier castle served as a control point at the border between the Myjava and the Váh valleys. The oldest part of the castle, dated to the 13 th century, is the main pentagonal tower situated at a prominent point of the terrain. During the 14 th and the 15 th century, intensive building activity resulted in a new built area north of the main tower. New fortification features (cannon bastions), parts of the lower ward and some wall sections were added to the construction at the end of the 15 th century. The final major building activities are dated to the 16 th century when a complete reconstruction of the upper part of the castle was conducted and new architectural features were added to the lower ward (Plaček, Bóna 2007, p. 91-93). The project's aim was to digitise the complete historical landscape setting before the reconstruction works commenced (in 2013). The recording was carried out by lbM, which was facilitated by the relative openness of the area, with only few obstacles to the visibility of the architecture. The raw data was collected with an UAV (light sailplane equipped with a camera).

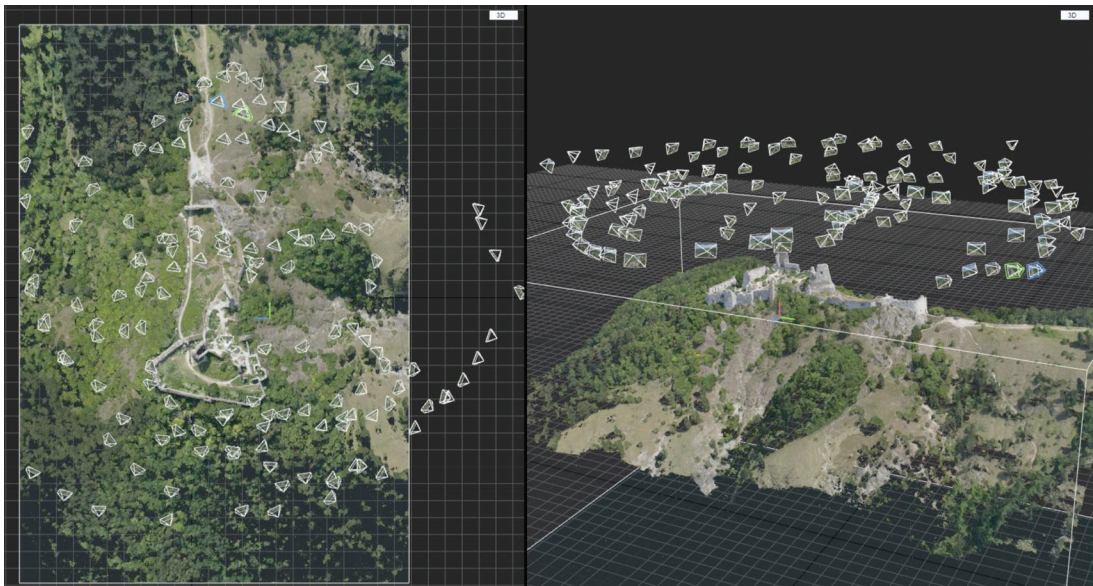


Figure 75. Čachtice (Slovakia). Castle, 13th-17th century. lbM (148 photos 12Mpx).
Distribution of cameras during photo taking.



Figure 76. Čachtice (Slovakia). Castle, 13th-17th century. Isometric views of the textured 3D model.

Dobrá Voda, Castle

Site type:	Castle
Location:	Dobrá Voda, Trnava District, W Slovakia
Dating:	13 th -17 th century
Recorded parts:	Complete castle area
Recording technology:	TLS, lbM
Recording equipment:	TLS Leica C10, camera Nikon D5200 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX), TS, GNSS Rtk Rover (differential GPS)
Software:	Agisoft Photoscan 1.1.0, CloudCompare 2.7, Microstation V8i trial version, Cyclone
Record:	Georeferenced 3D model (mesh), georeferenced orthophoto plans and cross-section views (Figs. 77-79)
Short description:	The castle is situated on the top and SW slopes of a limestone ridge. The oldest part (13 th c.) is represented by two towers and a palace in between. Two late medieval extramural settlements are located to the east and the west from the core area of the castle. The far end of the eastern settlement marks a polygonal building (chapel?). At the southern edge of the western settlement lie a tower gate and cylindrical bastion. The third settlement was built in the 16 th c. south from the castle, with walls connected with the castle and three cylindrical bastions and an entrance gate. The entire castle area was recorded. The terrain configuration has significant undulations; also, dense forest cover created shadowed many parts of the architecture. Individual castle buildings were in various stages of degradation. In such circumstances, TLS (Leica C10) was used as the main recording equipment, occasionally completed with lbM for more complex architectural elements. Data from TLS and lbM were registered separately and subsequently merged in CloudCompare. Georeferenced GCP measured by TS were the basis for common registration.

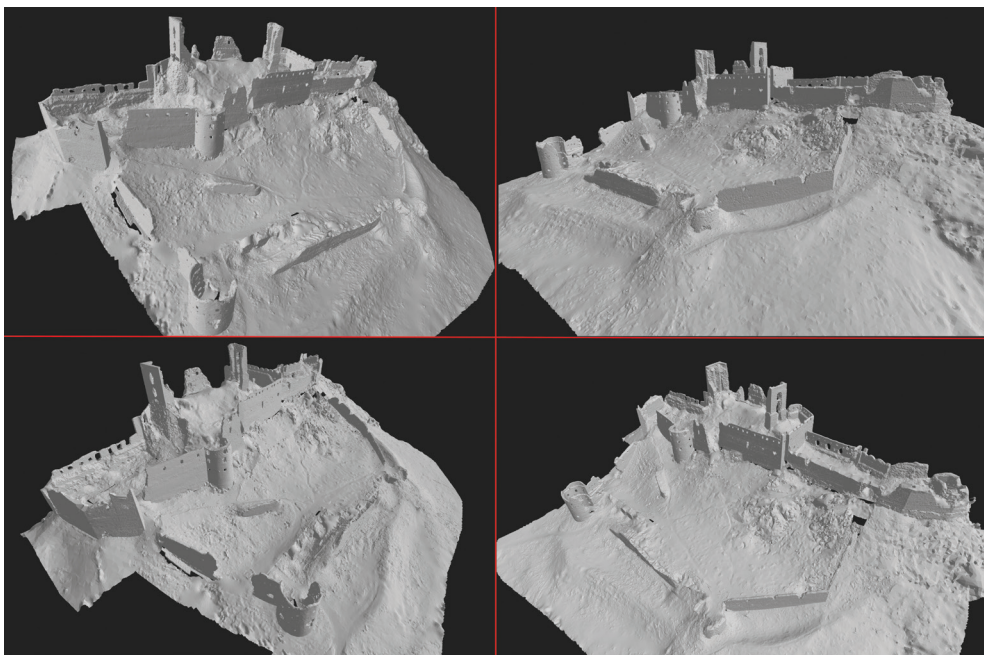


Figure 77. Dobrá Voda castle, 13-16th century. TLS (150 TLS stations).
Isometric views of the shaded 3D model.

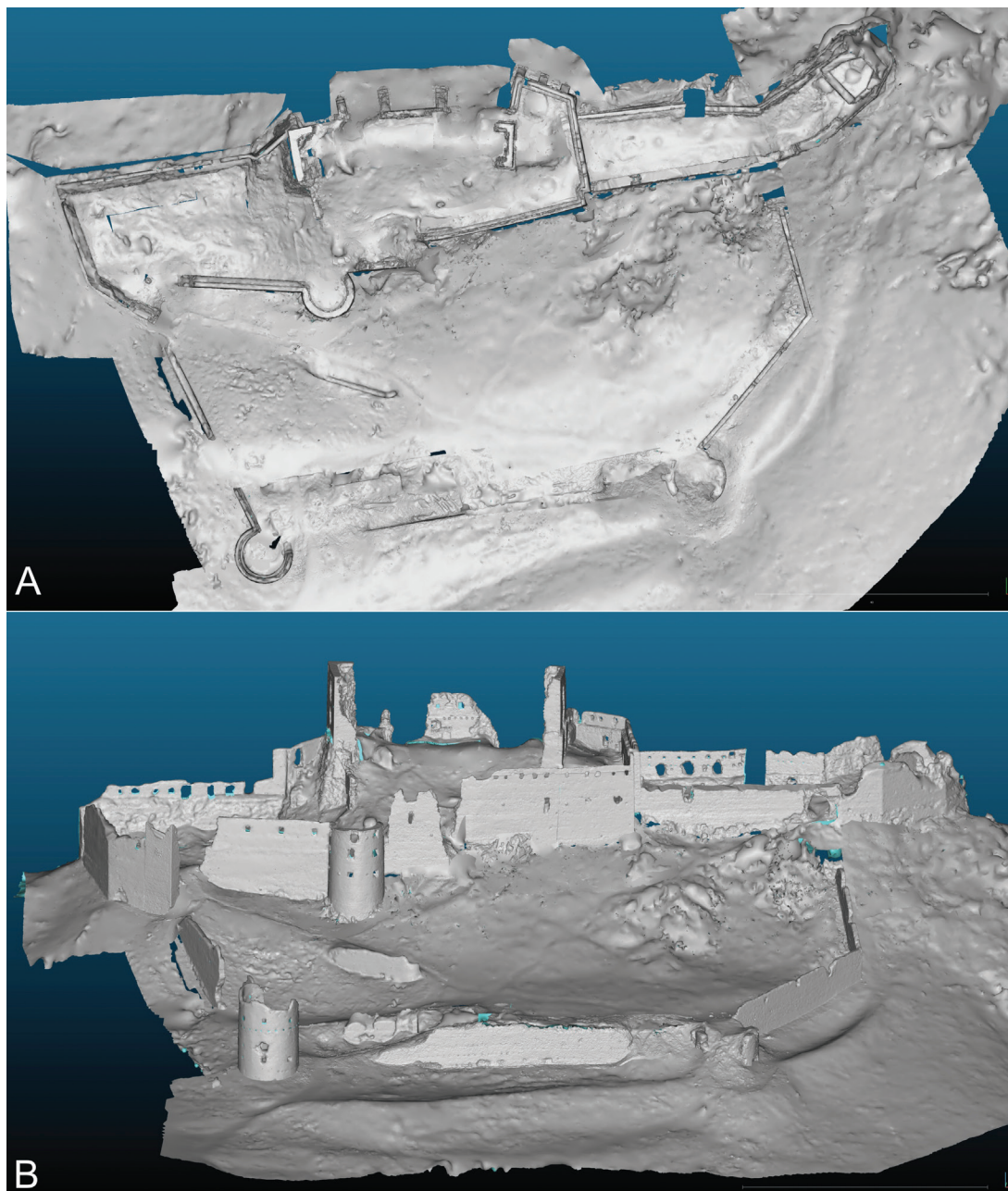


Figure 78. Dobrá Voda (Slovakia). Castle, 13-16th century. TLS. A: nadir view of the 3D model of the castle's ground plan, B: isometric view of the model of the castle complex.

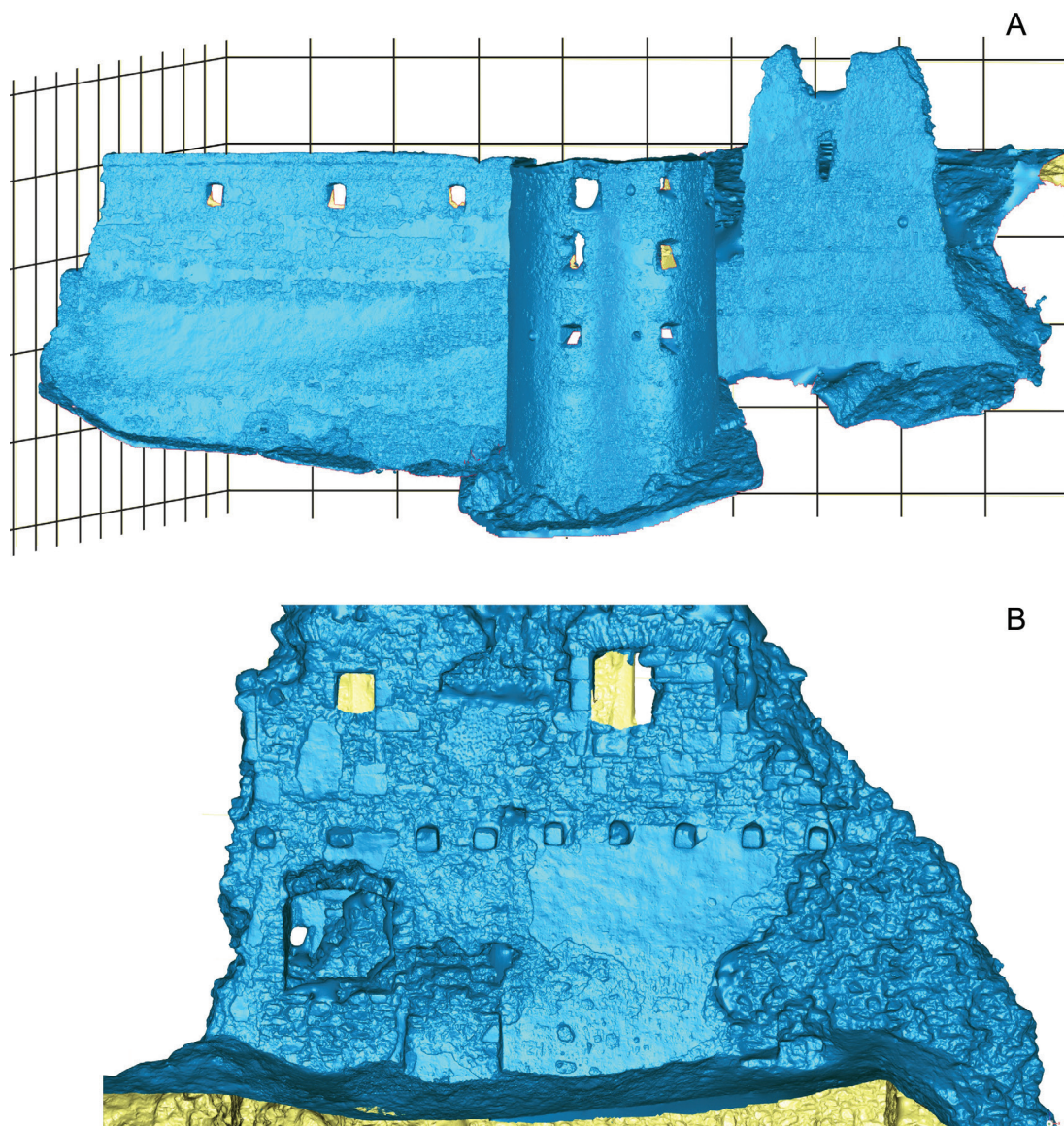


Figure 79. Dobrá Voda (Slovakia). Castle, 13-16th century. TLS. A: isometric view of the 3D model of the outer walls of the upper castle, B: view of the inner facade of the upper palace.

DISCUSSION

Castle architecture represents a special category of buildings determined by the landscape context and the nature of their construction; this places specific requirements on the digitisation process. As in the case of 3D documentation of building structures, documenting the remains of castles requires thorough reconnaissance of the terrain and an elaborate digitising scenario as well as a thorough plan of the work procedure. It is likely that a castle cannot be processed within a single set, especially in the case of more extensive complexes. Therefore, the collection and processing of the data should focus on smaller sections or individual structures of the castle complex. This places high demands on the general data management.

It turns out that the key determinant for the choice of digitisation strategy is the degree of elevation (terrain configuration) in different parts of the castle area and the extent and density of forest around the castle. Dense forest represents a substantial limiting factor to the application of basic lBM tools. This is especially true in the case of use of an UAV, which is necessary for the collection of data on vertical architectural elements. The example of Dobrá Voda castle shows that an UAV cannot be fully substituted by a high monopod stand in complex terrain with significant elevation variations combined with high structures. High density of trees made the use of TLS also difficult. The shadows created over, and by, the architecture required frequent change of scanner positions, as well as GCP, used for the registration of individual scans and their general georeferencing. Moreover, the positions of the surface scanner caused digitisation shadows on higher floors of individual structures, especially in areas of windowsills and linings of the windows or gun port openings. These elements usually cannot be captured by laser signal sent from the surface of the surrounding terrain.

Since UAV cannot be used for the photo documentation, most of the images were made from the ground level; the upper parts of the structures are thus captured from a highly oblique perspective. The lack of a sufficient number of perpendicular or almost perpendicular photos devalues the resulting texture, as the texture map is created by defining GCP between the 3D model (mesh) and the individual images. If part of the architecture is, in this work procedure, captured only at a very oblique angle, false perspective is created after such images are layered in the 3D model.

The situation is considerably simpler in the case of castles located in environments with little forest vegetation. Depending on the size and complexity of the castle area, only lBM or lBM in combination with TLS can be used. The potential of an UAV can be used in full, which is indispensable for the documentation of extensive castle ruins. Rough masonry (without any surface treatment) is characterised by a high degree of plasticity and texture structuring. This enables generating sufficient number of SIFT points in the process of bundle adjustment, which is the basic condition for a clean 3D model without much noise.

3D RECORDING OF SCULPTURES AND SMALL OBJECTS

Ján Zachar (Via Magna) & Nenad Jončić (University of Belgrade)

The main characteristic of the digitisation of sculptures and movable items of cultural heritage, that distinguishes it from the documentation of buildings and archaeological sites, is the size of the documented item. It usually does not exceed the size of the human body, if we do not count monumental sculptures that were not subject to research.¹ A special category of cultural heritage includes museum objects, historical sacral furniture and outdoor historical sculptures. The digitisation of an object performed in the interior poses a specific problem from the perspective of light parameters and parameters of the available space.

The case studies were processed in notebook Lenovo Y50 (Intel(R) Core(TM) i7-4710HQ CPU@ 2,50 GHz, RAM 16 GB, GPU NVIDIA GeForce GTX 860M, OS W8). In the case of SLS application, Artec Eva with Artec Studio 10 software was used. Artec Studio enables the whole workflow pipeline, from scanning through fine registration of particular scans, their alignment and subsequent global registration, up to the fusion encompassing removal of outliers and mesh generation with sharp or smooth fusion algorithm. The final step refers to the mesh simplification and its texturing (Figure 80).

For IBM, Agisoft Photoscan software was used with the following parameters set for the batch processing workflow: step – align photos (high accuracy with the key point limit of 40,000 and the tie point limit of 20,000 points); step – refinement of alignment (decreasing of global re-projection error to max. 1px); step – build dense point cloud (medium quality, aggressive depth filtering); step – build mesh (arbitrary surface type, dense

¹ Large monumental statues, high plague columns and monuments fall into the category of immovable objects; the principles defined in the chapter about the digitisation of architectural objects also apply to these.

point cloud as source data, interpolation enabled, custom face count: various values), and step – build texture (generic mapping mode, texture from all cameras, blending mode Mosaic, texture size 4096 texture count 1, and no colour correction) (Figure 81). When using CapturingReality RC, the parameters were as follows: step – align photos (max. feature per image 120,000, pre-selector feature 60,000, image overlap medium, detector sensitivity medium, max. re- projection error 2px); step – reconstruction (normal detail); step – build texture (Guter 3, texture resolution 8192, large triangle removal threshold 10, maximal texture count style, visibility based texture style) (Figure 82.).

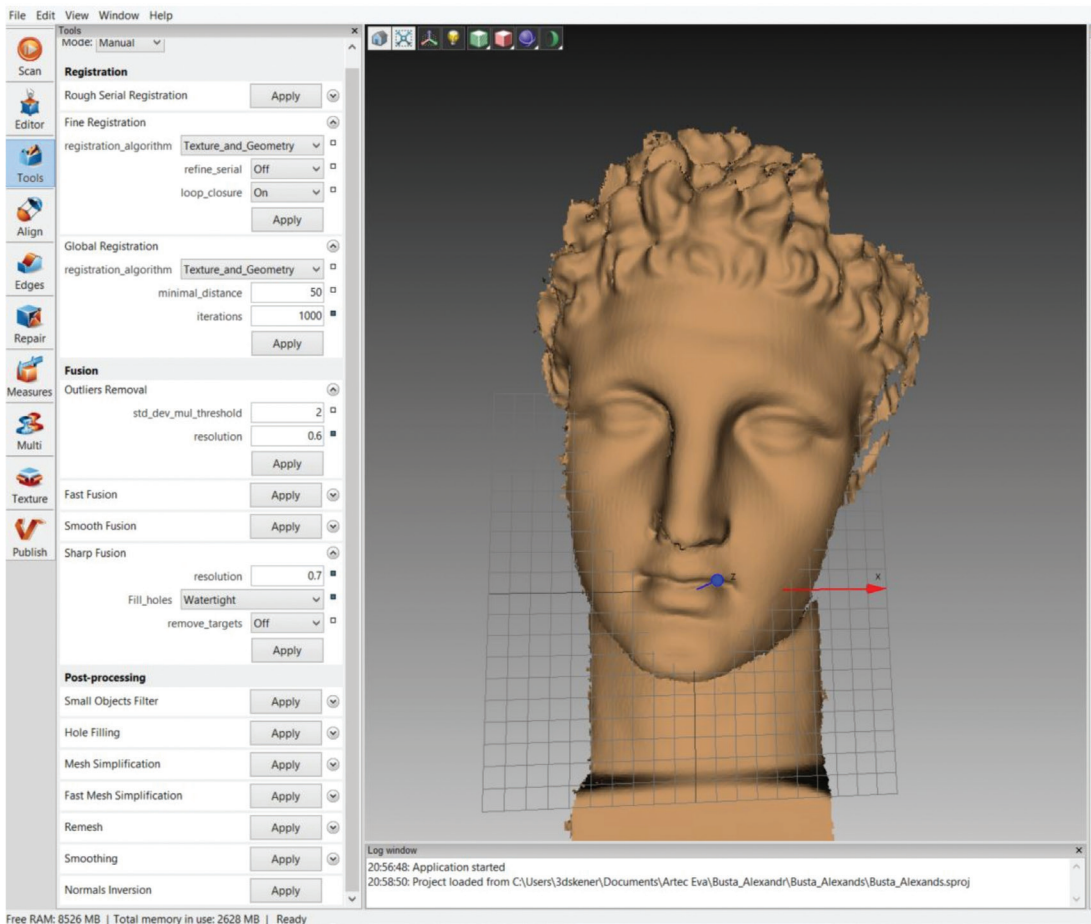


Figure 80. Workspace of Artec Studio with the settings used for processing scans.

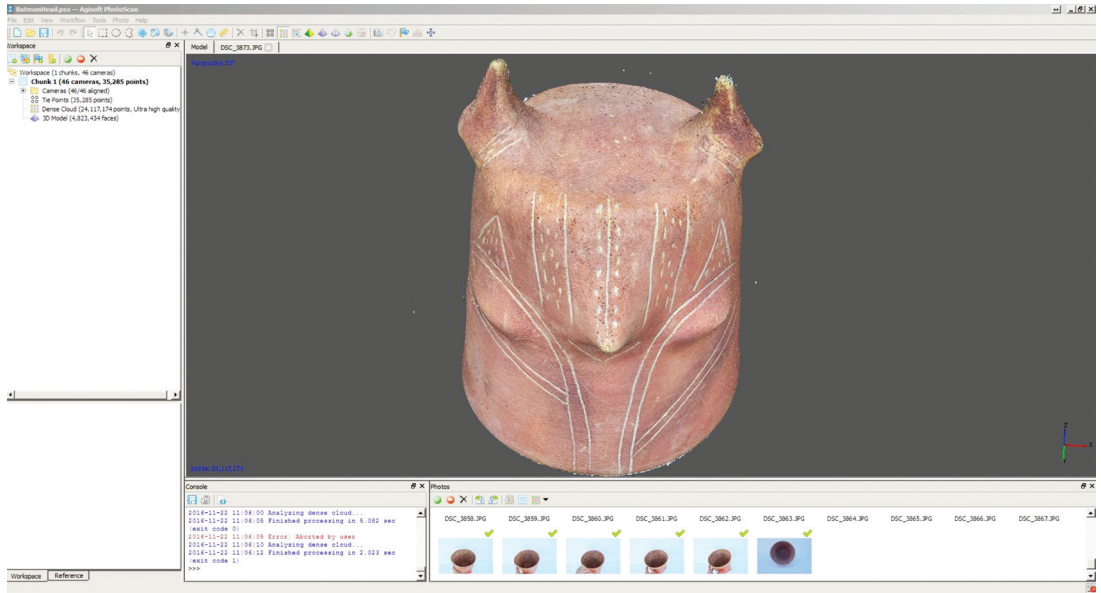


Figure 81. Workspace of Agisoft Photoscan.

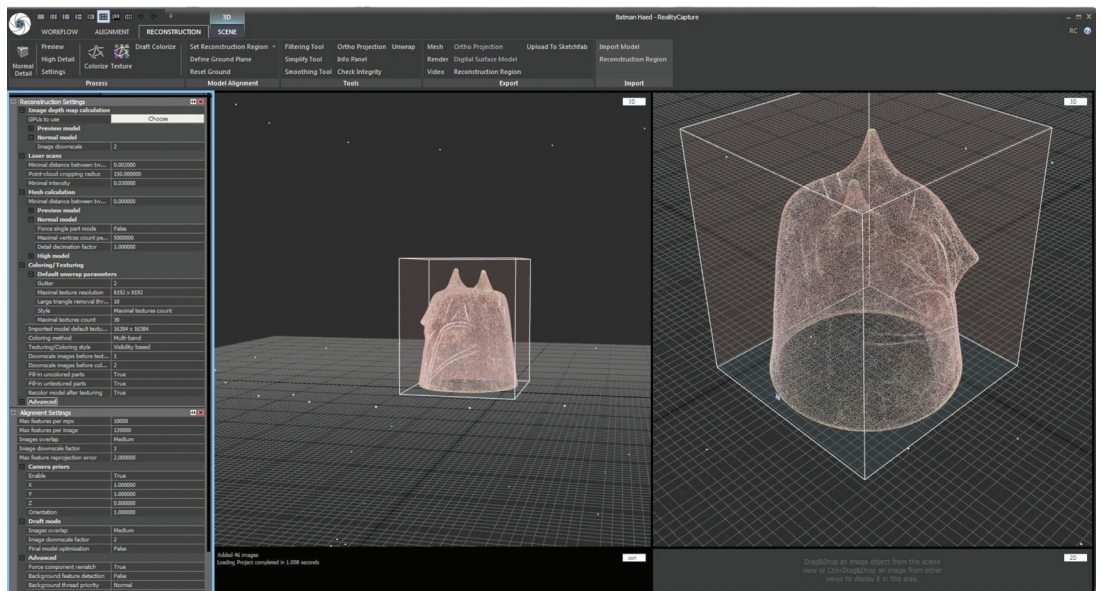


Figure 82. Workspace of CapturingReality RC.

Sculptures of St. John of Nepomuk and St. Florian, Beckov

Location: Church of St. Stephen the King, Beckov, Nové Mesto nad Váhom District

Object: Sculptures of St. John of Nepomuk and St. Florian

Material: Stone without surface treatment (sandstone)

Dating: 18th century

Recording technology: IbM

Recording equipment: Camera Nikon D90 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX)

Software: Agisoft Photoscan 1.0.0, CloudCompare 2.7

Record: Scaled 3D model (mesh) (Figs. 83-85)

Short description: Both Baroque sculptures sit on pillars flanking the entrance gate leading to the Church of St. Stephen the King. Their rendering represents a good example of the regional Baroque artwork. The pictures were taken by handheld camera (from folding ladder). Background masking was not used for the processing in Agisoft Photoscan.

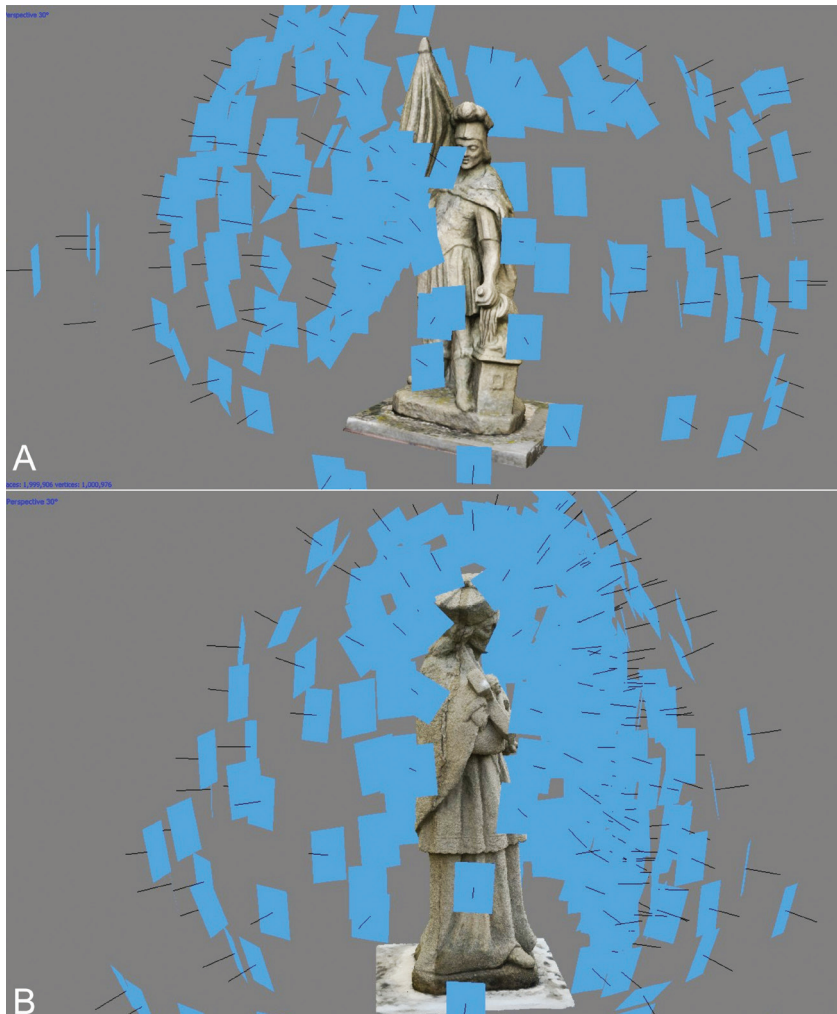


Figure 83. Sculptures of St. John Nepomuk and St. Florian, IbM. Positions of the cameras during photo taking. A: St. Florian (186 photos 24Mpx), B: St. John Nepomuk (269 photos 24Mpx).



Figure 84. Sculpture of St. John Nepomuk. A: textured 3D model, B: shaded 3D model.



Figure 85. Sculpture of St. Florian. A: textured 3D model, B: shaded 3D model.

Sculpture of the Virgin, Nové Mesto nad Váhom

Location:	Premises of the Virgin Mary Prepositure, Nové Mesto nad Váhom, W Slovakia
Object:	Sculpture of the Virgin Mary
Material:	Stone without surface treatment (limestone)
Dating:	18 th century
Recording technology:	lBM
Recording equipment:	Camera Nikon D90 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX)
Software:	Agisoft Photoscan 1.0.0, CloudCompare 2.7
Record:	Scaled 3D model (mesh) (Figs. 86, 87)
Short description:	The Baroque limestone sculpture of the Virgin Mary is situated on the premises of the Virgin Mary Prepositure on the lawn in front of the northern wall of the Church of the Nativity of the Virgin Mary. It represents a sophisticated piece of Baroque art with an emphasis on the dynamic folds of the drapery and the expressive gestures. Iconographically, it represents a specific type with elements of 'Regina Coeli' (the motif of a crown and a sceptre) and 'Immaculata' (the motif of Earth with a serpent underfoot). The sculpture was made in a life size. The ladder was used for capturing upper parts of the crown. The photographs for lBM were taken by the 'walk-around method'. Background masking was not used for processing of the data in Agisoft Photoscan.

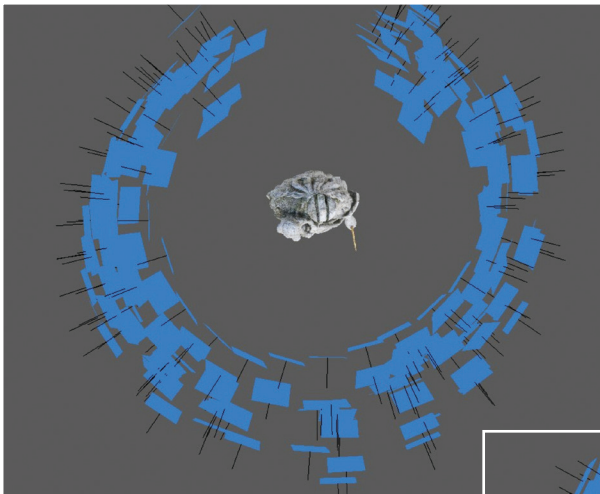


Fig. 86. Nové Mesto nad Váhom (Slovakia). Sculpture of the Virgin Mary, 18th century. lBM (184 photos 12Mpx). Distribution of cameras during photo taking.

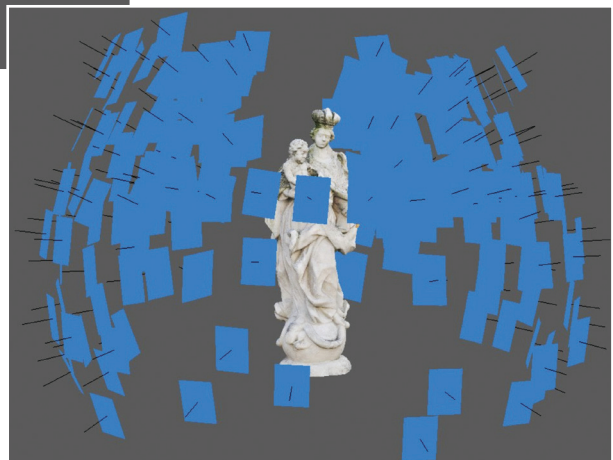




Figure 87. Sculpture of the Virgin Mary, Nové Mesto nad Váhom (Slovakia), 18th century.
A: textured 3D model, B: shaded 3D model visualised in the ambient occlusion mode,
C: shaded 3D model – detail.

Altar sculptures, Church of St. Barbara, Žilina

Location:	Church of St. Barbara, Žilina, NW Slovakia
Object:	Altar sculptures; figure of an angel, figure of St. Joachim
Material:	Polychrome wood (the polychrome is recent)
Dating:	18 th century
Recording technology:	SLS
Recording equipment:	Artec Eva Scanner
Software:	Artec Studio 10, CloudCompare 2.7
Record:	Scaled 3D model (mesh) (Figs. 88-90)
Short description:	<p>The sculptures form part of the main altar decoration of the early 18th century Franciscan Church of St. Barbara in Žilina. They are attributed to the Baroque artist Anton Weissmann. The sculptures were made in a life size and they bear typical features of the so-called Gothicising Baroque, especially visible in the carving of St. Joachim's face, which has markedly sunken cheeks and 'Gothicising' line of the forehead and cheekbones. On the other hand, the drapery is depicted in a dramatic movement in line with the principles of dynamic rhythm of the Baroque. The altar was under comprehensive reconstruction at the time of recording, and parts of it were dismantled. The sculptures were recorded by TLS Artec Eva in the sacristy, without any special lighting, and by using only the local light source. The distance of Artec Eva was between 40 cm and 100 cm from the surface of the sculptures. For this reason, it was rather complicated to capture the inward-facing parts of the drapery folds since they remained outside the range of the structured light created by the primary motion of the scanner. This produced undesirable digitisation shadows. The repeated attempts at capturing these parts of the sculptures consequently multiplied the number of partial scans and this, eventually, prolonged the data processing stage.</p>

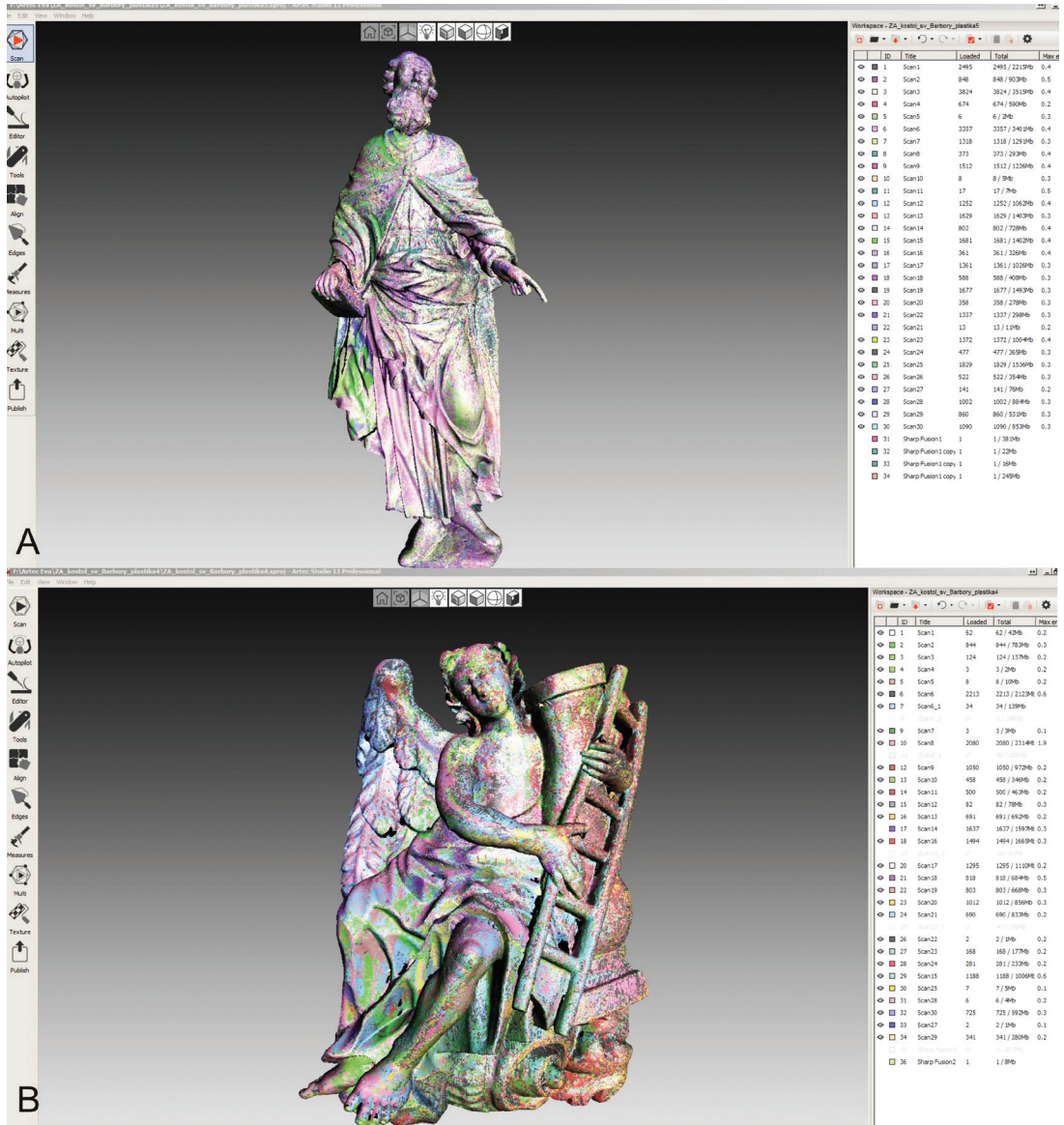


Figure 88. Altar sculptures, church of St. Barbara, Žilina. SLS Artec Eva. Visualisation of particular scans (each scan is depicted with a unique colour) in Artec Studio. A: St. Joachim. 30 scans, B: Baroque angel, 29 scans.

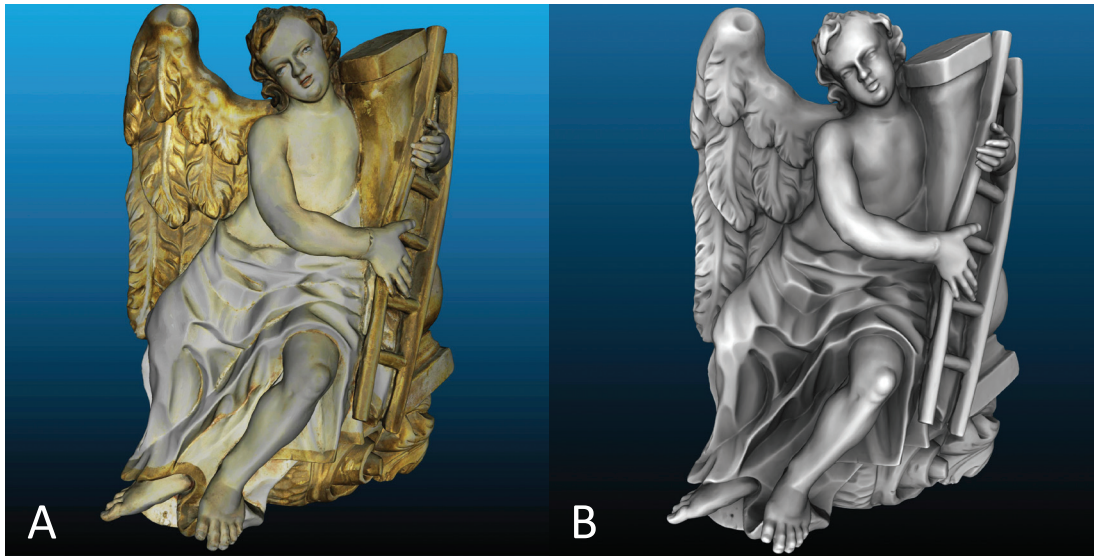


Figure 89. Altar sculptures, church of St. Barbara, Žilina. SLS Artec Eva. 3D model of the Baroque angel. A: textured model, B: shaded model with ambient occlusion filter applied.



Figure 90. Altar sculptures, church of St. Barbara, Žilina. SLS Artec Eva. 3D model of St. Joachim. A: textured model, B: shaded model with ambient occlusion filter applied.

Copy of the sculpture of Virgin Mary, Žilina,

Location:	Monuments Board Office, Žilina, NW Slovakia
Object:	Copy of the sculpture of the Virgin Mary
Material:	Plaster
Dating:	15 th century (original)
Recording technology:	SLS
Recording equipment:	Artec Eva Scanner
Software:	Artec Studio 10, CloudCompare 2.7
Record:	Scaled 3D model (mesh) (Figs. 91, 92)
Short description:	The recorded sculpture of the Virgin Mary is a life-size replica of the medieval original from Levoča. Scanning using the SLS Artec Eva took place in the interior of an office, using the available lights and without any special lighting.

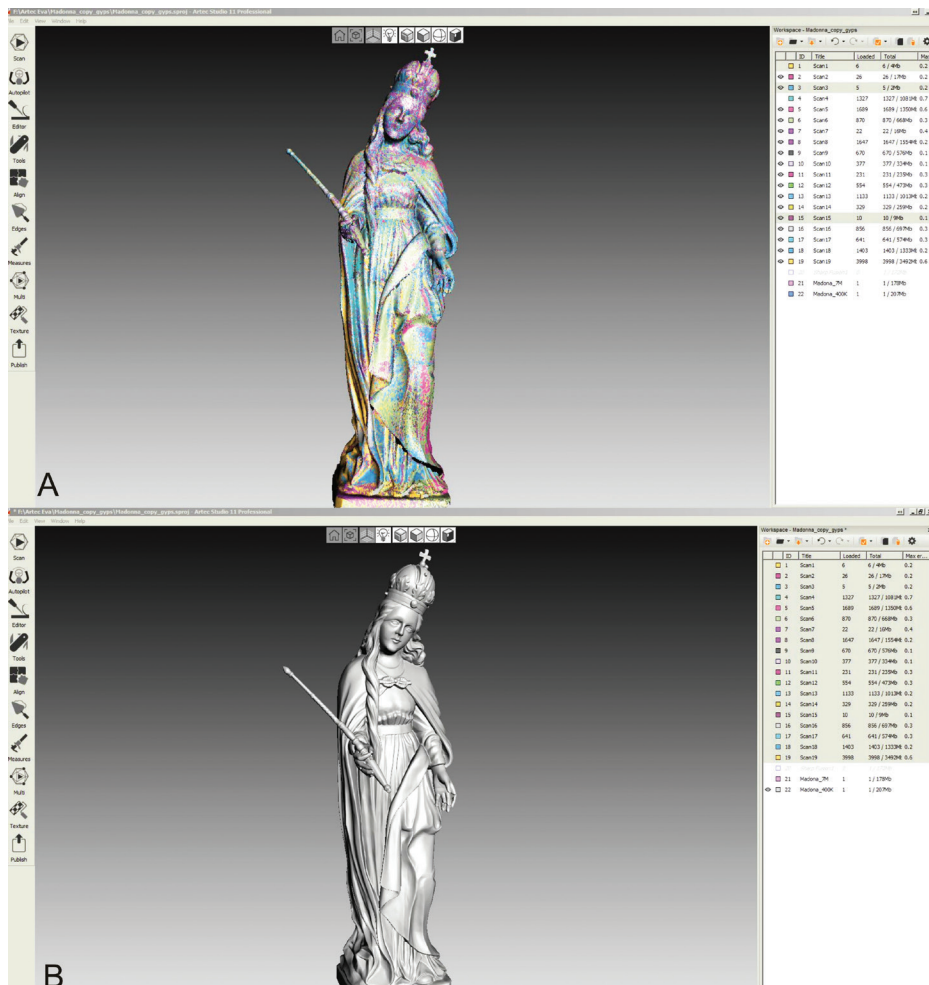


Figure 91. Plaster copy of the Virgin Mary sculpture (15th century, original), Žilina. SLS Artec Eva. A: visualisation of particular scans (each scan depicted with a unique colour) in Artec Studio (20 scans), B: visualisation of the final mesh (3D model) in Artec Studio.



Figure 92. Plaster copy of the Virgin Mary sculpture (15th century, original), Žilina. SLS Artec Eva. Shaded model with ambient occlusion filter applied.

Ceramic pot

Site:	Bratislava Castle, south-western Slovakia
Object:	Pot
Material:	Ceramics
Dating:	9 th century
Recording technology:	SLS, Ibm
Recording equipment:	Artec Eva Scanner, camera Nikon D90 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX)
Software:	Artec Studio 10, Agisoft Photoscan Pro1.0.0, CloudCompare 2.7
Record:	Scaled 3D model (mesh) (Figure 93)
Short description:	Both Ibm and SLS (Artec Eva) were used in the digitisation. For Ibm, monochromatic background was used and images were taken by the walk-around method. After the upper part and the inside of the vessel were photographed, the vessel was turned over for photographing the lower part and the bottom. The sequences of images from both sets of photographs were processed at the same time. No special lighting was used.

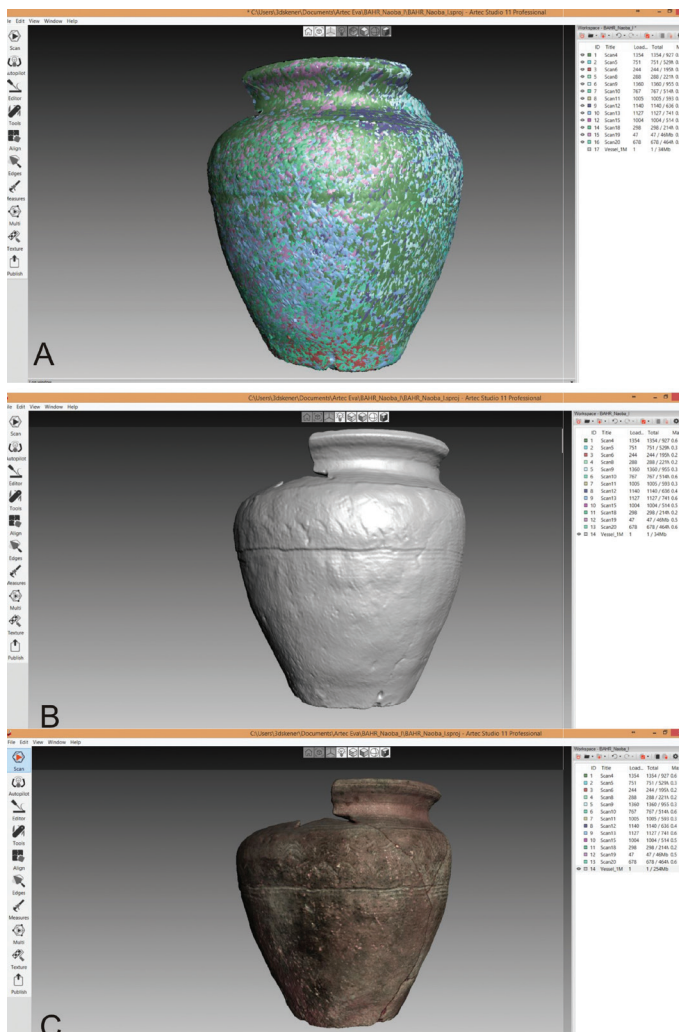


Figure 93. Clay vessel, 9th century, Bratislava Castle. SLS Artec Eva.

A: visualisation of particular scans (each scan is depicted with a unique colour) in Artec Studio (13 scans).

B: visualisation of the textured final mesh (3D model) in Artec Studio.

C: visualisation of the shaded final mesh (3D model) in Artec Studio.

Architectural elements, fragment of a vault rib

Site:	Prepositure of the Virgin Mary, Nové Mesto nad Váhom, SW Slovakia
Object:	Fragment of a vault rib
Material:	Stone
Dating:	14 th -15 th century
Recording technology:	SLS
Recording equipment:	Artec Eva Scanner,
Software:	Artec Studio 10, CloudCompare 2.7
Record:	Scaled 3D model (mesh) (Figs. 94, 95)
Short description:	Fragment of a vault rib was found during the archaeological research of the premises of the Prepositure of the Virgin Mary (2014). Individual fragments of the collapsed vault were found in the debris of the building interior. The scanning was performed by SLS Artec Eva in the interior of the structure and without any special lighting.

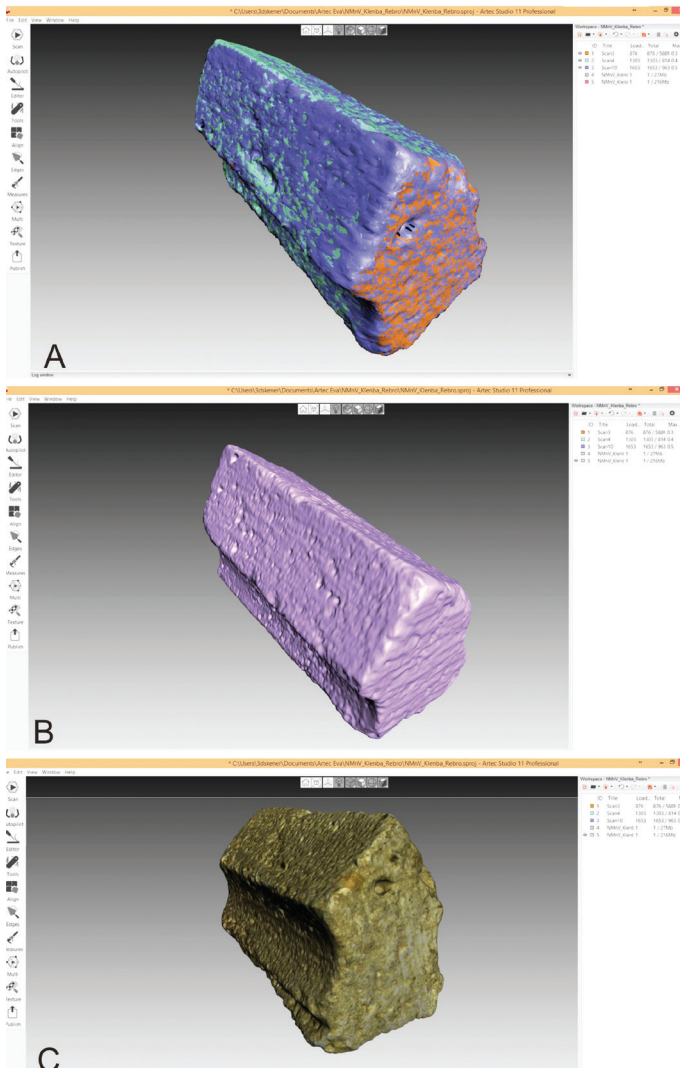


Figure 94. Fragment of a vault rib, 14th-15th century. Nové Mesto nad Váhom. SLS Artec Eva.

A: Visualisation of particular scans (each scan depicted with a unique colour) in Artec Studio (3 scans).

B: Visualisation of the textured final mesh (3D model) in Artec Studio.

C: Visualisation of the shaded final mesh (3D model) in Artec Studio.

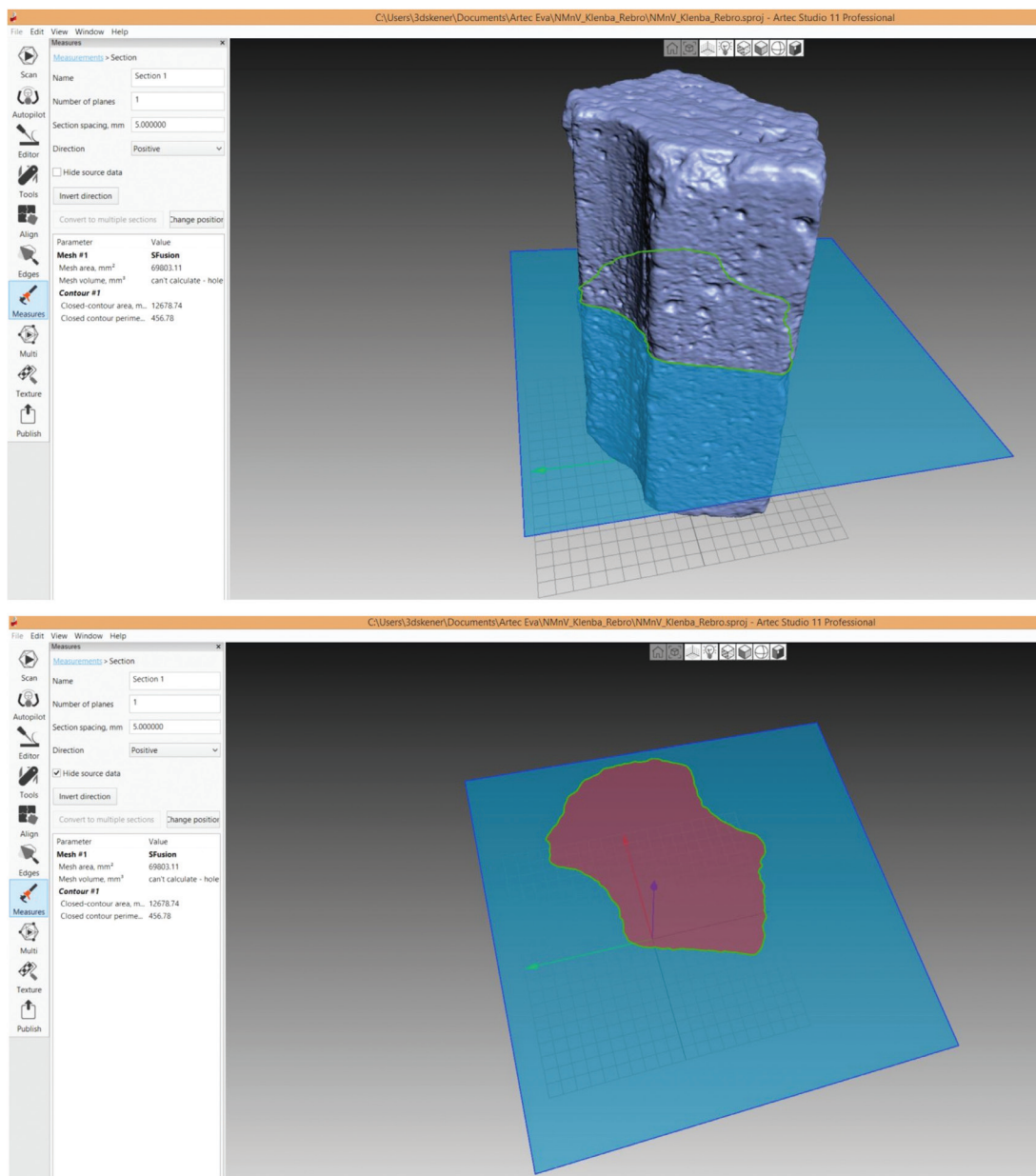


Figure 95. Fragment of a vault rib, 14th-15th century, Nové Mesto nad Váhom. SLS Artec Eva. Cross-section generation in Artec Studio software.

Prehistoric sculptures

Site:	Vinča, Serbia
Object:	Prehistoric sculptures
Material:	Ceramics
Dating:	Neolithic
Recording technology:	IbM
Recording equipment:	Camera Nikon D5100 (optics AF-S Nikkor 16-85 f/3.5-5.6 ED VR DX)
Software:	Agisoft Photoscan Pro1.0.0, CloudCompare 2.7
Record:	Scaled 3D model (mesh) (Figs. 96 - 98)
Short description:	Outdoor recording in IbM ('turntable method', natural light; camera placed on a stand, photos were taken by remote control). The movement (SfM principle), was provided by manual rotation of the object. The object was photographed in several 360 degree-rotation sequences to capture all of its parts. Since the photos were taken with a monochromatic background, they did not have to be de-masked during the processing stage. Processing of all photographed sequences was done at the same time.

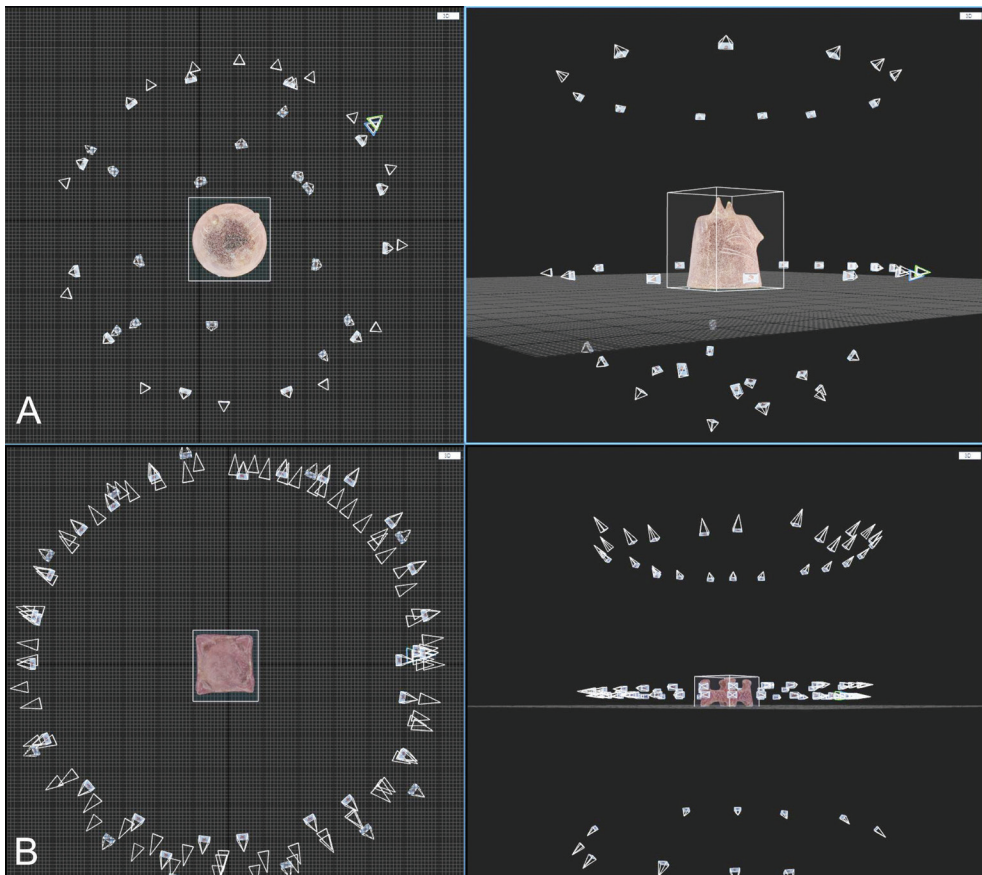


Figure 96. Positions of photographs taken within the IbM 'turntable method'. Software: Capturing Reality RC. Although the camera was static and the object was turned on the turntable, software treats the whole procedure as SfM, i.e. as if the camera was moving. Left window – nadir view, right window – side view. A: ritual object made of clay (46 photos 12Mpx), B: ritual object made of clay (113 photos 12Mpx).

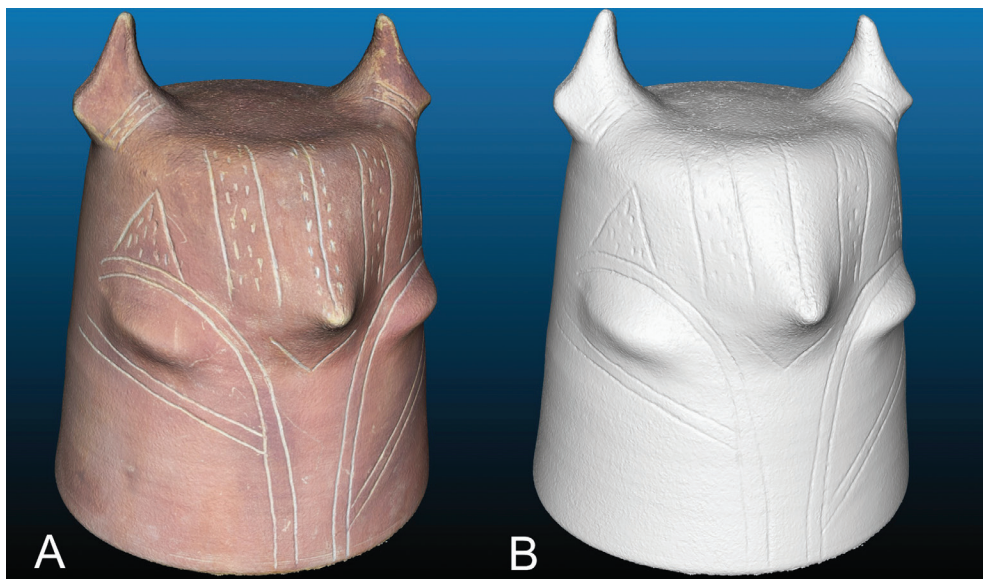


Figure 97. Clay prosopomorphic lids, Neolithic period. IbM, turntable method.
A: textured 3D model, B: shaded 3D model.

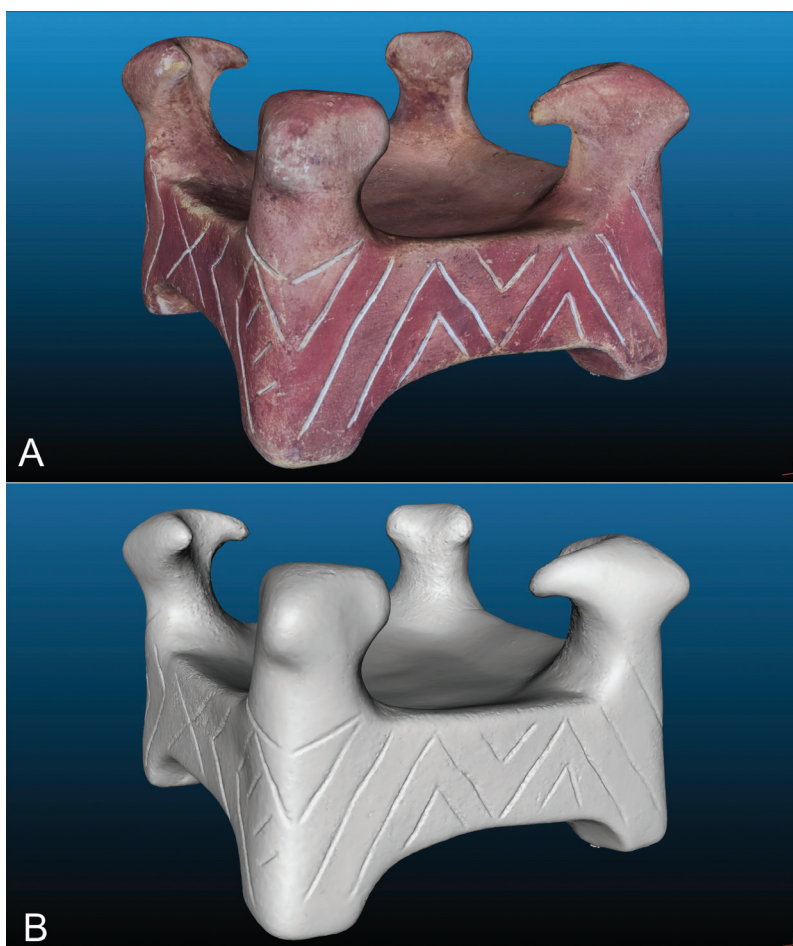


Figure 98. Clay object, Vinča, Neolithic period. IbM, turntable method.
A: textured 3D model, B: shaded 3D model.

DISCUSSION

The application of both IbM and SLS methods for the 3D documentation of sculptures and movable objects is a valid approach, whereby each method has its specific benefits and problems. The SLS of Artec Eva type currently represents probably the most widely used type of portable handheld scanner utilising the technology of structured light with declared point accuracy of 0.1 mm and the 3D resolution of 0.5 mm. The most frequent and most effective application is in the documentation of objects of small to medium size in interior spaces.

The Artec Eva instrument operates at the distance range of 40-100 cm from the documented object. This limits its usefulness for capturing very small objects, where it is more suitable to apply another type of the Artec series – Artec Spider, which can capture the surface already from the distance of 17 cm, thus allowing recording of very fine details. The ideal solution is to use both types of scanners (Eva for general views and Spider for intricate details). If only Artec Eva is used, it must be taken into account that some details of the documented surface can be accessible from the operational distance only with difficulty (e.g. inward-facing surface of folds of draperies in sculptures, etc.) and that it is necessary to scan them repeatedly from various positions. It is also necessary to practice scanning in order to successfully use and manoeuvre Artec Eva. This mainly relates to the method of tracking (capturing frames), which requires smooth and slow but at the same time continuous movement of the scanner. Too rapid movements, as well as non-compliance with the recommended distance from the object, can lead to the loss of tracking. The course of scanning can be followed through the interface of native software (Artec Studio) on a notebook or tablet to which the scanner is connected. This presupposes mastering simultaneous tracking of own movement around the documented object and observing the display of the notebook/tablet.

A substantial benefit of SLS application for indoor documentation is the fact that the process can also take place under unfavourable light conditions without the need for any special lighting. On the other hand, the application of SLS in an external space is significantly limited, as the system does not work in (intensive) sunlight.

The most effective way of data collection for IbM in the exterior is the walk-around method, in which the person scans the whole surface of the object by moving around it in several sequences. The number of sequences depends on the height and the general appearance of the object. This procedure is particularly well-suited for 3D documentation of historical sculptures. If IbM is used for the documentation of movable objects in the interior, it is better to use the turntable method because, in order to obtain sharp and high-quality images, the object of documentation must be well-illuminated. In the walk-around method, the light equipment needs to be constantly shifted and the documenter needs to move around the object; this can represent a significant obstacle if the space available for documenting is limited. Further, lighting of the object documented must be of diffuse nature in order to prevent the creation of strong shadows, which, from the perspective of 3D documentation, represent a 'dead zone'. Diffuse lighting can be best achieved by two oppositely placed light sources whose beams are aimed at the centre of the area documented, whereby the emitted light beams are diffused by a transparent material (translucent sheet, crepe paper, etc.) placed between the object and the light

sources. The movement is created by manually or automatically rotating platform on which the object is placed. The images are taken by means of a remote-controlled camera placed on a stand. Several image sequences are made from all sides of the object. When one sequence is completed, the object is manually turned to allow taking images of a previously obscured part of the surface. It is advisable to make images with the monochromatic background, since it enables very efficient masking of the background based on the principle of colour difference between pixels.² In many cases, uniform monochromatic background enables simultaneous registration of individual image sequences in a single file within bundle adjustment in IBM processing. In case the software application does not have the option to align such images, or in case the process of registration in one file fails, the images need to be processed within individual sequences and subsequently aligned according to GCP.

² Technically, the simplest method of masking, using the principle of difference between pixels in the raster, is to use specialised software (e.g. Adobe Photoshop) and subsequently export the masking layer together with the respective raster as an alpha channel. The majority of IBM software is able to identify the alpha channel of a raster and thus automatically import the masking layer of individual images.

SUMMARY

Milan Horňák (Via Magna)

3D digitisation is gradually becoming a standard geodetic method applied in the creation of technical documentation within the research on archaeological and historical buildings. It is especially useful for the transformation of a 3D model into 2D space, whereby orthogonal projections of 3D structures, such as ground plans of archaeological sites, different views and cross-sections of facades of historical or other structures, are generated. Various specific views, plans and cross-sections generated from a 3D model are of high accuracy. Moreover, it is possible to capture in 3D models the exact distribution of surface colours, thanks to the recorded texture – for instance, in case of wall paintings, mosaics, etc. 3D digitisation represents a significant progress in attaining accuracy when compared to 2D photogrammetry, especially because it can correct the radial and tangential distortion of conventional photogrammetry. This allows accurate measurement of archaeological sites and findings, even of those relatively high and large in size/area (especially architectural remains). The ortho-view thus also enables presentation of complex surfaces, such as vaults with wall paintings and ornaments, and realisation of this in an advanced form, within individual areas and without any distortion due to the projection of light onto curved surface of a vault or uneven surface of archaeological finds, or due to the height of some structured in height, etc.

The 3D model as such can be utilised in a wide range of applications from virtual presentations within cultural tourism or education through simulations of spatial relationships and interference in planned reconstructions up to simulations within the framework of crisis management in calculations of flood water risks etc. Repeated 3D digitisation can also capture a construction development of an object, or changes in structural conditions (e.g. shifts, cracks, etc.), so the technology can be used also for monitoring of the conditions

of historical building structures. The procedure of archaeological research can be in this way also “tangibly” recorded in the process of exploitation of individual surface levels.

Terrestrial laser scanning remains to be the most reliable method from among individual technologies of 3D documentation. This is related especially to the verifiable calibration-conditioned guarantee of accuracy as well as with the process of data collection, which by its technologic nature minimises the level of noise in the resulting model. On the other hand, TLS has also many negative factors. Probably the most significant is the price, which can be the main obstacle for wider application in the field of cultural heritage. Limited manipulation on elevated platforms also limits more extensive possibilities of application in the recording of high structures, where digitisation shadows can form in places of important structural elements. The resulting texture of model surface also poses a problem, as TLS scanners usually have weak photo sensors. The technology of structured light, which is close to the method of lBM, has been recently started to be applied especially in the case of portable scanners. Scanners equipped with this technology find wide application in the documentation of movable objects or immovable objects not exceeding 2 – 3 m. They can be used in the field of the cultural heritage especially for documentation of museum exhibits or movable findings and historical sculptures. The digitisation can be performed in the interior without the usage of any special lighting.

Currently, the method of lBM experiences the biggest boom in use. The recent rapid development of low-cost or open-source software for the creation of spatial models from series of images pushed lBM up the list of choices of the methods of recording in the process of preparation for the reconstruction of buildings, documentation of archaeological research, as well as overall monitoring and protection of historical heritage. This technology is versatile and has a range of possible applications. It can be equally useful for the digitisation of extensive archaeological sites and historical building complexes, as well as for small, movable findings. The mass expansion of this technology is also considerably facilitated by the user-friendly interface of the majority of software packages, as well as by the option to use supporting tools for the collection of data (monopod stand, microcopter). When using this documentation technology, it is necessary to scrutinise the quality of the input data, i.e. photos. The photo-documentation and its processing require special attention, because it is their quality that determines the success of the entire digitisation project.

In the CONPRA project we have, hopefully, demonstrated that all the technologies used and described and our papers became highly accessible and user friendly. Prior the project, none of the authors could be considered expert in these fields, however, soon they started to master new technologies and use them in their routine work.

List of abbreviations:

ASCII	American Standard Code for Information Interchange, file Format readable in many software,
BIM	Software for building information modelling, process involving the generation of digital representations of places, BIM files
CAA	International organization of specialists in computer sciences in archaeology
CAD	Computer aided drawing
CCD	Charged-coupled device, integrated circuit on silicon surface forming light sensitive pixels
CPU	Computer processing unit, colloquially “computer processor”
DEM	Digital elevation model (3D representation of terrain surface with a prime intention of elevation visualisation)
DSLR	Digital single lens reflex camera
DOF	Depth of field (one of the basic camera settings)
DWG	AutoCad native file format
EXIF	Exchangeable image (file) format
FLS	Farp software native file format
GCP	Ground control points (reference points measured by TS or GNSS Rtk Rover using to georeference 3D model)
GIMP	GNU Image manipulation program (open-source software for image editing)
GNSS	Global navigation satellite system
GPU	Graphic processing unit, colloquially “computer graphic card”
EV	Exposure values (one of the basic camera settings)
HDR	High dynamic range (technique used in imaging and photography to create a greater dynamic range of luminosity than it is possible with standard digital imaging techniques)
lBM	Image-based modeling (scanning technology using photos as raw data, sometimes referred to as 3D photogrammetry)
ISO (values)	Values for measuring the sensitivity of the image sensor in camera
ISPRS	International Society for Photogrammetry and Remote Sensing
LAS	File format, frequently for storing the LIDAR data, similar as LAZ
LAZ	see LAS
LCD	Liquid cristal display

LIDAR	Light Imaging and Ranging
MVS	Multi-view stereo (part of lbM processing workflow)
NURBS	Non-uniform rational basis spline (type of 3D model)
PS	Phase-shift (type of laser scanning technology)
PNG	Portable network graphics, file format frequently used for recording images
PTG	Leica native file format
PTS	Interchangeable file format
PTX	Interchangeable file format
PTZ	Leica native file format
RAM	Random access memory
RAW	Digital image file format, containing minimum processed data from the image sensor in camera
RGB	Red - green - blue, basic colours in computer colour model
RTK (rover)	Real time kinetic rovers, used for satellite navigation
SIFT (algorithm)	Scale invariant feature transform, algorithm for describing local features in digital image
SfM	Structure for motion, photogrammetric imaging technique for estimating 3D objects, basic procedure within lbM
SIFT	Scale-invariant feature transform (technology used for key points detection on particular photos during lbM processing step - Bundle adjustment)
SLS	Structured light scanning (scanner) (scanning using structured/gridded light as a technological mean)
TIFF (geoTIFF)	Tagged image file format, one of standard file formats for digital images
TLS	Terrestrial laser scanning (scanner) (scanning using laser as a technology mean)
TS	Total station, electronic theodolite
TOF	Time of flight
UAV	Unmanned aerial vehicle (remote controlled light aerial devices (e.g. copters, drones) with mounted camera used within lbM procedure for taking picture)
UV	Ultra violet

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