Processing 3D Point Clouds of Historical Timber Structures for Analysing their Structural Behaviour pressed for Time

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Fast assessment of the condition of historical timber structures is important in case of sudden damage or while renovation work. In angled and complex timber constructions, surveying with tachymeter is time consuming and requires additional manual work in post-processing, for a structural modelling of the wooden beams and their joints. Visual analysis is subjective and does not allow further quantitative evaluation. Thus, an automated method is required. The technology of 3D laser scanning has evolved significantly in recent years and allows the measurement of several hundred thousand points per second. Thus, point clouds covering an entire timber construction can be recorded quickly from multiple scanning positions. However, manual modelling of beams from point clouds is still a work-intensive task.

Developments in automated geometric modelling from point clouds are driven forward with the goal of overcoming the bottleneck in manual modelling. Developed methods for triangulated mesh generation or parametric modelling (e.g. “Non-uniform rational B-Splines” (NURBS) or simple geometric solids) are finding their way into more and more applications for thin walled or solid structures. Geometric fact-finding and modelling in historical timber constructions requires at least information about the axis and dimensions of wooden beams to be obtained. For a subsequent structural analysis, it is important to correctly locate the woodworking joints on the beams and determine their structural characteristics. The requirements for a reliable structural assessment – e.g. in terms of geometric accuracy, completeness of the geometric model as well as beam and joint characteristics – need to be discussed for different levels of detail (e.g. ideal straight or curved rectangular beams, deformations, cracks and other damages on beams).

While an elaboration with current manual methods for geometric and structural assessment takes weeks, our vision is to develop a method for a highly automated assessment within some hours respectively a few days. A fast, automated structural assessment also enables monitoring of existing structures with respect to progressive structural failure in the future.

Key words:
Point clouds; beams; automated geometric modelling; structural modelling; historical timber structures

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INTRODUCTION

For a better understanding of historical timber structures, on how they were designed and built by the carpenters and how they have deformed and changed over the years, geometric information about beams and woodworking joints must be collected on site for a later analysis [Eßer et al. 2016]. Depending on the requirements, this information can be visually captured by the person in the building, sketched on paper or digitally measured. The geometric reconstruction of the object of interest, in whatever medium and format, can then be considered for an analysis of the timber structure. In recent decades, numerical modelling and visualization techniques have proved universally applicable to the digital documentation and archiving of cultural heritage objects [Pieraccini et al. 2001; Levoy et al.

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2001; Ikeuchi et al. 2001; Remondino 2011]. The logical next step is the extraction [Macher et al. 2015] and modelling [Barazzetti 2016] of individual components which have already been investigated for some applications in the “Building Information Modelling” (BIM) context. Solutions for non-standardized or deformed components, such as wooden beams in historical roof structures, are still a main research topic for applications in digital heritage conservation.

The modelling of geometric entities (e.g. wooden beams) can be based on points, lines, and faces measured on objects surface by surveying methods, including tachymetry and 3D laser scanning. In comparison to the single point measurements with a tachymeter, the laser scanning technology allows recording of hundreds of thousands points per second, resulting in a dense point cloud. Data is typically acquired at multiple scan positions, registered in a common coordinate system and in this way aligned to a complete model of the timber construction. Such a model consists of millions of individual points on objects, which are visible from the different scan positions (see Fig. 1).

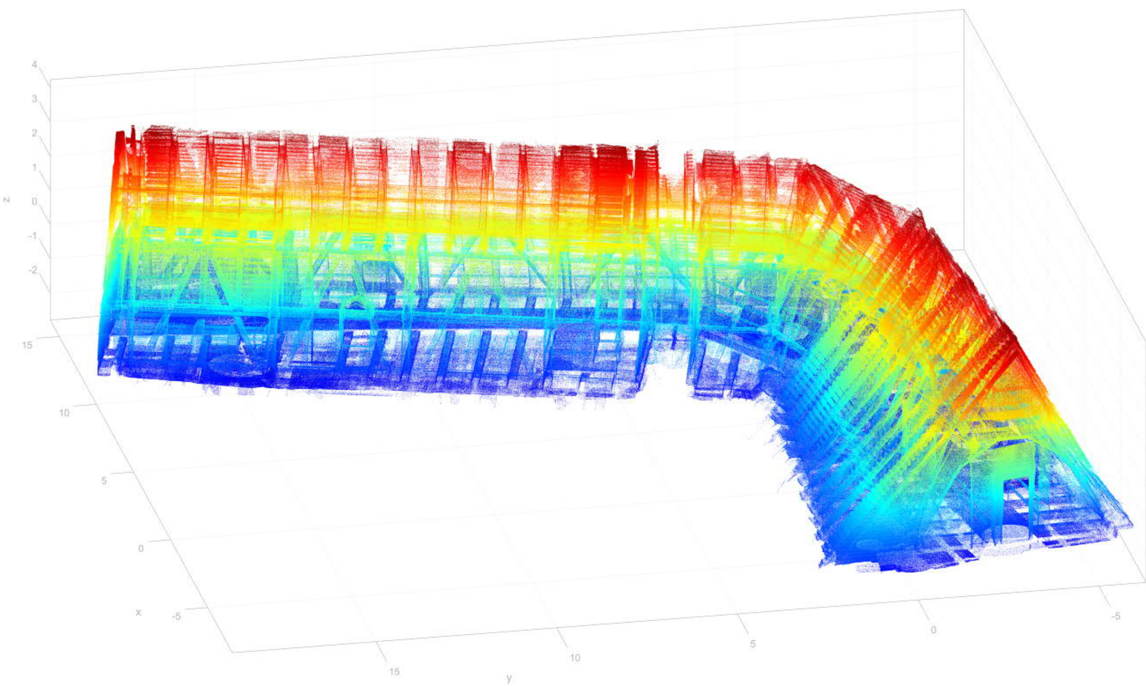

Fig. 1. Large point cloud of a complex roof construction of the Amalienburg in the Vienna Hofburg

The structural modelling is based on the geometric reconstruction and includes an analysis of the flow of forces, displacements, overstressing on structural members and joints.

The current state of the art for fact finding (i.e. geometric modelling) in timber structures and subsequent structural assessment consists of several manual tasks including:

a) Manual acquisition of information about the timber structure and geometric survey.

b) Manual modelling of 2D slices of the timber structure

c) Manual generation of an adequate structural systems in structural engineering software (FEM)

d) Prediction of the mode and risk of structural failure

The time required to complete the structural analysis is – depending on the size of the construction – usually several weeks to months. Based on recent developments in the automated geometric modelling from 3D point clouds, the following vision for a timesaving assessment of timber structures emerged:

a) Acquisition of point geometry with a 3D laser scanner

b) Automated transformation of points into geometrical elements like planar or curved surfaces.

c) Highly automated transformation of planes into cross sections, beam axis and mid-planes in terms of structural modelling

d) Modelling of joints between main structural elements.

e) Integration of joint characteristics based on manual observations

f) Structural analysis including predictions of risk and mode of structural failure

Due to risk of imminent collapse, the structural analysis of historical timber constructions may have to be performed under heavy time pressure. Thus, the aim of this development is a complete workflow for the analysis of large and complex timber structures within some hours or days.

Geometric modelling of complex structures from point clouds

The geometric reconstruction of objects scanned with terrestrial laser scanners, and more generally described by point clouds [Otepka et al. 2013] has been a major research topic in the recent years. While countless publications in the field of Cultural Heritage and Archaeology cover the topic of modelling individual objects in high detail, the main focus of the building industry in terms of "(Heritage) Building Information Modelling" (HBIM) lies on a complete modelling of complex structures.

Individual wooden beams were measured, modelled and used for deformation analysis by Gordon et al. [2004] and Cabaleiro et al. [2017]. This proofs the feasibility of the data acquisition method and its integration in structural analysis. However, concentrating on one beam leaves out the task of 3D modelling of an extensive set of beams, partially overlapping, and especially connected to each other in different types of joints.

For the geometric modelling of complex structures in the building and construction industry, methods have been developed for specific applications, like the identification of piping installations or indoor structures. Virtanen et al. [2018] present a method for modelling of indoor scenes. They describe the state of automation and the considerable manual effort to obtain clean results. Indoor scenes typically include objects of different type, i.e. relevant objects that shall be modelled and temporary models not of interest in scene reconstruction. In more controlled, but still complex, environments, like industrial sites, the reconstruction of piping installations was investigated earlier by Rabbani et al. [2007], but obtaining complete models is still challenging [Qiu et al. 2014]. In industrial installations connecting elements between pipes are typically challenging to detect, because they can be small. In timber constructions the joints between individual elements are challenging, because they are naturally occluding each other.

Structural analysis of complex buildings has been investigated by Castellazzi et al. [2015] and Gonizzi Barsanti and Guidi [2017]. Both publications propose a workflow for computation of finite element models from 3D point clouds. The derived models are then used for the structural evaluation.

A structural analysis of metal frame structures was carried out by Cabaleiro et al. [2014] by modelling the connections and the entire frame from 3D point clouds. The work uses the detection of sharp edges of the metal frame with Hough transform of the points in the point cloud. The detected edges are the basis for a 2D structural modelling. Yet, the thickness of the metal plates has to be measured manually.

Parametric modelling of cuboid wooden beams from point clouds in timber structures is shown in Yang et al. [2017] and Pöchtrager et al. [2018]. In the latter paper a roof construction with more than 400 beams was modelled automatically, which would still require manual editing to achieve a complete 3D model. We build on this work and propagate it to structural analysis.

Bassier et al. [2016] have already taken first steps into the development of a complete modelling workflow from point clouds, including geometric modelling of beams in with a triangulated mesh and subsequent structural analysis with "finite element method" (FEM). Their approach does not require the identification of individual beams. While this is an advantage for 3D geometric modelling, it was only shown for a smaller dataset (section of rafters). It furthermore does not allow modelling the individual beams and their joints.

Strategies for structural modelling

In general, three strategies for structural modelling in the context of historical timber structures are available respective applicable depending on the type of requested results for 3D, 2D and 1D modelling

3D modelling implies perfect view from all sides for the definition of the volumetric representation, knowledge about fitting of neighbouring members in the interior, the definition of contact areas between members and high computational costs. The material specification should be as accurate as possible to catch local structural effects.

If historical timber structures are already enriched respective strengthened by thin walled steel cross sections, a more abstracted strategy of structural 2D modelling in terms of plane elements with usually small member thickness would be possible. This approach could be based on the definition of the shape for the single planes only by edges and manual completion by the thickness. In principle, such engineered thin walled cross sections could also be handled by 1D modelling, but with no possibility for the assessment of local stability like buckling.

1D modelling saves both computational costs and costs for structural modelling by idealisation respective densification to simpler structural elements like beams or plates. The global structural behaviour could be addressed quite well, local reasons for possible failure mechanisms have to be matched by mechanical simplifications. Anyway, this approach is perfect for a quick assessment of the structure and identification of critical, highly stressed domains especially in the cases stressed in time.

Characterization of historical timber structures

The beam-like structure usually consists of either straight beams with minor geometrical imperfections of the beam axis due to growth irregularities or dedicated curved beans. Such curved beams directly are taken from grown trees like subsections of the trunk in combination with branches or are prefabricated from short boards with appropriate curved shaping of the longitudinal edges and assembly in a staggered manner by nails to rectangular cross sections (= construction system of Philibert de l'Orme; see [Erler 2013]).

The cross sections of single members usually are rectangularity shaped with dimensions following the architectural demands or the needs from structural loading. Sometimes, sharp edges are missing in order to exploit the maximum structural cross section from an existing circular stem. If the dimensions of cross sections are varying, substructures may be assembled either with respect to the mid-plane of the structure or with respect to the plane of one side view as it was typical for old half-timbered houses. This time, the single beam axes as theoretical centre-line of each beam are no longer connected by points of intersection but have to be linked otherwise for interoperability in global structure. Possibly, over time, beams with initial perfect prismatic geometry at the time of chipping may start with rotation of the cross section along the beam axis due to shrinkage and local fibre deviation during the time of growing. The stability of the initial perfect rectangular cross section may also be corrupted by tensile cracks perpendicular to the grain due to the reduction of the moisture content and therefore shrinkage within the side faces of the cross section sometimes leading to cupping of the cross section.

Single members are implemented with a length as long as possible in order to avoid labour intensive connections usually also being the bottleneck with respect to the overall load carrying behaviour. The type of the connection usually was chosen with respect to the characteristic domination internal forces, the acceptability of the effects by net cross section in terms of stress peaks or stress concentrations and the impact of local stiffness on the global structural displacements.

At the beginning of the construction work, the members are trimmed and fitted together on the ground according to the initial geometrical concept of the structure usually still without any constraints in terms of forces. Only after implementation on site, these prefabricated substructures start taking loads from self-weight or external loads like dead load, snow or wind and change their initial shape due to either elongation by normal forces, significant bending due to bending moments or relative displacements of neighbouring cross sections connected with joints. If members are overstressed, the course of the beam axis may become disrupted, hopefully not being responsible and therefore the starting point for global structural failure.

Requirements for a reliable structural assessment

The structural model of a historical timber construction should at least consist of connected beam elements following the initial geometrical layout, which is definitely not that of the geometrical survey by 3D laser scan. The observable course of the beam axis is the compilation of the initial geometry enriched by the field of displacements due to manifold reasons. The strategy for reconstruction of the early stage of geometry cannot be standardized. One way could be to fit the deformed structure back to the supposed architectural framework and idealized entities usually given in terms of cones or planes for rafters or tie beams. The connected structural elements like struts have to be adopted as well in line with the assumption of initial stress less and therefore not deformed structural elements.

Another way might allow starting with the deformed structure, if the displacements o not have impact on the global structural behaviour, as it is the case for issues like stability. After calculation of the field of displacements, this field will be subtracted from the observed geometry, if it is affine to the observed on with respect to quality and quantity. Anyway, the strategy of best fitting to global geometrical entities like planes or cones is not appropriate for the reconstruction of the initial geometrical stage of the construction. The mechanical characterisation of the members could also be affected by local irregularities like cracks, fissures or degradation of the material possibly due to too long impact of moisture and fungal decay. Additional documentation by photos could help to identify those irregularities, which also could lead to increased global system displacements.

The next decisive step of structural modelling is the adequate setting of connections in between the structural elements and to the ground respective adjacent supporting elements likes walls, columns or abutments.in opposition to modern connection systems, traditional carpentry connection systems exhibit explicit nonlinear structural behaviour. This procedure can either be manually implemented or supported by libraries in structural engineering software for software supported generation of substructures.

Once, the structure is working with self-weight, it is time for the application of external loading like wind, snow or live load. Such loads usually are not applied to the directly loaded elements like battens on roofs or wooden boards on top of flooring systems, but concentrated on the underlying structural elements like rafters or tie beams.

The final verification against structural (= buckling) and failure of materials respective connections is organized within load combinations, which should be representative for realistic loading scenarios. The calculation software should also be capable to catch intermediate changes of the structural system caused by local failure of substructures or connections.

MATERIALS AND METHODS

Methods for collection and interpretation of geometrical input data

The proposed method for geometric modelling of the timber structures is based on a dense point cloud recorded by a 3D laser scanner. On the surface of wooden elements, the point density should be 1-2 points per cm² to represent all details like cracks and other damages on the wood as well.

The workflow for geometric modelling – developed in Pöchtrager et al. [2018] – uses a point cloud segmentation based on the normal vectors of the points. Extracted planar segments of the point cloud are used to identify the side faces of the wooden beams. Matching adjacent side faces are brought together to form the geometric entity of a beam. Many of the used wooden beams have rectangular cross sections, which mean the modelling methodology needs to look for adjacent side faces that are orthogonal to each other and share a common longitudinal axis. Additional rules for the beam modelling are needed for non-rectangular cross sections. Purlins with arbitrary shaped polygonal cross sections – possibly with more than four side faces – are typically used in trusses like *Liegender Stuhl*. (see Fig. 2).

If all side faces of a beam are captured by the laser scanner and extracted in the segmentation step, an accurate parametric modelling is achieved by minimizing the squared distances of the side faces to the measured points on the beam. The least squares fitting of the model is robust against small damages and cracks on the beam, but it might be affected by large (systematic) deviations of the beam from the expected geometry. A further challenge in the modelling is the determination of the correct dimension of the wooden beams for which not all side faces were recorded by the laser scanner (e.g. only two or three sides). In this respect, assumptions about the beam cross section need to be made. The dimensions of side faces can also be computed from the edge points along the beams in the laser scan. For beams with arbitrary cross section and more than four side faces, the local coordinate system should be linked to one of the dominating side faces respective edges. The shape of the cross section should then be specified by a closed polygon, which can correctly be interpreted by the engineering software Dlubal DICKQ [Dlubal 2007].

Curved beams can be handled either by connecting short linear beam sections with rigid joints along the curved axis, or by direct modelling of the curved beam axis based on the curved side faces. Depending on the degree of curvature a differentiation between initially curved beams (e.g. de l'Orme) and those deformed over time is possible.

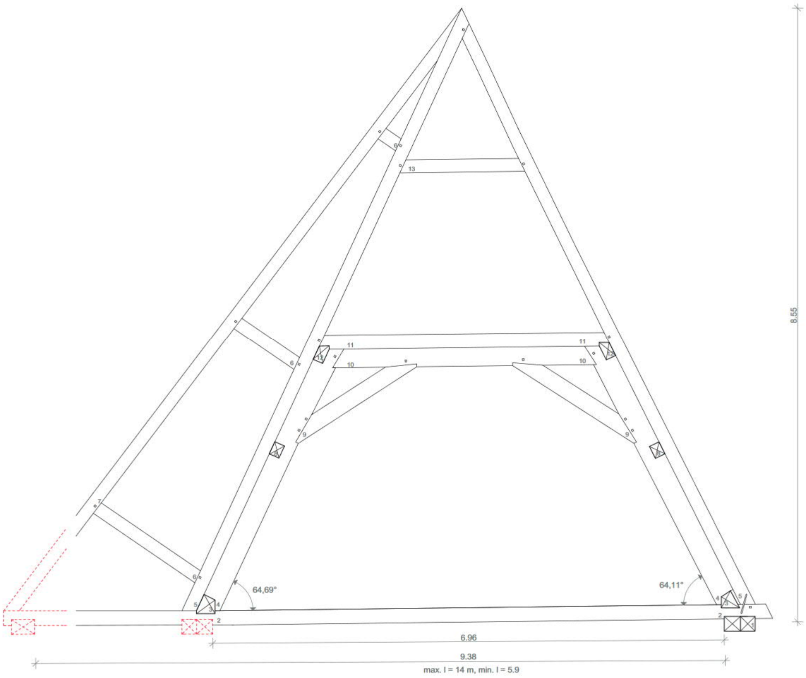

Fig. 2. Cross section of rafters in the Amalienburg
(© A. Domej, N. Hamader, and B. Kapsammer, all TU Wien, 2015)

Advanced methods for post-processing of geometrical data

After the geometric modelling of the wooden beam elements is finished, a further processing and analysis is needed on the functionality of the beams and their woodworking joints.

Detection and classification of woodworking joints:

The general goal is an automated detection and modelling of joint elements (= rigid beam-like coupling elements) based on the geometry of neighbouring beam elements. The joint is simply modelled as shortest connecting line between two beam axes. One solution for an automated joint modelling would be to find all connecting vectors between beams with a specified maximum length (e.g. 0.2 m).

In a later step, based on a joint classification characteristics can be assigned to the individual joints. For a reliable determination of joint characteristics, a manual documentation of representative joints in the timber structure is required. Subsequent to the manual documentation the joint characteristics can be automatically assigned to all similar joints based on a regular occurrence, with respect to the structural performance (= setting of hinge definitions and slip curves), following the rules of traditional carpenter design procedures. Additionally, typical geometrical pattern near expected joints, on the surface of beam elements, indicate the characteristics of a joint and can be used for validation.

Handling missing beams:

In some areas of the geometric model, beams are still (partially) disconnected from the structural system. This can either be because of deficiencies in the data acquisition with the 3D laser scanner, or in the segmentation and modelling process. The problems that come with the quality of the scan data are mostly in scan shadow areas and related to the inhomogeneity of the point density. Besides that, the generalization in the parametric modelling of the beams also leads to missing connections. This might occur for highly deformed beams. Especially in historical timber structures, however, parts may already be missing or connections may have been loosened over the time.

In general, it is better to be more generous in the automated detection of woodworking joints, as they can be easily removed or deactivated later in the structural assessment.

Fitting of deformed geometry to the original shape

The original shape is the starting point for the structural assessment. The differences between deformed and original shape are represented in the field of displacements, calculated by the structural engineering software.

Assessment of the original shape of e.g. a roofing structure should not be accomplished by best fitting planes, but has to be connected to basic architectural geometrical entities like planes, arches, domes…, which themselves must be attached to points of the original construction without stress or constraints, as it was prefabricated on the ground. At this stage, architects could also contribute with their expertise in conceptional geometrical design of building structures at that time and possibly even today without software support by CAD systems. Addition with the negative sign of the field of displacements, even calculated with the already deformed and documented system as quasi-initial geometry, could provide indications on the global original shape of the structure.
At this stage, architects could also contribute with their expertise in conceptional geometrical design of building structures at that time and possibly even today without software support by CAD systems.

Data exchange

A proper data format is required to provide simple and error-free data exchange between consecutive work steps in different software packages. Especially the step from geometric modelling to structural analysis requires attention, also because this is the interface between the disciplines of geometry and engineering. The “Industry foundation classes” (IFC) define a standard file format for data exchange in the building industries and are therefore a major component in the collaborative working in the “building information modelling” (BIM) context. To cover a large variety of scenarios for data exchange, the current schema versions in widespread use – IFC 2x3 and IFC 4 – provide the following subsets (buildingSMART 2019):

- IFC2x3 Coordination view – for architecture and technical building services
- IFC2x3 Structural analysis view – for structural design
- IFC2x3 FM handover view – for facility management

To differentiate between two main use cases the IFC2x3 Coordinate view has been divided into:

- IFC4 Reference view – for reference models that are not edited by the user
- IFC4 Design transfer view – for modifying the element geometry after import

The IFC standard can be represented in various file formats, like the ASCII STEP file, the XML file, ifcXML, and the zip-compressed ifcZIP. Within the developed workflow STEP (Standard for the Exchange of Product Model Data, [ISO 10303-21 2016]) files are used to exchange model information (e.g. geometric and structural information) between the processing tools. The STEP files transfer physical properties of the components in the timber structure and their functional interaction. For beam-like structures, the beam axis with its specification about the path between the two end points, the dimensions and in certain cases the varying orientation of the cross section must be modelled. Besides the geometry of the beam the used material needs to be stored, as well as and the geometries and characteristics of the joints.

It is not only important to uniquely define a data structure for exchange of data, also the quality of the data should, eventually, be propagated to allow estimating, how this is affecting the output of the structural analysis. This topic is treated in the USIBD specifications on accuracy and difference between acquired and represented data [USIBD 2019a; USIBD 2019b].

Model enhancement for structural analysis

The 3D model has to be further processed, before start of the iterative calculation due to nonlinearities on the level of structural behaviour or connections, issues not supported by 3D-laser scanning have to be handled. Support devices with kinematic constraints have to be supplemented and external loading from standards in addition to the self-weight of the members have to be applied and compiled to realistic load combinations for the final approval. Even the solver of the structural engineering software needs support by special settings in order to guarantee correct results.

Due to numerous nonlinearities, the numerical model needs validation by observable geometrical items like deformations, relative displacements respective rotations of neighbouring cross sections) on site. It would be helpful, if these features would already be part of the preliminary survey on site if still possible.

RESULTS AND DISCUSSIONS

In order to test the capabilities for a complete analysis and to identify the gaps in the processing, several tests were carried out, which are discussed in the following.

Stages of software development for the geometrical procedures

In the first step, a small section of the point cloud of the Amalienburg roof was cut out and the modelling of the beams with a rectangular cross-section was performed with the following settings:

Table 1. Parameters for geometric modelling

Parameter	**Value**
Minimum width of the beam	0.10 m
Maximum width of the beam	0.25 m
Maximum deviation from orthogonal side faces	± 0.1 rad (~ 11.45 °)
Maximum joint length	0.15 m

A typical challenge in tachymetric and laser scanning surveying, both are line-of-sight methods, are areas not visible from the chosen stand points. Increasing the number of stand points solves this problem at the cost of larger on-site time only partly, because inaccessible areas may remain. Such occluded beams or their back-faces need to be completed either based on assumptions (e.g. constant cross section) or by manual measurements and modelling. In the presented modelling results, the beams are extended to their woodworking joints, with user-guidance. The user selects two beams with a common connection point, which are extended if the length of the connecting vector is shorter than the maximum accepted joint length. The extension of the beams to their full length is to some extent additionally validated by points of the point cloud. Fig. 3 shows the transformation from the point cloud to the geometric modelled beams. The dimension of the beams and the geometry of the joint vector form the basis for the structural analysis.

The quality and weakness of the modelling can be analysed in Fig 4. The cloud-to-mesh distance shows that the beams are modelled very well and objects that are not of interest – like the roof tiling or electrical installations – are not considered. Those elements are shown in red colour, as their distance to the modelled beams is larger than 0.03 m. Yet, a major weak point is the modelling of strongly deformed beams and beams that do not have a rectangular cross-section. Fig. 4 shows that some beams have not been modelled well on the edges and that the lower purlin, which has five non-orthogonal side faces, has not been modelled at all. The next development steps in geometric modelling would therefore be the integration of non-planar side surfaces (e.g. with polygonal axis) as well as the modelling of beams with arbitrary polygons as cross sections. Additional detection and modelling of large cracks caused by shrinkage or overstressing and other damages on the wood is necessary for an accurate structural analysis.

Another field of application besides modelling timber structures could be the geometric reconstruction of thin walled cross sections in metal frame constructions. In comparison to the wooden beams, which are filtered within the point cloud based on a minimum and maximum width, the detection and filtering of metal frame components might need to integrate the following aspects in the modelling process:

- Clearly different reflectance properties of the surface than for wood.
- Metal sheets are usually too thin for accurate estimation of the thickness from 3D laser scanning
- Additional shadowing scenarios due to chords or flanges of the metal frame components

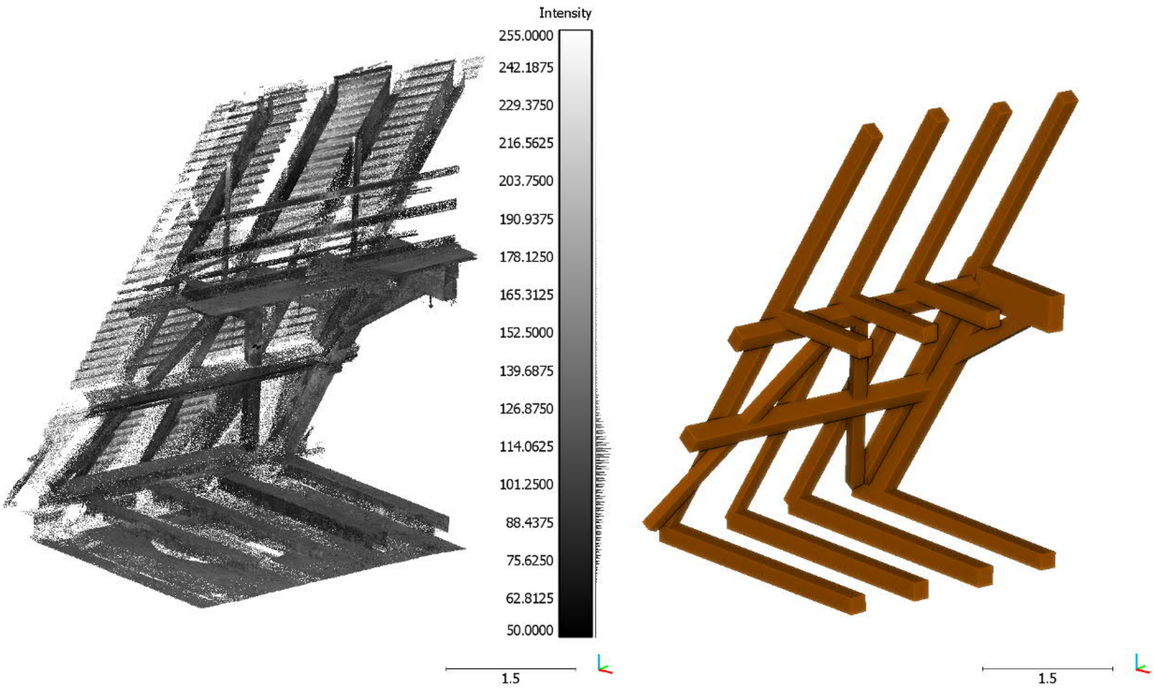

Fig. 3. Point cloud of a section of a roof structure (l) and the modelled beams with rectangular cross section (r)

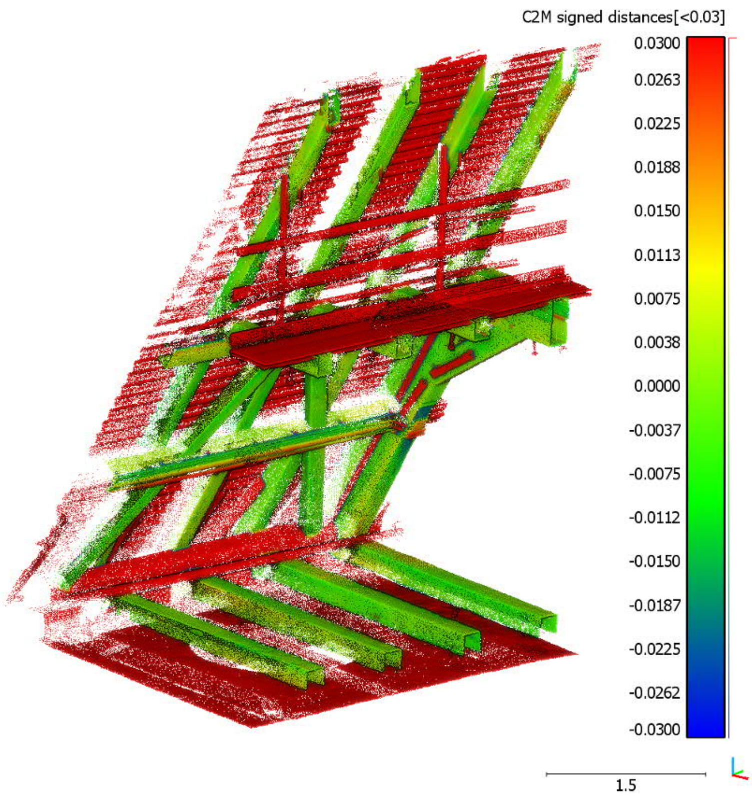

Fig. 4. Cloud-to-mesh distance showing the quality of modelled components as well as unmodelled areas

Stages of development within structural engineering software

To proceed with the structural modelling, the geometrical entities like coordinates of the nodes at the beam-ends, the spatial orientation of the cross section e.g. in terms of rotation angles and the width respective height have to be unpacked from the STEP file and enriched. Material specific parameters can already be taken from libraries containing strength and stiffness values according to harmonized European product standard EN 338 [Austrian Standards 2016, ÖNORM EN 338:2016 06 01] for solid wood, which only have to be assigned to the beam elements. Without any detailed investigations, the strength class C24, representative for medium range quality of solid timber e.g. from spruce, could be assigned as very first and uncomplicated approach [Steiger and Arnold 2009]. Sometimes it is convenient, to establish several material profiles for sake of better possibility of filtering complex structures.

At this stage, the beam elements are still rigidly connected without any settings for realistic mechanical behaviour e.g. as step joint. Today, the definition of adequate setting of nonlinear diagrams for each component of the internal forces or moments still has to be performed manually. Only by selection of some short rigid connection elements or ends of beams, this complex setting could also be software supported by predefined settings for typical connections from libraries. However, the knowledge about correct structural modelling of these special types of hinges, either on the level of beam theory or more advanced sub-modelling by local integration of 2D or 3D formulation, is still work in progress and a challenging issue of timber research.

For sake of final reporting, the documentation of consistent chains of approvals against failure could again be software supported, as it is already realized for similar issues of modern timber design. Updates of such generated reports could be automated with progressive refinement of the structural model.

Experience with structural modelling of even big and complex real structures

Before the background of very fast scanning devices and collecting big geometrical data from complex timber structures, the chance of adequate structural modelling and realisation of reliable results has to be discussed as well. At that time, such buildings usually have been designed from experience without support of structural software. Due to the sensitivity of the global structural behaviour to the stiffness characteristic of the joints, assessment of the load carrying behaviour is impossible without structural modelling. Nevertheless, the use of engineering software enables both a quick check of the system and profound parameter studies for an estimation of the most realistic structural behaviour. The investigations about the impressive timber roof structure of the “Spanish Winter Riding School” (SRS Vienna) as part of the Imperial Palace in Vienna (= Hofburg), has demonstrated (Fig. 5), that even big structures with a characteristic of 23.600 beam elements, about 13.650 knots, therefore about 82.000 equations could satisfactorily be handled with good results by a laptop with quad core and the only need of 5 GB memory despite of numerous iterations because of the nonlinear structural behaviour of the carpenter connections. Following, the bottleneck for an accurate assessment is not 3D scanning of lack of adequate tools for structural assessment, but the time lack due to manual translation of points into abstract beam axis and cross sections.

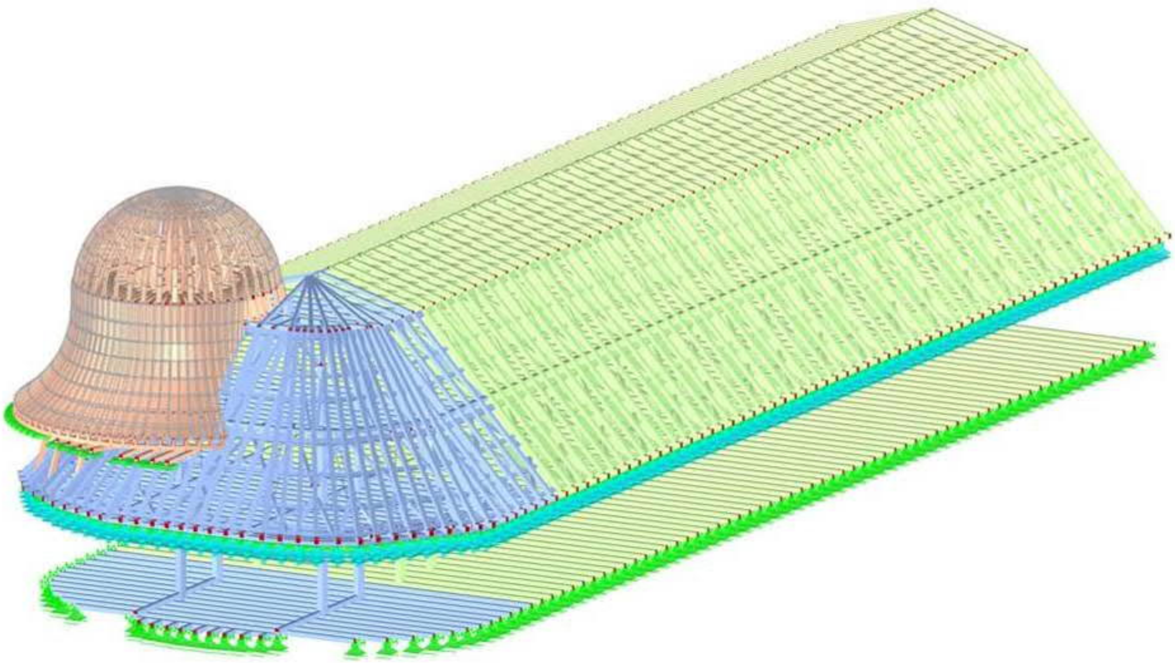

Fig. 5a. Structural model (SRS Vienna)

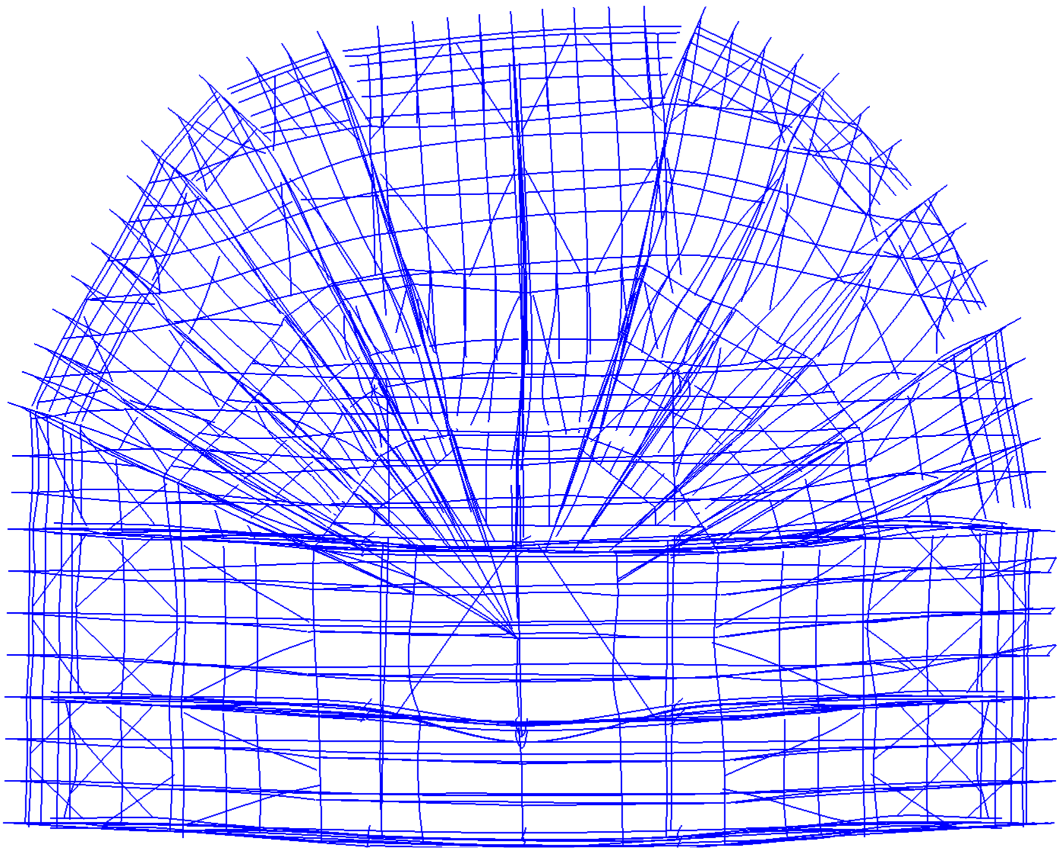

Fig. 5b. Field of displacements with gapping due to realistic realisation of the construction (SRS Vienna)

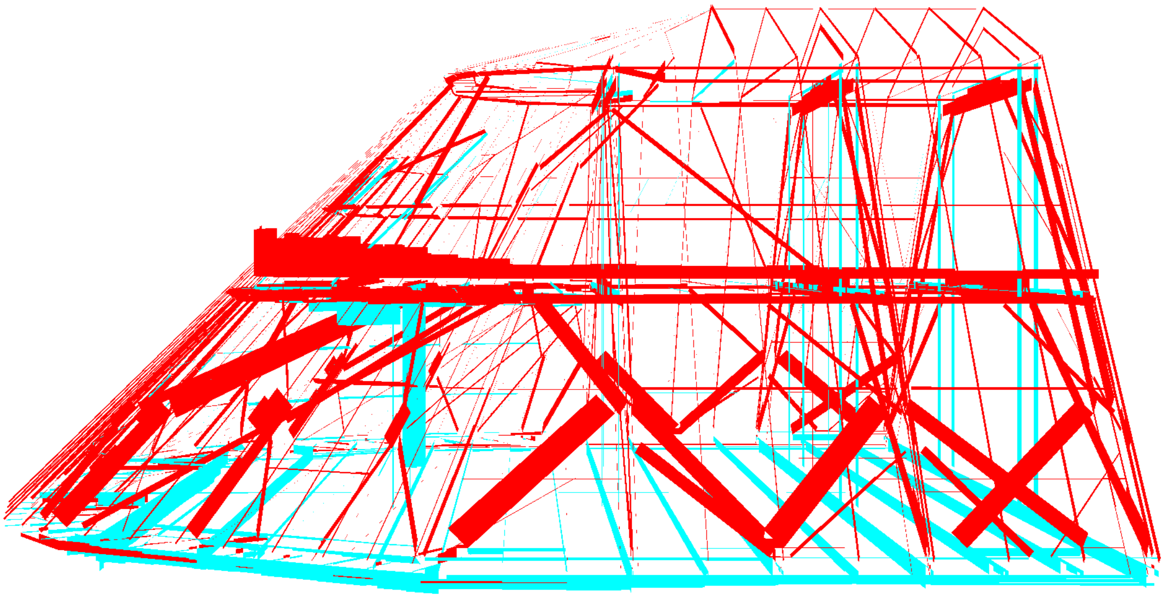

Fig. 5c. Complex distribution of normal forces in the apsis with blue=tensile and red=compression (SRS Vienna).

CONCLUSIONS

The recent developments in automated point cloud processing and the modelling of geometrical building components are important to speed up the process of preparatory geometric fact finding for adequate structural elements. Due to the high degree of automation and a clearly defined workflow starting from the raw point cloud, the process of the geometric modelling is transparent and reproducible and human error can be significantly reduced. The proposed workflow can be the basis for a fast and reliable structural assessment of huge and complex historical timber constructions, with some manual steps and issues still to be resolved.

While in the presented results only beams with straight axes and rectangular cross-section were modelled, an extension of the existing method for the representation of curved beam axes is crucial. Curvature of beams appears either due to deformation from external loading or from the original design as curved wooden beam. The second major extension refers to the modelling of beams with arbitrary polygons in the cross-section. For this purpose, the set of rules for the modelling of beams from the side faces must be adapted and extended.

Future perspectives of this work are the integration into BIM applications including the assignment of IDs to each member (beams and joints) for later identification or generation of the corresponding analytical models.

The combination of fast scanning devices with fast translation into a structural system could also be implemented for monitoring of existing structures with respect to potential progressive structural failure. The focus for decision-making could be based either on identification of excessive local relative displacements or also with respect to the structural behaviour of key members.

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REFERENCES

Austrian Standards. 2016. Structural timber – Strength classes (ÖNORM EN 338: 2016 06 01). Retrieved from https://shop.austrian-standards.at/action/en/public/details/570827/OENORM_EN_338_2016_06_01

L. Barazzetti. 2016. Parametric as-built model generation of complex shapes from point clouds. *Advanced Engineering Informatics*. 30. 298-311. doi:https://doi.org/10.1016/j.aei.2016.03.005

M. Bassier, G. Hadjidemetriou, M. Vergauwen, N. Van Roy, and E. Verstrynge. 2016. Implementation of Scan-to-BIM and FEM for the documentation and analysis of heritage timber roof structures. In *Euro-Mediterranean Conference* (pp. 79-90). Springer, Cham.

buildingSMART. 2019. Summary of IFC Releases. Retrieved February 14, 2019 from http://www.buildingsmart-tech.org/specifications/ifc-overview

M. Cabaleiro, J. Hermida, B. Riveiro, and J.C. Caamaño. 2017. Automated processing of dense points clouds to automatically determine deformations in highly irregular timber structures. *Construction and Building Materials*, *146*, 393-402. doi:https://doi.org/10.1016/j.conbuildmat.2017.04.037

M. Cabaleiro, B. Riveiro, P. Arias, J.C. Caamaño, and J.A. Vilán. 2014. Automatic 3D modelling of metal frame connections from LiDAR data for structural engineering purposes. *ISPRS Journal of Photogrammetry and Remote Sensing*, 96, 47-56. doi:https://doi.org/10.1016/j.isprsjprs.2014.07.006

G. Castellazzi, A.M. D'Altri, G. Bitelli, I. Selvaggi, and A. Lambertini. 2015. From Laser Scanning to Finite Element Analysis of Complex Buildings by Using a Semi-Automatic Procedure. *Sensors* 15, no. 8: 18360-18380. doi:https://doi.org/10.3390/s150818360

Dlubal. 2007. DICKQ – Querschnittswerte und Bemessung von dickwandigen Querschnitten. Retrieved September 11, 2019 from https://www.dlubal.com/-/media/C7C35B3A92CF4AFD8AA47F68D72CA6F8.ashx

K. Erler. 2013. Kuppeln und Bogendächer aus Holz. Von Arabischen Kuppeln bis zum Zollinger-Dach. Fraunhofer IRB Verlag. Stuttgart: ISBN: 978-3-8167-8833-1, 35 - 41

G. Eßer, G. Styhler-Aydin, and G. Hochreiner. 2016. Construction History and Structural Assessment of Historical Roofs - an Interdisciplinary Approach. In K. Van Balen, E. Verstrynge, ed. *Proceedings of the Structural Analysis of Historical Constructions - Anamnesis, Diagnosis, Therapy, Controls*. Taylor and Francis Group, London: ISBN: 978-1-138-02951-4, 790 - 795.

S. Gonizzi Barsanti and G. Guidi. 2017. A GEOMETRIC PROCESSING WORKFLOW FOR TRANSFORMING REALITY-BASED 3D MODELS IN VOLUMETRIC MESHES SUITABLE FOR FEA. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XLII-2/W3. 331-338*. doi:https://doi.org/10.5194/isprs-archives-XLII-2-W3-331-2017

S.J. Gordon, D. Lichti , M.P. Steward, and J. Franke. 2004. Modelling point clouds for precise structural deformation measurement. *International Archives of Photogrammrtry and Remote Sensing*, 35.

K. Ikeuchi, T. Oishi, J. Takamatsu, R. Sagawa, A. Nakazawa, R. Kurazume, K. Nishino, M. Kamakura, Y. Okamoto. 2007. The Great Buddha Project: Digitally Archiving, Restoring, and Analyzing Cultural Heritage Objects. *International Journal of Computer Vision*. 75. 189-208. doi:https://doi.org/10.1007/s11263-007-0039-y

ISO. 2016. International Organization for Standardization. Industrial automation systems and integration — Product data representation and exchange — Part 21: Implementation methods: Clear text encoding of the exchange structure. ISO 10303-21. Retrieved from https://www.iso.org/standard/63141.html

M. Levoy, K. Pulli, B. Curless, S. Rusinkiewicz, D. Koller, L. Pereira, M. Ginzton, S. Anderson, J. Davis, J. Ginsberg, J. Shade, and D. Fulk. 2001. The Digital Michelangelo Project: 3D Scanning of Large Statues. *Proceedings of the ACM SIGGRAPH Conference on Computer Graphics*. 1. doi: https://doi.org/10.1145/344779.344849

H. Macher, T. Landes, and P. Grussenmeyer. 2015. Point clouds segmentation as base for as-built BIM creation. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences. II-5/W3*. doi:https://doi.org/10.5194/isprsannals-II-5-W3-191-2015

J. Otepka, S. Ghuffar, C. Walshauser, R. Hochreiter, and N. Pfeifer. 2013. Georeferenced point clouds: A survey of features and point cloud management. *ISPRS International Journal of Geo-Information*, 2(4), 1038-1065. doi:https://doi.org/10.3390/ijgi2041038

M. Pieraccini, G. Guidi, and C. Atzeni. 2001. 3D digitizing of cultural heritage. *Journal of Cultural Heritage - J CULT HERIT*. 2. 63-70. doi:https://doi.org/10.1016/S1296-2074(01)01108-6

M. Pöchtrager, G. Styhler-Aydın, M. Döring-Williams, and N. Pfeifer. 2018. Digital reconstruction of historic roof structures: developing a workflow for a highly automated analysis. *Virtual Archaeology Review, 0*. doi:https://doi.org/10.4995/var.2018.8855

R. Qiu, Q.Y. Zhou, and U. Neumann. 2014. Pipe-run extraction and reconstruction from point clouds. In *European Conference on Computer Vision* (pp. 17-30). Springer, Cham. doi:https://doi.org/10.1007/978-3-319-10578-9_2

T. Rabbani, S. Dijkman, F. van den Heuvel, and G. Vosselman. 2007. An integrated approach for modelling and global registration of point clouds. *ISPRS journal of Photogrammetry and Remote Sensing*, *61*(6), 355-370. doi:https://doi.org/10.1016/j.isprsjprs.2006.09.006

F. Remondino. 2011. Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote sensing*, *3*(6), 1104-1138. doi: https://doi.org/10.3390/rs3061104

R. Steiger and M. Arnold. 2009. Strength grading of Norway spruce structural timber: revisiting property relationships used in EN 338 classification system. *Wood science and technology*, *43*(3-4), 259-278. doi: https://doi.org/10.1007/s00226-008-0221-6

USIBD. 2019a. U.S. Institute of Building Documentation. Level of Accuracy (LOA) Specification Version 3.0. Retrieved September 11, 2019 from https://usibd.org/product/level-of-accuracy-loa-specification-version-3-0/

USIBD. 2019b. U.S. Institute of Building Documentation. 3D Imaging Specification Version 1.0. Retrieved September 11, 2019 from https://usibd.org/product/3d-imaging-specification-version-1-0/

J.P. Virtanen, M. Kurkela, T. Turppa, M.T. Vaaja, A. Julin, A. Kukko, and H. Hyyppä. 2018. Depth camera indoor mapping for 3D virtual radio play. *The Photogrammetric Record*, 33(162), 171-195. doi:https://doi.org/10.1111/phor.12239

X. Yang, M. Koehl, and P. Grussenmeyer. 2017. PARAMETRIC MODELLING OF AS-BUILT BEAM FRAMED STRUCTURE IN BIM ENVIRONMENT. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, 42.

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The Three-dimensional Digital Representation of South Stoa (Portico) and Agonotheteion Mosaic in Ancient Corinth, Greece

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The intention of this interdisciplinary work is the integration of 3D recording techniques to survey and document the archaeological area of the South Stoa monument in Ancient Corinth, one of the most significant archaeological sites in Greece. South Stoa is an impressively large building, which covers an area of more than 4 acres (165 m long and 25 m wide) and consists of: (a) the portico, the northern part – facade with the outer and inner colonnade and (b) the southern part with Hellenistic shops and Roman public buildings. Between the southern buildings, there is the Roman "Agonotheteion", a monument that includes 45 sqm, also known as "Eutychia" (good luck) mosaic. The study group, which was set up and organized by the "American School of Classical Studies in Athens" (ASCSA), carried out an ambitious project (proposal) of the restoration of South Stoa Portico and the conservation of the Agonotheteion mosaic, based on an accurate 3D recording of the area (3D data and photogrammetry – orthoimages - for documentation, conservation, preservation and visualization purposes). The procedure allowed high accuracy measurements of the two monuments, which due to their size, nature and construction were completely different, the correction of the initial published dimensions of the portico, the identification of its initial level, the efficient process of a big quantity of information and the guarantee of the safe detachment of the mosaic.

Key words:
Digital heritage, 3D Modeling, 3D Data Analysis, ancient Corinth.

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INTRODUCTION

Ancient Corinth is one of the most significant archaeological sites in Greece, due to its historical importance as a Panhellenic administrative and commercial center in the late Classical and early Hellenistic times. Among the impressive monuments of the archaeological site are the Apollo temple, the Altar of Paul the Apostle, the Peirene fountain, the Theatre, the South Stoa etc.

South Stoa (Fig. 1) is an impressively large building, which covers an area of more than 4 acres (165 m long and 25 m wide). Its construction is considered crucial for the architectural and urban design of the ancient city of Corinth during its transition from Classical to Hellenistic period. During the Roman era, most of the shops were demolished and were replaced by administrative and other public buildings. One of them is the Roman "Agonotheteion", a monument that includes a 45 sqm mosaic, also known as "Eutychia" (good luck) mosaic.

In 2012, the "American School of Classical Studies in Athens" (ASCSA) carried out an ambitious project of proposing the restoration of the South Stoa Portico (reconstruction of the ground elevations and boundaries, displacement of the archaeological remains etc) and the conservation of the Agonotheteion mosaic for the Hellenic Ministry of Culture. However, the complex process of data acquisition and interpretation of the monument and its surroundings by reports, drawings and photographs is the first and most important step before starting the restoration works [Yilmaz et al. 2007].

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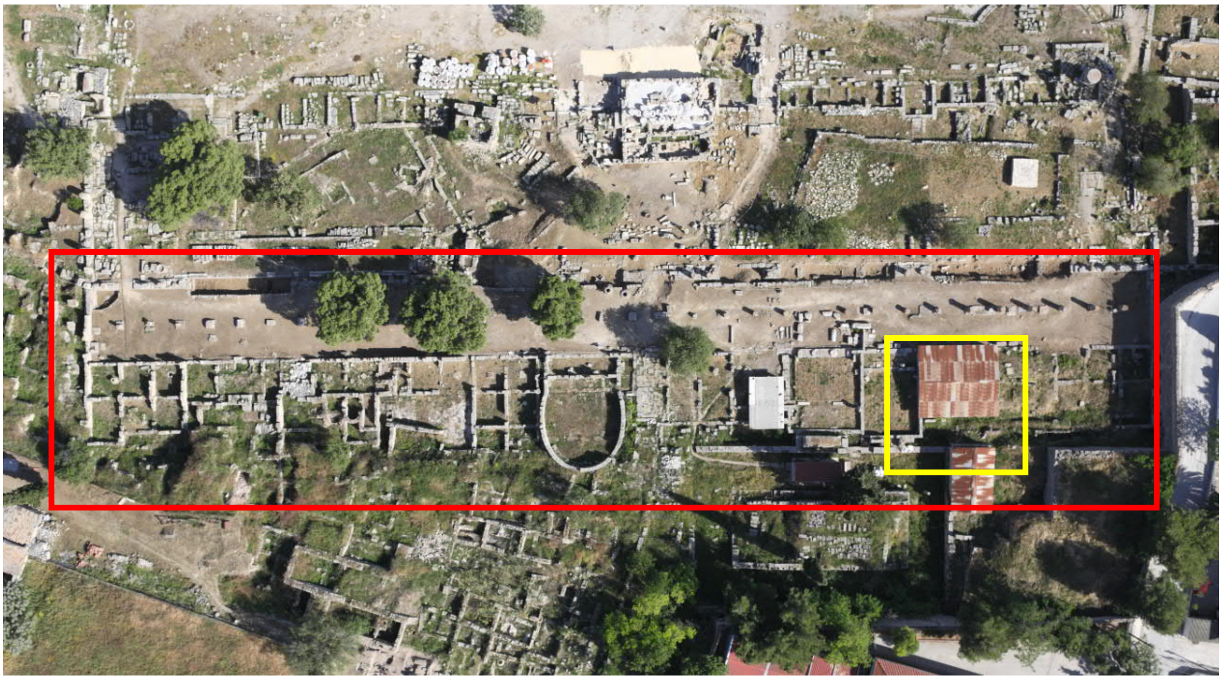

Fig. 1. The South Stoa (red line) and the Agonothteteion (yellow line) in Ancient Corinth, Greece

In order to complete the study of the two monuments, which due to their size, nature and construction were completely different, the project team that consisted of Konstantina Siountri (Architect), Vasilis Soulis (Archaeologist, Architect) and Anastasia Karagiorgou (Survey Engineer) had to thoroughly document the geometry and to fully map the pathology of the objects, either the subject was the 165 m colonnade or a single mosaic *tessera* with absolute precision (measurements, details of the colors and textures etc.).

For that reason, according to similar techniques used at the data management of ancient cultural heritage in Greece [Sapirstein 2015] and Italy [Fiorillo et al. 2013], the methods of topographic site mapping, photogrammetry [Pavlidis et al. 2007] and construction of 3D georeferenced models were used in order to analyze the heritage site and structures

HISTORICAL OUTLINE AND DESCRIPTION OF THE MONUMENT

According to the publication of the monument's excavation [Broneer 1954], the Stoa was constructed by Philip II and is associated with the founding of the Alliance of Greeks, also known as the Alliance of Corinth, and dates to 338 BC. However, according to newer findings [Coulton 1976], the Stoa dates to the early 3rd century BC and hence must be attributed to Demetrius the Polarcetes, who revived the Alliance in 302 BC. The construction phases that followed, throughout the Roman period, from the first imperial years to the destruction of Corinth by Erulus in 267 AD and later by Goths in 395 AD, reflect the long history of the city of Corinth.

The monument consists of: (a) the portico, the northern part – facade with the outer and inner colonnade and (b) the southern part with Hellenistic shops and Roman public buildings. The difficult achievement of the archaeological research and study of the architecture of this large-scale monument is attributed to the ASCSA. The excavators of the monument were a) R.B. Richardson in 1896, Th.W. Heermance in 1904, b) O. Broneer in 1933 (II World War), between 1946 and 1948 and in 1950 and finally c) C.K. Williams [1972; 1973; 1978; 1978a; 1979; Williams and Bookidis 2003]

The study of the monument's architecture and history was published by the excavator O. Broneer in 1954. After two decades, J. J. Coulton studied the historical evolution of the style of the Stoa and its characteristics. His work was published in the mid-1970s.

The South Stoa belongs to the type with a single-story exterior portico (Portico) and a two-story rear section with shops on the ground floor [Broneer 1954]. It has a length of 164.38 m at the facade's stylobate and a width of 25.15 m from the stylobate to the rear wall of the shops, covering an area of more than four acres. It dates to the last decades of the 4th century BC and it was the largest and most carefully designed Stoa that had been built until then. The construction material is the well-known gray-green tufa stone of Corinth, which was used for all public buildings in Corinth during the years before the Roman period.

The South Stoa is characterized by a high-quality detailed construction. The curvature is referring to the architecture of the temples and is not common in galleries. However, in South Stoa we find curvature at the stylobate of the outer colonnade and at the base of the walls. The curvature at the center of the stylobate at the facade's colonnade is estimated at 0.15 m [Broneer 1954], i.e. 0.09 % of the total length, much less than 0.16 % of the curvature of the long sides of the Parthenon [Coulton 1976].

The Portico had a Doric colonnade of 71 columns and an internal Ionic colonnade with 34 columns. The use of the "imposing" Doric rhythm was used due to the large width of the building, resulting to a high roof by the absence of a floor in the Portico, combined with the existence of a floor at the rear of the building. The Doric colonnade had columns with a "lower diameter" (D) of 0.96 m, an "upper diameter" (d) of 0.794 m, a height of 5.70 m (5.94 x D) and a distance between the vertical their axes of 2.34 m (2.44 x D). The columns were tense, but they were not tilted inward, despite the curvature. The corner columns were not thicker than the rest.

The *crepidoma* of the facade's colonnade consisted of two steps. In front of it, on the ground, there was a stone semi-circular cross-section canal that was connected with 18 square cleaning wells at regular distances. The Doric columns were based in the center of each of the second stone of the stylobate. The stones of the foundations and the stones of the *crepidoma* of the colonnade had a length of 1.17 m, equal to half the distance between the columns. The width of the stones of the foundations was 0.585 m, equal to one quarter of the distance between the columns. On the east and west sides of the building, the foundations, the *crepidoma* and the superstructure of the walls maintain a length of 1.17 m.

Portico was 12.385 m wide [Broneer 1954] from the outer side of the stylobate to the wall of the shops. Inside the Portico interior were the 34 Ionic columns of the inner colonnade, which had a "lower diameter" (D) of 0.66 m, an "upper diameter" (d) of 0.562 m and a "height" (h) of 6.24 m (9.45 x D) [Broneer 1954]. The distance between the vertical axes of the Ionian columns was 4.68 meters, twice of that of the Doric one, that is, an Ionic in each second Doric column of the facade. Because of this arrangement, each Ionic column had an independent foundation and there was no continuous stylobate.

On the ground floor of the back section of the gallery were 33 shops with two rows of rooms. Based on the pottery found in the shops, it is clear that these were functioning as restaurants, with warehouses and food preparation areas. All rooms in the front row except two had one well. The wells were supplied with fresh running water through a longitudinal duct connected to the water transfer system from the fountain of Peirene. The wells served not only for the supply of water but also for the cooling of wine and food. The shops were evenly spaced. The internal dimensions of the stores are in the range of 4.80 x 4.49 m [Broneer 1954]. The last store in the east was about 0.10 m wider than the rest. The floor above the shops was probably an accommodation space. The existence of the upper floor is documented by the great height of the gallery, as is evident from the Doric columns of the facade. If there was no floor, the shops would have a large internal height, unmatched with the dimensions of their floor plan.

For the construction of the South Stoa a central road of the classical city was removed, and buildings were demolished. Also, at its western end, a large tank, with an impressive underground water storehouse system was removed. This tank probably dates to the late classical period and seems to serve many of the buildings that existed in the area before Stoa was erected.

Thus, the building of the South Stoa, by eliminating all the pre-existing elements in a densely populated area of the classical city, was a decisive step in the urban planning of Corinth and became the most important public space and the center of the life of the city in the Roman years [Williams 1981].

In the Roman years, a series of renovations and dramatic reconstructions were carried out, during which the shops in the rear section were demolished and replaced by administrative buildings and other public buildings, except for the last three west shops that were preserved as they were in the initial phase. The process of these modifications, which began in the years of Augustus continued until the end of the 2nd century AD. Until Nero's years, the Agonotheteion, the Fountain, the Southern Basilica and the Bouleuterion had been built.

In 1933 Oscar Broneer during his excavations discovered one of the most important Roman mosaics in Greece dated to the late 2nd and early 3rd century AD, named as “Eutychia” (good luck) mosaic. Around the central panel are 12 smaller squares, four to a side, containing birds, rosettes and other floral designs in colorful *tesserae*. The mosaic’s central figural panel (1.30 m x 1.27 m) depicts a nude athlete and a seated, semi-draped goddess who holds a shield inscribed with "Eutychia" (good luck) as well as a vessel from which water streams into a basin, recalling two famous Corinthian trademarks, the Aphrodite of Acrocorinth and the nymph Peirene. The 45 sqm mosaic is interpreted as an allegory of the Isthmian Games and the goddess as Corinth herself. The inscription on the shield, “Eutychia” (good luck), reflects on the fortune of the victor and offers the same to the viewer. The donor of the mosaic is unknown [Robinson 2012]. In 1930’s he walls of the Roman Agonotheteion were rebuilt and a roof was placed in order to protect the underneath artifacts.

THE CASE OF THE PORTICO

Since Broneer’s excavation and the subsequent arrangements, the trenches of foundations of the external colonnade were left exposed and visible. The existing floor level inside the portico is in most parts uneven, while almost the entire length of the monument diverse from the ancient level. There are problems of understanding the third dimension of the monument since very few elements of the portico are preserved in situ, like parts of the foundation of the internal and external colonnade. Therefore, neither the rhythm nor the size of the columns can be easily understood by visitors (Fig. 2).

Fig. 2. Aerial photos of the Doric External Colonnade (red line) of South Stoa, Corinth

Indicatively, along the external colonnade there are about 10 parts of the stylobate (from 141 in total) and about 23 parts of the steps (from 141), about 50 elements of the layer of euthynteria are visible and some of the underlying layers of the foundation (layers -III, -III, IV).

Fig. 3. Broneer's designs of publication in 1954 (© [Broneer 1954])

From the early beginning of the project, it was obvious that apart from the historical and architectural research of the findings and the archives, the project team had to carry out an integrated survey of the monument in order to extract quantitative data that document the location, size and dimensions of monument's components. The collection and processing of images through aerial and terrestrial photogrammetry could enable the construction of 3D georeferenced models and the management of the huge amount of data from the office environment, reducing the number of visits in the field.

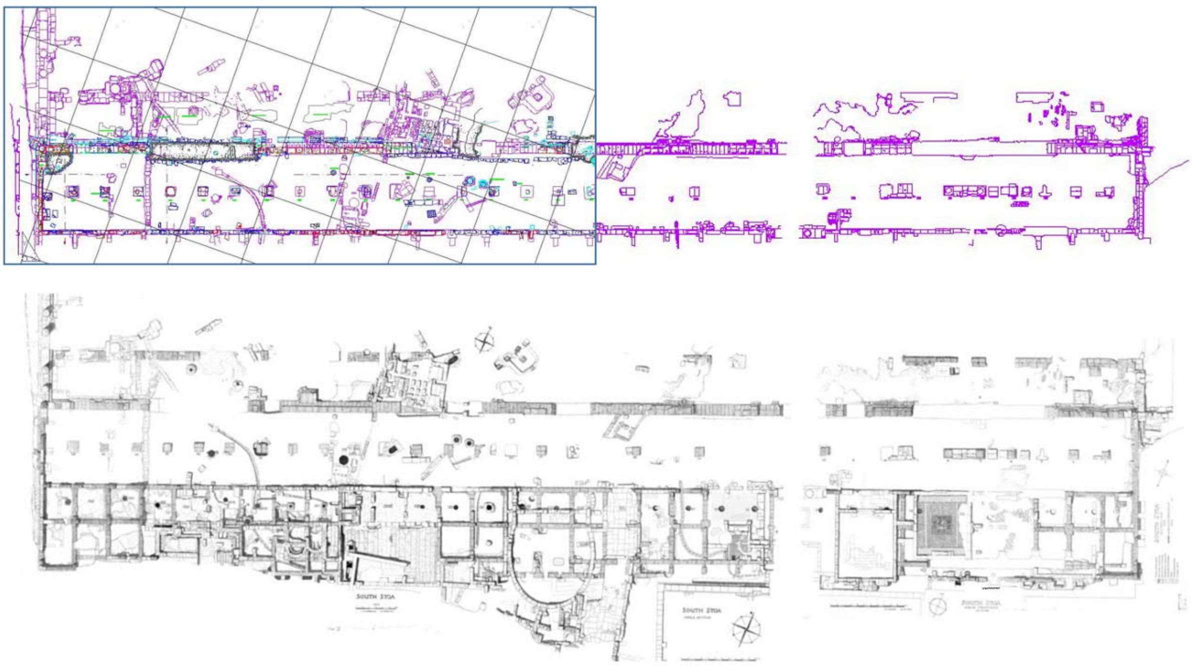

Fig. 4. The united plan of Broneer's designs with geolocation and the new plan with the track of changes

The challenges were multiple and demanded customized auxiliary equipment (customized focal length, calibration, depth of field of the camera). For each type of cultural object (with different scale as well as the different structure), the requirements in the process of photogrammetry and imaging techniques differed in order to achieve better and accurate results [Moysiadis and Perakis 2011].

As far as it concerns the aerial photogrammetry, in 2012 the use of UAS (Unmanned Aerial Systems – Drones) was not widespread. Therefore, the combination of a large helium balloon with a calibrated wide-angle lens camera was chosen in order to obtain a large number of overlapped photographs, at different levels, based on a reference coordinate system that allowed the extraction of accurate 3D data and produced accurate and visually detailed geometric information.

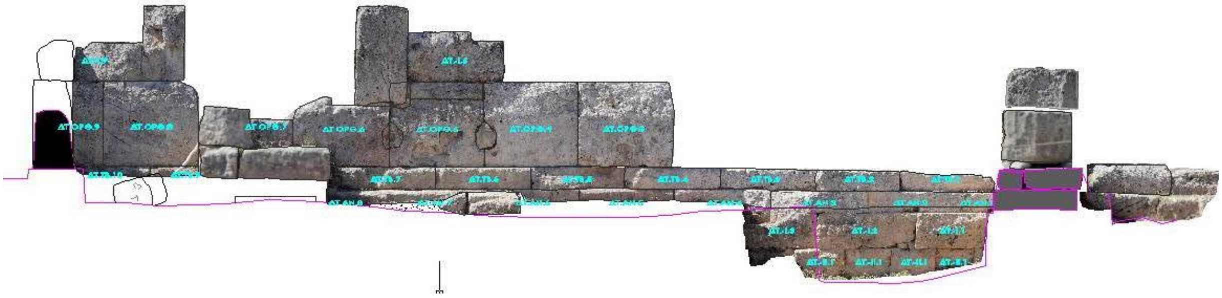

Fig. 5. Section in the western part of the South Stoa Portico

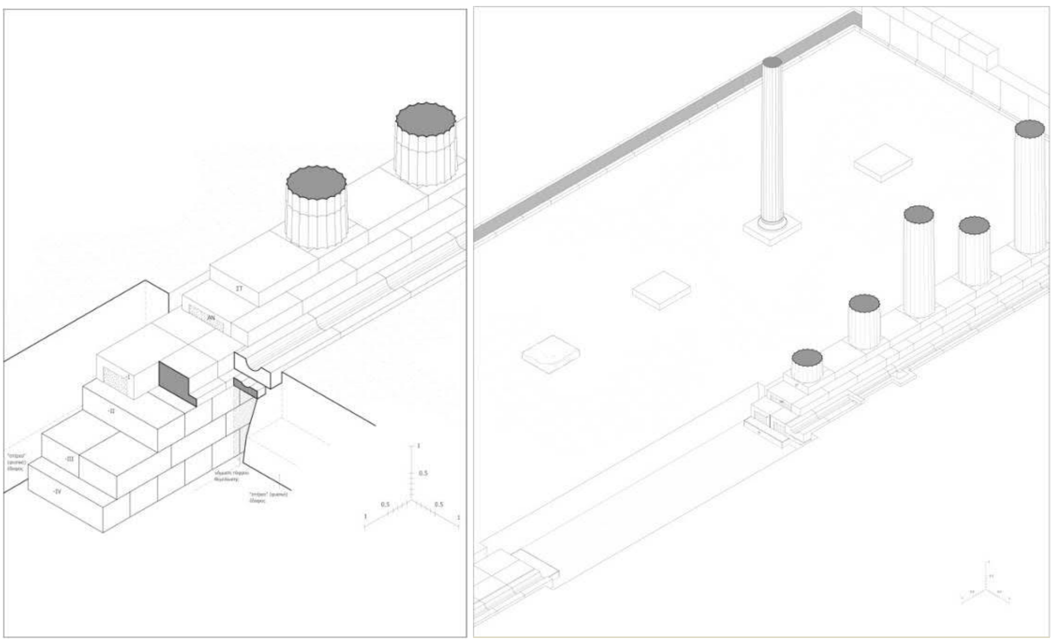

Fig. 6. The partial restoration of the foundation and the crepidoma of the external colonnade and the proposal for the internal remaining columns

One of the main tasks of the team was to succeed to insert Broneer's designs (Fig. 3), from the excavator's publication in 1954, into the system and through geolocation to give them exact X,Y coordinates. In that way it was possible for the first time to unite the different sheets of drawings in one single accurate plan. This allowed the project team to proceed in mapping (apart from the existing pathology of the monument) the changes (displacements, further excavations etc.) that have taken place from 1954 until today (Fig. 4).

The survey of the remaining parts of the foundation from layers -III, -III, IV allowed the team to confirm Culton's study about the curvature 0.09 % of the total length (it is estimated at 0.15 m in the center of the stylobate of the facade colonnade). However, as far as it concerns the distance between the vertical axes of two columns (interaxial width <*μεταξόνιο*), although the theory of Broneer was proven quite accurate, the project led to corrections regarding the areas of the monument's corners.

Regarding the South Stoa Portico, some of the project goals that were achieved can be described as follows:

(1) The restoration of the foundation and the *crepidoma* of the external colonnade in order to regain the form of the original construction (Figs. 5 and 6)

(2) The formation of the space between the external colonnade and the wall with the facades of the shops and public buildings in a way that restores the unity of the interior of the stoa

(3) The partial elevation of the external and internal colonnades using the best-preserved elements

(4) Enhancement of the monument.

THE CASE OF AGONOTHETEION

The detachment and conservation of ancient mosaics is considered a quite demanding procedure requiring high expertise and technical knowledge [Županek et al. 2016]. The scope of the study was the geometric documentation of the mosaic floor (horizontal and altitude) and the accurate digital preservation of the geolocation of each *tessera*. One of the major problems of pathology of the mosaic was the retreat of the subsoil, probably because of the existence of a wide network of pipelines, wells and galleries in the wider area. The unevenness of the surface of the structure led some areas being submerged and others being on the rise. In addition, there were intense problems of partial detachment of the *tesserae*, moisture phenomena, severe problems of biological actions that made the three-dimensional mapping necessary not only for the reinstallation of the tesserae in its original place, but also for the complete documentation of the existing multicriteria condition (Fig. 7).

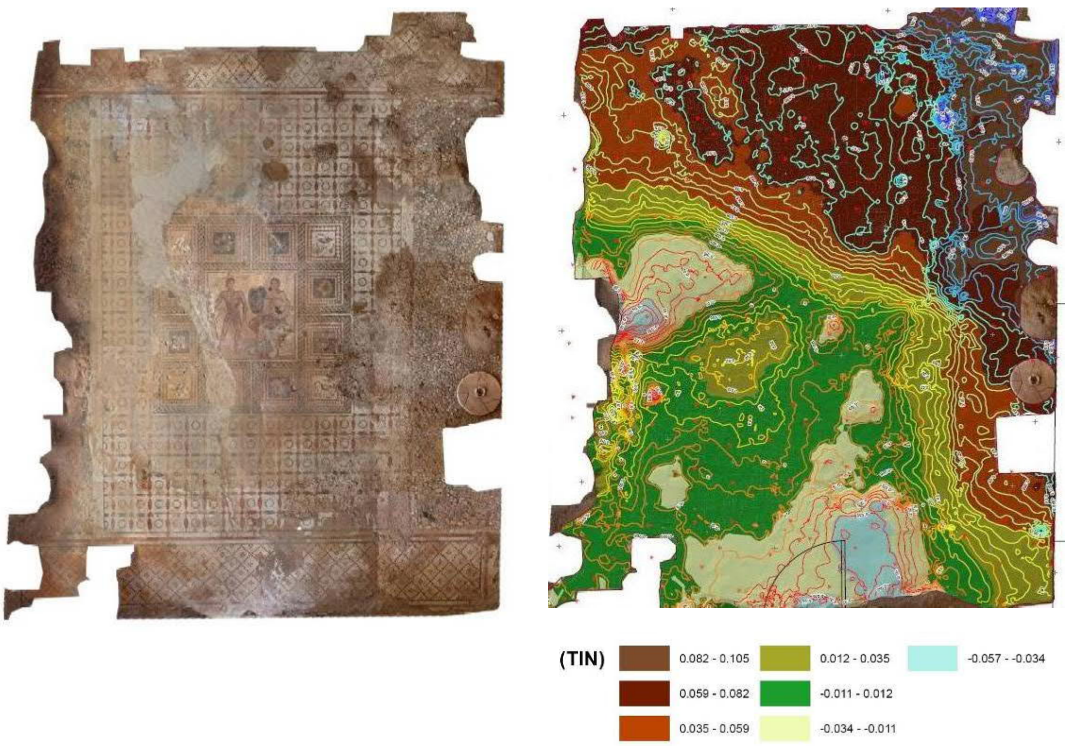

Fig. 7 The digital mapping of mosaic of Agonotheteion with multilevel information

The produced image was used as a background for the recording of the pathology and the mapping of its damage. After the evaluation and analysis of its situation, the team collaborated with the Conservator of ASCSA in Ancient Corinth, Nicol Anastassatou, in order to produce all the necessary designs of pathology and its conservation. The project was approved in 2013 by the “Central Archaeological Committee” (CAS) of the Hellenic Ministry of Culture.

The geometric documentation of the mosaic included the following substations:

(1) Field Works technical photography. The photographs were taken with a full format “digital single lens reflex” (DSLR) camera. A calibrated wide-angle lens was used so that the interior orientation elements were known. In addition, in order to keep similar lighting conditions throughout the procedure, technical lighting was used. The shots were made in such a way that they could be used in the photogrammetric procedure that followed. The overlap between the shots was of the order of 65 % cross-strip and 30 % cross-block and was obtained with special camera equipment in order to minimize the speeds ω, φ, κ. It is noted that the photographic equipment was customized for the needs of the photogrammetry and did not exist in this form on the market. Some of its parts (such as the vertical system) were entirely made by the group of photographers.

(2) Topographic measurements – measurement of photo-stable labels. Given the fact that the mosaic was extensively damaged, the team paid special attention so as not to aggravate its condition. On the other hand, these damages should not affect the accuracy of the measurements (local fields of surface). Additionally, custom targets for the labeling (before the photography) were used as well as custom lights of almost zero weight in order to avoid local loads.

(3) Photogrammetric processing that involved the process of recovery of the exterior orientation of the shots, creating a DSM (Digital Surface Model) and the production of deliverable geometric documentation with accuracy 0.5 mm, including the mapping of digital (.pdf) and analogue map-raft with multilevel information. ortho mosaic, altitude curves, elevators, hillshade surface mapping (Fig. 8), surface classification based on features such as gradients, wear etc.

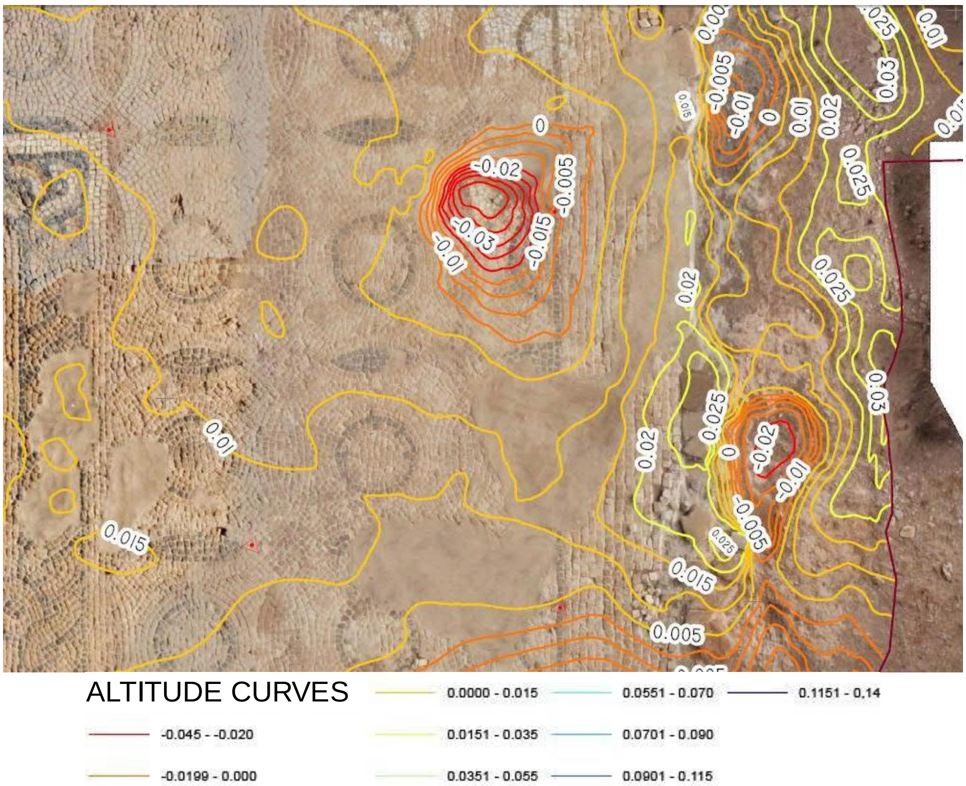

Fig. 8 The ortho mosaic with altitude curves, elevators, hill shade surface mapping

The form of the deliverables of the geometric documentation of the mosaic provided the conservator of ASCSA all the necessary data of recording the pathology. Under the conservator's instructions, the project team designed different types of pathology (Fig. 9) like surface deterioration of *tesserae*, biological damage factors, past interventions, areas with disturbed *tesserae*, internal void etc. As far as it concerns the mosaic, today the detachment has already been completed, bedding layers and underlying strata are excavated and its conservation, including cleaning and remounting on a new support, is in progress.

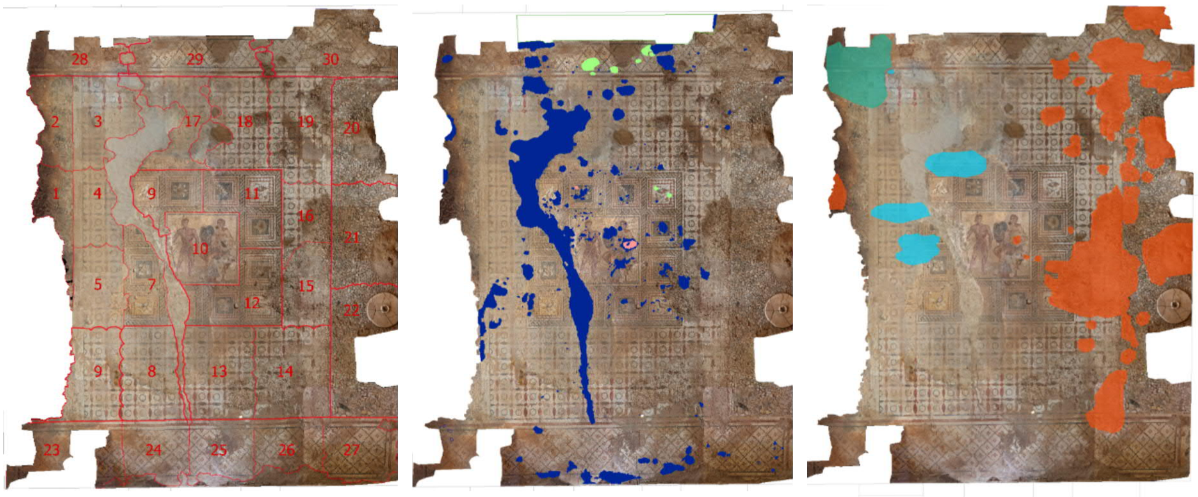

Fig. 9. The geometric documentation of the mosaic pathology

CONCLUSIONS

In this paper, the implemented 3D representation projects of South Stoa (Portico and Agonothteteion) in Ancient Corinth succeeded to deliver accurately structured data dealing with issues of monitoring geometry and pathology of the monument (e.g. correction of the initial published dimensions of the portico, the identification of its initial level). Photogrammetry and topography analysis were employed and integrated, in order to obtain 3D results that were used to produce orthoimages, maps and sections of the site. This procedure led to the digitization the georeference and the quality monitoring of the historical surveying and drawings of O. Broneer [1954] and therefore to comparisons. This technic made possible a) the track of changes in the morphology of the area and the position of the elements of the monument during the last six decades, b) the recognition of their original elevations, c) the partial restoration of the internal and external colonnade and d) the enhancement of the monument.

Apart from the big scale interventions, the project of mosaic allowed a detailed documentation of its whole structure that led in 2013 the Services in Competence (Ephorate of Antiquities in Corinth, Directorate of Anastylosis of Ancient Monuments, Directorate of Conservation of Antiquities and the Central Archaeological Council of the Hellenic Ministry of Culture) decide on its full detachment, removal to the laboratories and conservation with the vision of reinstalling it in its original place. Furthermore, the produced material can be used for informative and educational purposes and applications.

REFERENCES

O. Broneer. 1954. Corinth I.IV: *"The South Stoa and its Roman Successors"*, Princeton – New Jersey.

J.J. Coulton. 1976. *The architectural development of the greek stoa*, Oxford, 1976.

F. Fiorillo, B.-J. Fernández-Palacios, F. Remondino, and S. Barb. 2013. *"3d Surveying and modelling of the Archaeological Area of Paestum, Italy"*, Virtual Archaeology Review, [S.l.], v. 4, n. 8, p. 55-60.

A. Moysiadis and K. Perakis. 2011. "*The potential of conventional surveying, photogrammetry and laser scanning in monuments of cultural heritage documentation*", Proceedings of the 3rd International CEMEPE & SECOTOX Conference Skiathos, June 19-24, pp. 12911296

G. Pavlidis, A. Koutsoudis, F. Arnaoutoglou, V. Tsioukas, and C. Chamzas. 2007. *"Methods for 3D digitization of cultural heritage"*, Journal of Cultural Heritage, vol. 8, no. 1, pp. 93-98.

B. Robinson. 2012. “*Corinth: A Mosaic of Allegory, Athletics, and City Identity*” (AJA, Vol. 116, Jan 2012, p 105-132).
P. Sapirstein. 2015. “Photogrammetry as a tool for architectural analysis: The Digital Architecture Project at Olympia”, Proceedings of the 1st Conference on Computer Applications and Quantitative Methods in Archaeology, Greek Chapter. Rethymno, Crete.
C.K. Williams. 1972. *“Corinth, 1971: Forum Area”*, Hesperia 41, ps 143-184.
C.K. Williams. 1973. *“Corinth, 1972: The Forum Area”*, Hesperia 42, ps 1-44.
C.K. Williams. 1978. *“Corinth 1977, Forum Southwest”*, Hesperia 47, ps 1-39.
C.K. Williams. 1979. *“Corinth, 1978: Forum Southwest”*, Hesperia 48, ps 105-144.
C.K. Williams. 1978a. *“Corinth excavations, 1979”*, Hesperia 49, ps 107-134.
C.K. Williams. 1981. *“Corinth: Excavations of 1980”*, Hesperia 50 (1981), ps 1-44.
C.K. Williams and N. Bookidis. 2003. *Corinth XX: The Centenary 1896 – 1996*, Princeton.
H.M. Yilmaz, M. Yakar, and S.A. Gulec. 2007. *Dulgerler O. N, "Importance of digital close-range photogrammetry in documentation of cultural heritage"*, Journal of Cultural Heritage, vol. 8, no. 4, pp. 428-433.
B. Županek, M. Lesar Kikelj, K. Žagar, and S. Kramar. 2016. “*A new lightweight support for the restoration and presentation of a large Roman mosaic”*, Journal of Cultural Heritage, Volume 19, p. 477-485.

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Scratches? Scribbles? Scripture! Revealing the Unseen – 3D Scanning of Glagolitic Graffiti of the 10th Century at the Monastery of St. Naum

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The Monastery of Saint Naum in Macedonia is part of the UNESCO World Heritage Site "Natural and Cultural Heritage of the Ohrid region". The area is unique not only for its architecture but also its outstanding linguistic heritage. The monastery was named after Saint Naum and founded at the end of the 9th century and is visited by many tourists every day. In the transition from the narthex to the central church, the visitor immediately notices two shiny white marble columns. These columns carry unique inscriptions/graffiti, which represent some of the earliest evidence of the Glagolitic alphabet, a precursor of the Cyrillic alphabet. During the project, previously unseen inscriptions were revealed on the columns.

The huge number of tourists poses a danger to the historic surfaces of the columns, as the constant touching and rubbing of the inscriptions is causing deterioration. Therefore, there is an urgent need to image and archive the inscriptions. Using macrophotography with raking light did not work well as the columns' curvature and shiny surface caused blurring in the images, and some of the graffiti were not visible. Therefore, a structured light scanner with a 3D point resolution of 30 µm or less was used to record the columns, to both preserve and reveal these unique graffiti. The recording of the surfaces was deliberately carried out without texture information to exclude errors caused by the shiny and discoloured marble of the columns. The resulting high-resolution 3D model can be virtually illuminated from any angle, for example using raking light, allowing detailed observations and analysis. In addition to digitally preserving and archiving the inscriptions, the resulting surface models can be easily accessed by Slavistic and linguistic experts for a variety of research purposes.

Key words:
3D Scanning, Cultural Heritage, Graffiti, Surface Analysis, Revealing Lost Inscriptions.

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INTRODUCTION: THE ST. NAUM GRAFFITI DOCUMENTATION PROJECT

The documentation of the graffiti at the Monastery of St. Naum was an interdisciplinary project involving academics from Slavonic linguistics and the preservation sciences, carried out by the University of Bamberg. For the first report on the project, see also Kempgen [2019]. Initialized by Prof. Dr. Kempgen in 2015, the scanning work was carried out by the Preservation Sciences department of the University of Bamberg during one week in September and the post processing in the following months afterwards.

The project's aim was the precise 3D documentation of several Glagolitic and Cyrillic graffiti on two columns in the church at the Monastery of St. Naum in Macedonia; the resulting models should enable the linguists to study and analyse these inscriptions off site and enhance the legibility of the writings. The 3D-Documentation should work far better than 2D photos because of the potential to utilise multiple lighting scenarios, for example raking light. In

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addition the models can be easily shared with linguistic researchers, for example, over the web. The project was funded by the Bavarian State Ministry of Education and Cultural Affairs and supported by the former and current rector of the University of Bitola.

THE MONASTERY OF ST. NAUM

The Monastery of St. Naum is located on the Ohrid Lake in the south of Macedonia right next to the border with Albania (Fig. 1). It was founded at the end of the 9th century by Saint Naum. The Saint, who died in 910, was buried in an annex in the monastery's church. His burial place is visited by a huge number of tourists every day. Besides the grave of the saint, the church is decorated all over with amazing wall paintings. The monastery is nowadays part of the UNESCO World Heritage Site "Natural and Cultural Heritage of the Ohrid region". The site was inscribed to the UNESCO World Heritage List in 1979 due for its natural uniqueness and in 1980 the inscription was extended to cover the area's built and intangible heritage. This included the region's ancient Slavonic monasteries, as well as the unique spread of education, culture and writing in the old Slavonic world and other unique features in the region's preserved ancient city centers [UNESCO 1980].

Today the Monastery of St. Naum is partly reconstructed, as the monastery itself was destroyed in the 19th century and rebuilt afterwards. The church in the middle of the complex survived the destruction, but has nevertheless been renovated several times since it was built at the end of the 9th century. For more information about the building history and the monastery itself see Grozdanov [1995].

Fig. 1. The Monastery of St. Naum, Macedonia 2015.

THE OBJECTS

The main concern of the project was to document the graffiti on two columns inside the church. They are located in the nave behind a narthex, which was added to the church sometime after its construction (Fig 2). The columns are made of white marble and the surfaces have been polished. The columns are spolia, and the only existing remains of the original church.

The columns are in the shape of double columns so they are not cylindrical; the middle part is flat and the front and the back are roughly halved cylinders. As well as the flat areas, these curved parts also carry a lot of inscriptions and crosses from different times. The bases and capitals of the columns are also made of white marble and show a big cross at the front, which is not graffiti but an intended artistic feature. They also show traces of machining and the tools used. Today, the surfaces of the columns, bases and capitals are soiled by dirt, dust and candle wax and appear brownish.

As mentioned before, on the columns there are several graffiti, with varying dates of creation. Most date back to the 10th or 12th centuries, and some of them have been known since the 19th century. Antonin published some inscriptions from the Ohrid region, including some from the Monastery of St. Naum [Antonin 1886]. Some of them were drawn, photographed and documented by Antonin and by other Slavicists after him [Miljukov 1899; Ivanov 1908; Stefaniḱ1966; Grozdanov 1995]. Besides these rudimentary partial documentations, when the project started there was no satisfactory documentation of the current state of the entire columns, including all the graffiti.

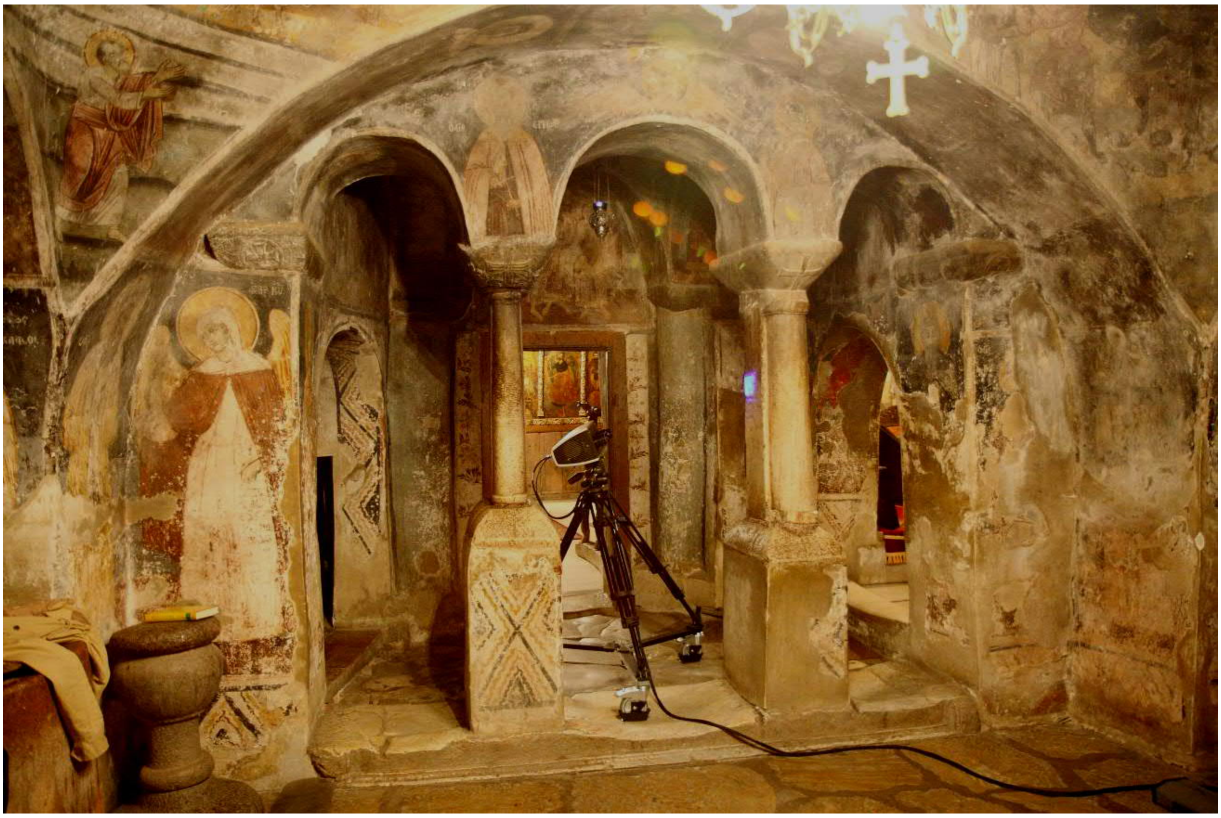

Fig. 2. The columns in the church, surrounded by wall paintings, 2015.

The graffiti vary in size and shape. Though some of them are extremely small, they can still be seen with the naked eye, because the author's intention was that they can be seen and read by other visitors to the place (Fig. 3). Although the writings can be seen, and even though some of them are scratched quite deep into the surface, they are barely legible. The crosses on the curved part of the columns have in particular been scratched quite deeply. The bigger crosses on the front of the columns are well documented in 19th century drawings [Miljukov 1899]. It is also known that the columns carry Glagolitic and Cyrillic inscriptions. Some of them represent complete phrases, others just a name or a few characters. Even small sketches like a fishnet can be seen.

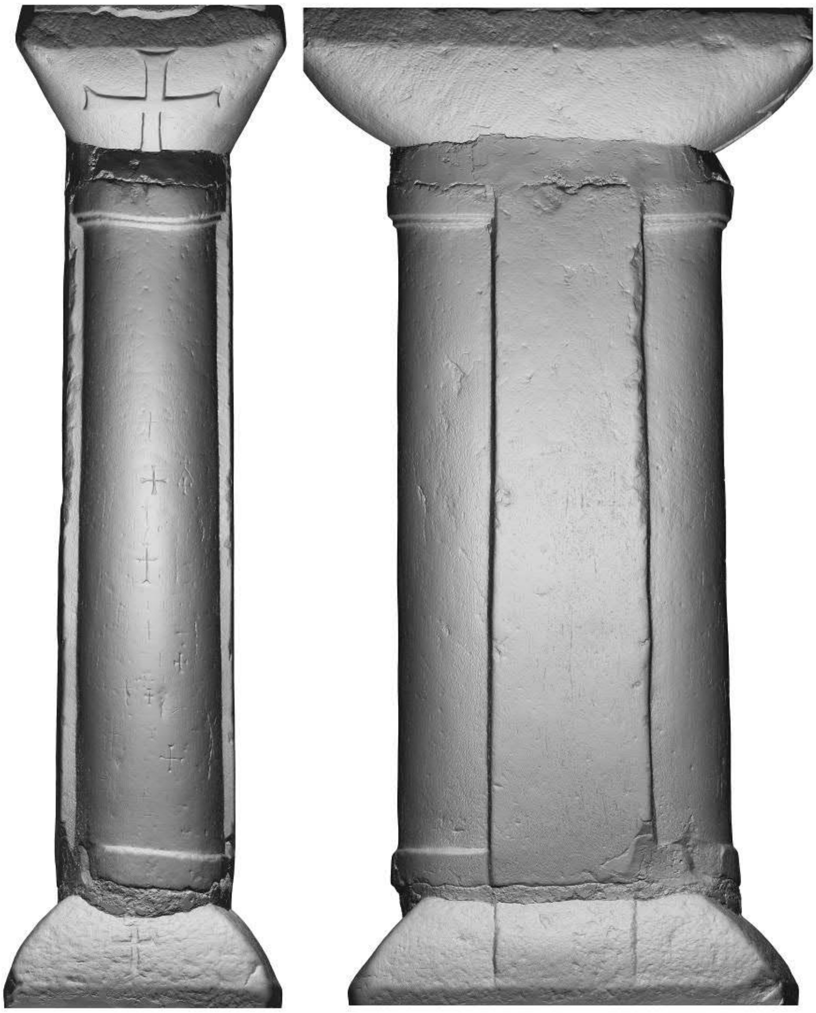

Fig 3. 3D model of the right column with crosses on the front.

The Glagolitic script is the oldest Slavic script, created by Saints Cyrill and Method in 863. The Glagolitic alphabet was the precursor of the Cyrillic alphabet, created some decades later in the capital of the Bulgarian kingdom, Preslav, using the Greek alphabet as its basis (and incorporating Glagolitic characters for sounds the Greek alphabet did not have letters for). In the Ohrid region, the Glagolitic alphabet was spread by Saints Kliment († 916) and Naum († 910), disciples of Cyrill and Method. While the Glagolitic alphabet was soon phased out in eastern Bulgaria, it lived on until the 12th century in Macedonia, where Saint Kliment had founded the "Ohrid Literary School" in 886 with Saint Naum succeeding him as head of the school. In Ohrid itself, no inscriptions or manuscripts from that time have survived; therefore, the inscriptions in the Monastery of St. Naum are among the oldest traces of the early cultural history of the Slavs.

Some characters on the columns are not scratched very deep into the surface, so the difference to the surrounding area is in the submillimetre range. In addition, the scratchings partly overlay each other and are therefore even harder to decipher. As mentioned before only the most readily noticeable inscriptions have been drawn, traced and photographed, and a complete documentation can both be used by Slavicist, and archived to preserve a permanent record for the current state was missing.

THE DOCUMENTATION WORKFLOW

Recording ancient inscriptions or other delicate cultural heritage with new digital (three-dimensional) techniques has been practiced for several years; the technologies used vary from image based approaches like photography with raking light or photogrammetry, more elaborate photographic approaches like Reflectance Transformation Imaging or Image Based Modelling, to the use of many different 3D-scanning technologies using structured light or laser technologies [Samaan et al. 2016; Historic England 2018]. For the previous use of "Structured Light Scanning" (SLS) for delicate cultural heritage see also Schäfer et al. [2012].

To meet the project's aims, a high-resolution documentation was needed. It was also vital not to put the graffiti at any further risk, for example by tracing them, so a completely contact free method for recording was required. Simply tracing the graffiti with translucent drawing paper would not have led to an acceptable result anyway, because of the very slight depth of most of the inscriptions. A further difficulty was that the work could only be carried out at night due to the many tourists and religious visitors in the church during the day. Working off the monastery's opening hours was particularly important, both to avoid disturbing the tourists, and to avoid being disturbed by them. Another challenge is presented by the fact that the marble columns have been polished, not only during manufacture, but also due to the constant touching and rubbing by the visitors. Nowadays, the surface is also dirty and appears browned at several areas. At the same time the columns are shiny due to the marble's crystalline structure. Another problem when trying to document them with photos is the curved structure; even with raking light, photography does not result in sufficiently legible inscriptions.

The decision to use a high-resolution Structured Light Scanning device was made according to the most important challenges: The construction of the columns from marble, and the surface soiled by candle wax and bounded dust. High-resolution Structured Light Scanning (SLS) of the columns was therefore carried out using a Steinbichler L3D 5M structured light scanner with changeable lenses and blue LED light source [Rahrig et al. 2018]. The camera has a 2448 x 2050 pixel sensor [Carl Zeiss/Steinbichler 2013]. The changeable lenses allow the resolution to be adjusted according to the size of the measuring field, which can improve results in especially delicate areas. The entire columns and capitals were documented with a resolution up to 100 µm, giving a precise 3D documentation of the current state, and enabling previously unseen inscriptions to be found. Certain areas with particularly delicate characters where inscriptions can be seen but not read sufficiently were documented with a resolution up to 30 µm. The higher resolution significantly enhances the legibility and helps to characterize and identify the very difficult to decipher characters.

The entire columns, as well as the details, were recorded in short time slots over three nights. Each column, including base and capital, is approximately 1.40 m high. The right column shaft itself is 0.98 m high and about 0.46 m deep.

Eight details were recorded in order to better reveal the most delicate inscriptions. In addition to the scanning of the columns a photographic documentation using raking light was done.

It was very important to document the Cyrillic and Glagolitic graffiti because the monastery is visited by many tourists each day and the inscriptions can be easily damaged by scrubbing/rubbing the surface, or even by scratching in new graffiti. If the graffiti were to be destroyed, a unique part of the intangible cultural heritage of the old Slavic scripts in Macedonia would disappear forever. SLS, used as a non-destructive technique – for example to enhance the legibility of weathered letters of greek inscriptions on stone [Papadaki 2015] or bas-reliefs [Schäfer et al. 2012] – is not a new approach. Nevertheless, the SLS scanner from Steinbichler/Carl Zeiss with a blue LED light source was considered to be the best technique to achieve the aims of this project, and has produced good results in several other case studies involving marble at the University of Bamberg [Rahrig et al. 2018]. The use of laser scanning can create an unsatisfactory result on marble because of sub-surface reflection due to the marble's crystalline structure. Regarding the columns in the church in the Monastery of St. Naum the surface of the marble is polished, which can have negative effects like extreme reflectance of the surface that is impossible to record. The problem with using lasers to record polished marble is that the laser penetrates the material, which then causes errors in the surface measurements. Godin et al. [2001] investigated both reflection and subsurface scattering in laboratory conditions and discovered already a bias in depth measurement which causes surface noise.

This phenomenon when scanning marble with lasers was also recognized by Tsakiri et al. [2003]: they stated a significant difference in noise between plaster and marble elements of sculptures. Regarding the characters of the graffiti in the Monastery of St. Naum, the noise produced by a laser scanning device would have led to unreadable results; the noise would have drowned out the shallow engravings completely. The SLS system's accuracy and resolution also made it ideal for recording some of the finest characters.

Image Based Modelling and "Reflectance Transformation Imaging" (RTI) were also considered. Using RTI for the documentation of inscriptions and nearly planar surfaces can lead to great results, as shown by several case studies like the Herculaneum Project or several others [Greco and Flouda 2017; DiBiasie Sammons 2018], but because of the curved structure of the columns and the aim to have an accurate 3D documentation of the entire column in one model, the SLS System was preferred.

POSTPROCESSING

Post-processing of the data was carried out off-site. Using the scanner's proprietary software - Cometplus 9.62 - a best-fit matching was done for each data set. After filtering redundant points and carrying out a slight noise reduction to compensate for the effects of the marble noise, the data sets were meshed. The surface models were exported as .stl files and imported into Geomagic Studio (2014) for further processing, including hole filling, and to decimate the models. Along with the raw data, the 100% .stl files were archived, as well as a 10% version which will be used to share high-resolution, but still manageable data among researchers [Rahrig 2017]. The file sizes vary from 100 MB (reduced models) to more than 1GB for the full resolution 3D models. Orthoimages were also processed to provide a quick impression of the models, and the eight high-resolution areas were aligned to the models of the entire columns.

Fig. 4. Front part of the right column: 3D model unrolled and visualized using normal map rendering in Meshlab.

The .stl format was used because it is achivable, viewable in most of the current 3D software solutions and can even be used in various (free) software solutions like Meshlab[1] (Version 2016.12).The resulting high-resolution 3D model can be virtually illuminated at any angle, for example using raking light, allowing detailed observations and analysis. It can also be unrolled and rendered as a normal map. To unroll the curved parts of the columns, CloudCompare[2] v.2.8.1 was used. In order to make edges stand out from the surrounding areas, the normal map rendering mode in Meshlab was used (Fig. 4). Using these tools helps significantly enhance the legibility of the delicate inscriptions. For sharing and to facilitate further work with the data, a web-based tool like the Digital Epigraphy Toolbox [Bozia et al. 2014] might be useful, but the size of the data sets might be problematic, and further processing may be necessary.

RESULTS

Only some examples of the project's results are shown, as the complete evaluation of the data is still a work in progress. First of all to illustrate the problem of faded out inscriptions the well investigated inscription – published by Grozdanov [1995] – is a good example of the problems and limitations of previous techniques used: Grozdanov visited the church and made several drawings from the columns. He displayed several lines of phrases (Fig. 5) on the right column and drew them alongside the many crosses. In contrast to these early drawings, today the first line in Fig. 5 can hardly be seen any more with the naked eye. Our scanning succeeded in making visible what remains of the inscription, at least to such a degree that previous readings of the inscription can be confirmed. The scanning data sets provide an interpretation-free, dimensionally stable documentation and show the location of the graffiti on the column, whereas the drawings might not show the correct position of the graffiti to each other and contain an unclear level of interpretation brought in by drawer.

Fig. 5. Details of the right column, left top: Photograph of the column showing the difficult and shiny surface; right top: Detail of the drawing by Grozdanov; left below: Detail of the model of the column in resolution up to 100µm where only parts of the graffiti is visible; right below: Part of the column in resolution up to 30µm, showing in addition the nearly faded out parts of the graffiti above the blue frame.

[1] http://www.meshlab.net/
[2] http://www.cloudcompare.org/

Another interesting challenge was the overlaying structures, where the characters are disturbed by other graffiti. The focus was on the fishnet and a writing of a name on the flat middle part of the right-hand column. The middle part is flat enough to use raking light from various angles, but the fishnet overlays the writing, making it hard to read or to determine which engraving was carried out first. With the use of the 3D surface model and suitable lighting conditions, the writing which was previously characterized as “ALEXANDER” [Mixeev 2013] could be verified.

As shown in Fig. 6, with the wrong lightning setting the inscription is invisible on the texture-less surface model. The lack of texture can, at times, obscure the required information; however, when combined with appropriate raking light illumination, the texture free surface can dramatically enhance legibility and reveal more information than one might find in a photograph.

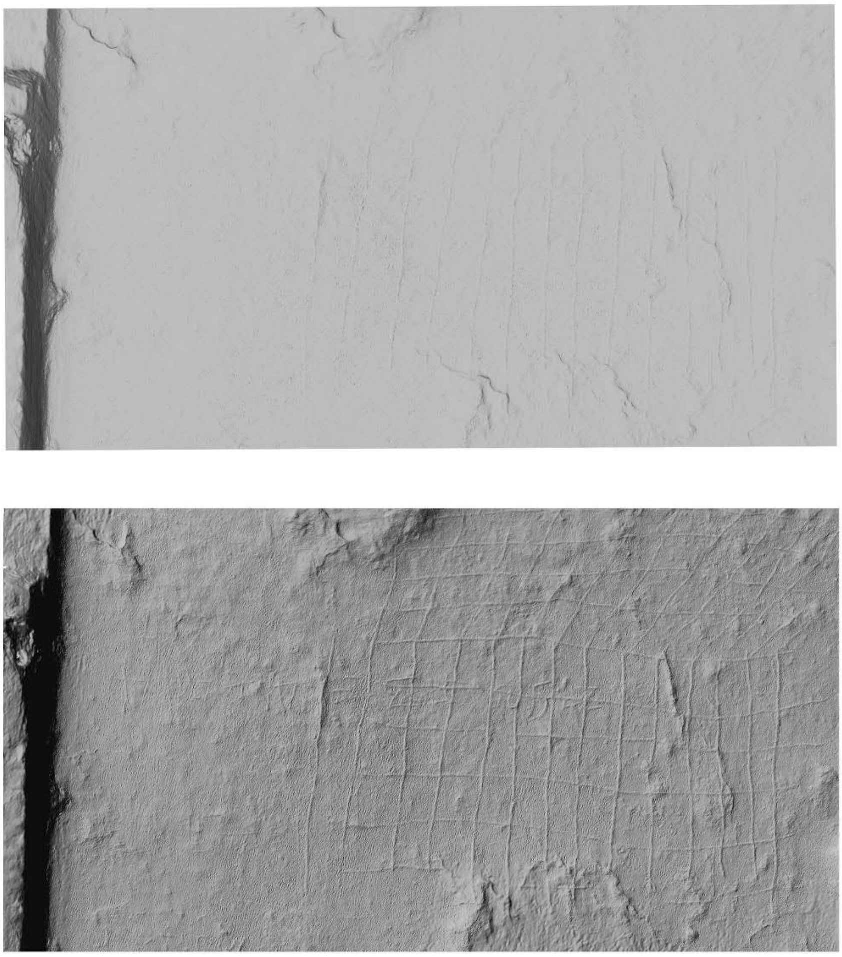

Fig. 6. 3D surface model with inadequate lighting (above) and suitable lighting conditions and legible characters (below).

As mentioned above, another challenging problem, both on-site and using photos, is that it is impossible to decide whether the fishnet or the writing was created first. Knowing which one came first can help in dating the inscriptions, as the ALEXANDER writing is Glagolitic and can therefore be dated to the 11th century [Mixeev 2013]. With the help of a normal map the authors were able to discover that the vertical lines of the fishnet must have been scratched over the existing lines of the ALEXANDER writing (Fig. 7).

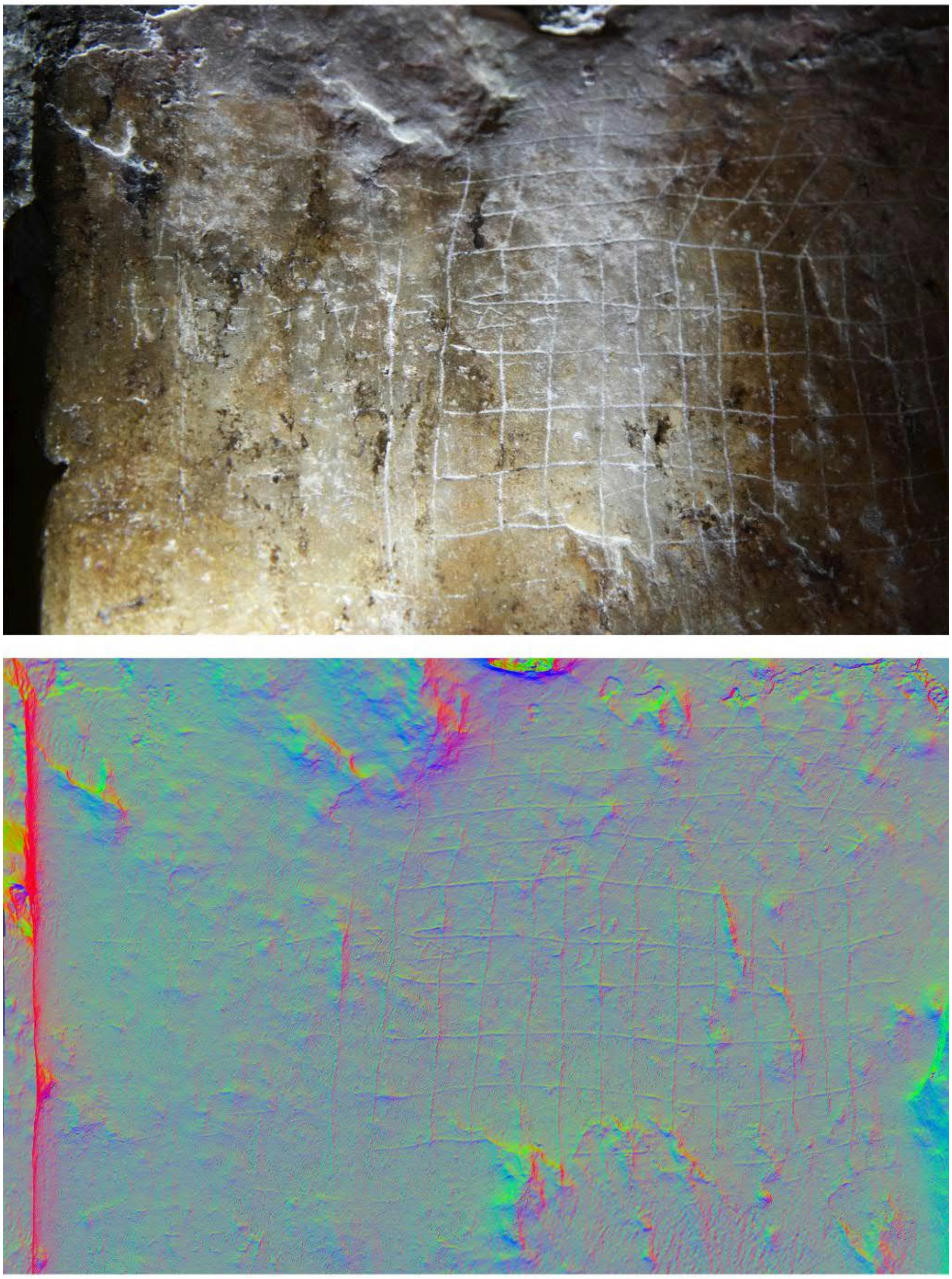

Fig. 7. Alexander-writing: photograph with raking light (above) and 3D surface model with normal map rendering (below).

The project has even made entirely new discoveries, for example, the blue light of the scanner has revealed a previously unknown inscription. It can be identified as the short form of established Cyrillic wording with the meaning “the servant of god [name] died”; a typical phrase found in graffiti. To decipher these characters and their meaning was only possible due to the 3D-Surface model. Rotating it and using the infinite lightning possibilities of the software, as well as the normal map rendering mode, dramatically enhanced the legibility (Fig. 8).

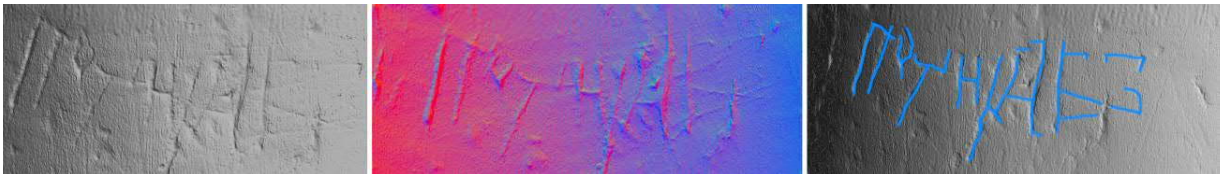

Fig. 8. 3D surface model, normal map, drawing the characters on the surface

CONCLUSION –WHAT TO DO WITH THE SCANS?

As we have demonstrated, some of the inscriptions have already been verified or deciphered, but there are also some which are a work in progress and which are much discussed among Slavicists. It is therefore important that the 3D models should remain accessible for specialists in the future, and to this end the data was shared in the .stl format, allowing them to be imported into a variety of software including free applications such as Meshlab and 3D tool. With the help of these models, which have already been shared with both Slavicists and Glagolitic specialists, it is now possible to observe and analyse the inscriptions virtually and independently off-site. The data sets will also help to preserve the intangible heritage for future generations even if the inscriptions themselves are damaged.

To archive the datasets they are exported as .stl files and stored on external hard drives, DVDs and on the server of the department of the preservation sciences at the University of Bamberg. According to a datasheet developed by the 3D-AG (consisting of the Bamberg University's “Centre for Heritage Conservation Studies and Technologies” (KDWT) and Bavarian State Office for Heritage Management) essential parameters like date and time of recording and post processing, and the persons working on the project were listed as well [Rahrig 2017]. The aim was an easy to handle standardised method of archiving the datasets in interoperable and sustainable file formats which can be easily transferred to other archives in the future. As mentioned above, using a standard file format also enables the data to be used in different free software solutions, ensuring that it will be possible to continue discovering new inscriptions and creating new research in the future.

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REFERENCES

Arximandrit (Kapustin) Antonin.1886. Iz Rumelii. Sanktpeterburg.

Eleni Bozia, Angelos Barmpoutis, and Robert S. Wagman. 2014. OPEN-ACCESS EPIGRAPHY: Electronic Dissemination of 3D-digitized Archaeological Material. In *Proceedings of the International Conference on Information Technologies for Epigraphy and Digital Cultural Heritage in the Ancient World (EAGLE 2014),* Paris, France, September 29-30 and October 1, 2014.

Carl Zeiss Optotechnik GmbH (former: Steinbichler GmbH). 2013. Comet L3D 5M, technisches Datenblatt. https://optotechnik.zeiss.com/, retrieved November 30, 2013.

Jacqueline F. DiBiasie Sammons. 2018. Application of Reflectance Transformation Imaging (RTI) to the study of ancient graffiti from Herculaneum, Italy. In *Journal of Archeological Science: Reports*, Volume 17, 2018 184-194.

Guy Godin et al. 2001. An Assessment of laser range measurement on marble surfaces. In *5th Conference in Optical 3D Measurement Techniques*. 2001.

Alessandro Greco and Georgia Flouda. 2017. The Linear B *pa-ti-to* Epigraphic project. In *Annvario della Scuola Archeoligica di Atene e delle Missioni Italiane in Oriente*, Vol. 95. 2017. 143-160.

Cvetan Grozdanov.1995. Sveti Naum Ohridski. Skopje.

Historic England. 2018. 3D Laser Scanning for Heritage: Advice and Guidance on the Use of Laser Scanning in Archaeology and Architecture. Swindon. Historic England.

Jordan Ivanov. 1908. Bălgarski starini iz Makedonija. Sofija.

Sebastian Kempgen. 2019. Die Säulen in der Klosterkirche von Sveti Naum: ein Projektbericht zur Digitalisierung des sprachlichen Kulturerbes in Makedonien. *Wiener Slavistischer Almanach 2018* (2019) in print.

Pavel Nikolaevič Miljukov. 1899. Christianskija drevnosti Zapadnoj Makedonii. (Otdělnyj ottisk iz “Izvěstij Russkago Arxeologičeskago Instituta v Konstantinopolě”, Tom IV, vypusk 1.) Sofija.

Savva Mixajlovič Mixeev. 2013. Dva kratkix glagoličeskix graffiti v monastyre sv. Nauma pod Oxridom i v Sv. Sofii v Stambule. Slověne 2013, 2, 52–63.

A.I. Papadaki et al. 2015. ACCURATE 3D SCANNING OF DAMAGED ANCIENT GREEK INSCRIPTIONS FOR REVEALING WEATHERED LETTERS. In *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-5/W4*, 237-243. DOI:10.5194/isprsarchives-XL-5-W4-237-2015.

Max Rahrig. 2017. Wohin mit all den Scans? – Über die dauerhafte Archivierung von 3D-Daten bedeutender Kulturgüter am Beispiel des Bamberger Kaisergrabs In: *Birgit Franz und Gerhard Vinken (edt.) Das Digitale und die Denkmalpflege: Bestandserfassung – Denkmalvermittlung – Datenarchivierung – Rekonstruktion verlorener Objekte, (Veröffentlichungen des Arbeitskreises Theorie und Lehre der Denkmalpflege e.V., Band 26)*, S. 130 – 139, DOI:10.11588/arthistoricum.263.348.

Max Rahrig, Rainer Drewello, and Andrea Lazzeri. 2018. OPTO-TECHNICAL MONITORING – A STANDARDIZED METHODOLOGY TO ASSESS THE TREATMENT OF HISTORICAL STONE SURFACES. In *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2, 945-952*, DOI:10.5194/isprs-archives-XLII-2-945-2018.

Mariam Samaan et al. 2016. Close-range photogrammetric tools for epigraphic surveys. In *Journal on Computing and Cultural Heritage*. 9, 3, Article 16 (October 2016), 18 pages. DOI: http://dx.doi.org/10.1145/2966985.

Anja Schäfer et al. 2012. Large Scale Angkor Style Reliefs: High Definition 3D Acquisition and Improved Visualization Using Local Feature Estimation, in: Revive the Past - Proceeding of the 39th Conference on Computer Applications and Quantitative Methods in Archaeology, Beijing, 12-16 April 2011.

V. Stefanić.1966. Prvobitno slovensko pismo i najstarata glagolska epigrafika. In: Slovenska pismenost. 1050-godišnina na Kliment Ohridski. Ohrid, 13–30.

M. Tsakiri, Ch. Ioannidis, and A. Carty. 2003. Laser scanning issues for geometrical recording of a complex statue. In *Proc. of the 6th Conference ‘Optical 3-D Measurement Techniques*, Zurich, Switzerland, 22-25 September 2003.

UNESCO. 1980. UNESCO-World-Heritage-List, No. 99. http://whc.unesco.org/en/list/99, retrieved January 20, 2019.

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