

Three-Dimensional Documentation of Hadrian's Temple in Ephesus (Turkey) Using Different Scanning Technologies and Combining these Data into a Final 3D Model

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Abstract:

The so-called Hadrian's Temple is one of the most famous monuments in the ancient city of Ephesus (Turkey) and occupies a prominent location in the western section of Curetes Street, one of the chief thoroughfares of the site. This paper explains the on-site conditions for creating an up-to-date architectural documentation including three-dimensional digital scan data of the temple and also discusses the different 3D surface scanning systems which were employed for this task: fringe projection and time of flight laser scanning based on phase shifting. With respect to the required resolution and the scale of the documentation both methods are ideally suited to digitally record certain areas of the Temple. Furthermore, this paper puts a focus on how both types of 3D scan data can be combined in a final 3D model within specific post-processing steps. The scanning results as well as the virtual reconstruction of Hadrian's Temple will be presented in this paper.

Key Words: *Archaeological Documentation, Hadrian's Temple in Ephesus, 3D Scanning, Virtual Reconstruction*

Introduction

A project currently conducted at the Austrian Archaeological Institute and funded by the Austrian Science Fund (FWF Project P20947-Go2) includes the so-called Hadrian's Temple (Fig. 1) - located in the western section of Curetes Street. Its building type is essentially a variation of the tetrastyle prostylos temple layout, with an oblong pronaos or front hall

and a larger main room. The street facade is formed by two pillars anchoring the axis of the antae and two regular columns between them. The small Temple which was re-erected in 1957/58 is one of the most famous monuments in Ephesus (Turkey). Since its discovery more than 50 years have passed but a systematic study and publication of the arrangement of building remains are not available yet.



Figure 1. Hadrian's Temple in Ephesus (Turkey).

Although the original interpretation - a Temple of Emperor Hadrian - is now widely rejected, questions about chronological function and details of reconstruction are widely and often controversially discussed by researchers, and remain unresolved. In the framework of the project currently conducted at the Austrian Archaeological Institute, a detailed study of the construction history as well as archaeological research is being carried out for the first time.

The building and its history

In the summer of 1957, the reconstruction work and rebuilding of this ancient structure began (Miltner 1959). The short period of time between discovery and reconstruction left little time to study the building history and phases. However, Franz Miltner's first interpretation of the structure as an imperial cult temple was contradicted by a subsequent study of the building inscription.

The inscription on the architrave of Hadrian's Temple (Fig. 1) provides important information on the structure: it was dedicated to the city goddess Artemis, the emperor Hadrian and the people of Ephesus.

From literary sources we know that the permission to build an imperial cult temple for Hadrian in the province of Asia Minor was

granted to Ephesus between 130 and 132 AD. Such an undertaking bestowed great honours on the city and many cities in Asia Minor competed for such an authorization (Burrell 2009). In the preliminary excavation report, Miltner interpreted the building – presumably in accordance with the building inscription – as the “official” temple for the worship of the emperor Hadrian (117–139 AD; Hueber 1995, 86–88; Outschar 1999; Quatember 2010). The text of the inscription from “Hadrian's Temple” on Curetes Street also includes names of officials and donors that are known from other contexts. Therefore it is possible to date this building quite securely to 117/118 AD (Wörrle 1973). This implies that it predates the official Temple of Hadrian by approximately 15 years. As a result, this clearly contradicts Miltner's initial identification as the imperial cult temple for the province of Asia Minor but a consensus has still to be established.

Goals of the Hadrian's Temple Project

Before issues such as interpretation and function could be addressed, it was of vital importance to clarify the architectural history of the structure. The first step towards this goal was to produce an up-to-date documentation of the building.

For the reasons listed below 3D surface scanning methods were chosen (Quatember et al. 2010):

- Time is a very important factor for such an archaeological undertaking. Hand drawings as the standard form of architectural documentation take a long time and require a substantial amount of infrastructure such as scaffolding.
- In comparison to the traditional form of documentation i.e. drawings to scale done by architects or archaeologists, 3D surface scanning clearly has advantages for this project.



Figure 2. 3D Scanning with structured light scanner at night.

For example, the time issue is of uppermost importance, not only to the researches, for whom field time is precious and expensive, but also for the tremendous number of visitors to the site (up to two million people a year). Working on-site for a long time and setting up scaffoldings that restrict the view clearly contradicts the justified interests of tourists who expect unlimited access to one of the most prominent buildings of Ephesus. So working at night with fringe projection systems (Fig. 2) has been chosen as the best way not to disturb tourists as well as researchers. In addition to the architectural documentation, the scanning results shall provide the basis for mapping cracks and fissures during the examination of the monument by a professional conservator. Therefore it was necessary to document not only the ancient building parts, but also modern concrete additions from the 1950s anastylosis. Again, architectural hand drawings would require more time than 3D scanning and the work of architects would require the construction of scaffolding for an extended period of time.

In archaeology, the standard form of publication is still a book or monograph. Therefore, the creation of ortho-projections was the main objective. 3D models are very valuable for presentations but not a goal in itself during this undertaking.

Existing conditions for the undertaking

The existing environmental conditions pose a major challenge to the scanning, the scanning system, and the digitisation process itself, and therefore shall be discussed here. First of all, there are the dimensions of the building. Hadrian's Temple is approximately 10x10m in plan, with an overall height of about 8m. Due to modern reconstruction work, the building and its architectural components form a solid structure that cannot be transferred or disassembled. Its height in particular presents difficulties to data acquisition. The operating distance for the two fringe projection scanners used for this project (Fig. 2) measures 1,300mm and 730mm respectively. Within these parameters, the accessibility of all the stone surfaces had to be ensured. To fulfil this task, an approximately 6m high scaffolding was constructed. The scanners were set up on tripods which could be extended up to a height of 3m. The size of Hadrian's Temple also does not allow for the construction of a protective roof or tent for the scanning process. To avoid the interference of direct sunlight, all measurements therefore had to be taken at night. For the documentation of the entablature the Breuckmann triTOS scanner was employed. Its operating distance of about 1.30m ideally suited the mobile elevated platform, which was used for three nights to reach the uppermost parts of the building (Fig. 2).

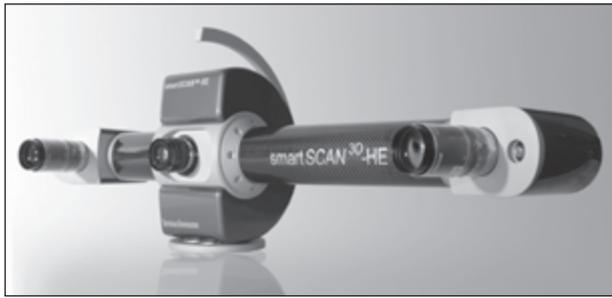


Figure 3. 3D surface scanner smartSCAN^{3D}.

Methods and Data Acquisition

Archaeological publications involve a detailed stone-by-stone documentation including cuttings, tool marks and architectural ornamentation. As monographs and books remain the standard form of publication in the discipline of archaeology the aims of the 3D scanning are ruled by this need for rendering a suitable structure for print media. The creation of the ortho-projections is thus a very important part during the post-processing of data. In addition, the ortho-projections will be used for mapping cracks and fissures by a professional conservator who will examine both the original building parts of the temple and its modern additions during the course of the project. Lastly, the 3D information will also be used for the reconstruction of the complex roof structure. In contrast to hand drawings, 3D surface scanning eliminates subjective factors from the documentation. Yet, it contains all necessary information for the scholar to draw interpretative conclusions.

The documentation of architectural blocks made out of marble, especially those including rich decoration like Hadrian's Temple, requires high precision for any kind of recording. Fringe projection techniques like the Breuckmann system employed in this case, are ideally suited for the documentation of the highly ornamented architectural building members of Hadrian's Temple. The documentation of the marble building parts was successfully completed within two weeks. In areas where

a lower resolution seemed sufficient a laser scanning system based on phase shifting was chosen. This technique is suitable for areas that contain fewer details, e.g. rubble walls. For both the sake of completeness as well as the aforementioned purpose of mapping, modern concrete additions like the front columns had to be documented too. Also, in this case laser scanning proved to be the most efficient technology in relation to the desired resolution. The two different scanning methods were also chosen to achieve the desired resolution and scale of the 2D images for the final publication.

Fringe projection scanning

A new generation of topometrical high definition 3D surface scanners (Fig. 3), based on fringe projection techniques and optimized for the requirements of arts and cultural heritage, allows for the three-dimensional digitization of archaeological objects like sculptures and small buildings with the highest resolution and accuracy. Moreover, the texture and/or colour of the object can be recorded, offering a one-to-one correspondence of 3D coordinate and colour information. Important parameters of the system configuration such as field of view, triangulation angle and resolution may be defined application orientated by the user.

One important advantage of topometrical 3D scanners is the fact that they offer an imaging acquisition of 3D-data. Therefore, 3D data recorded from different sensor positions or orientations can be aligned to each other by using the 3D geometry of the object itself. A high accuracy positioning system (e.g. coordinate measuring machine, optical tracker) for moving the object or sensor, or index marks for aligning the different scans are not required. This makes topometrical 3D scanners especially suitable for scanning highly valuable objects and for in-the-field applications (Quatember et al. in press).

For scanning Hadrian's Temple two different



Figure 4. Left: Scan data captured with structured light scanner; Middle: triangular meshing; Right: detail area (© Breuckmann).

3D surface scanners were used (see Table 1):

- SmartSCAN^{3D} system with a Field of View (FOV) of 600mm,
- TriTOS system with a larger FOV of 1,400mm.

With the structured light 3D scanners by Breuckmann the highly ornamented marble architectural building members of Hadrian's Temple were three-dimensionally digitized with approximately 1,750 single scans in highest resolution. The area that can be captured with one scan is - depending on the scanner's FOV - 0.2m² /1m²; the lateral resolution is 0.3mm/1mm.

Phase Shifting Laser Scanning

Laser scanners by Zoller + Fröhlich are fast profile-scanning 3D laser measurement systems based on time-of-flight resp. phase

shifting technology. In Ephesus, approximately 90 panorama scans of the whole building, the rubble walls in the Temple's main room as well as neighbored structures were captured with a Z+F IMAGER® 5006i during a second scanning campaign of five days.

In a period of five to ten minutes per scan about 50m² to 100m² were scanned with a lateral resolution of about 5 - 10mm. These measurements were realized during daytime. Figure 5 shows the point cloud captured with the Zoller + Fröhlich scanner.

Multi-Scaling scanning

There are several publications describing the scanning of objects or scenes with different scanning devices with different resolutions (Callieri et al. 2011; Remondino 2011; Remondino et al. 2009; Stumpf et al. 2003). The main reasons for such an approach are:

	smartSCAN3D	triTOS
Field of View (FOV)	600 mm	1,400
Camera	2 x 1.4 MPixel colour	1.4 MPixel b/w
Light source	100 W halogen	
Sensor weight	4 kg	2 kg
Operating distance	730 mm	1,300 mm
Acquisition time	1 sec per scan	
X,Y-resolution	350 µm	800 µm
Depth resolution	15 µm	50 µm

Table 1. Specifications of the employed surface scanners.

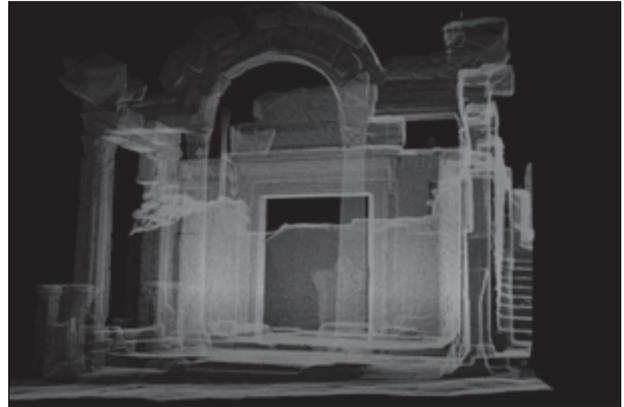


Figure 5. Left: 3D Scanning with Z+F laser scanner; Right: Point cloud from 3D laser scans (© ÖAI).

- The object recorded with high resolution must be integrated and positioned into the surrounding area, building, etc.
- The purpose of the project does not require digitizing the whole object or the whole scene with highest resolution.
- The low resolution scans are used as a reference for aligning the many single high resolution scans, especially to avoid larger scaling errors due to error propagation.

The workflow for realizing the first two objectives is quite straightforward, when the different scan devices are well calibrated, guaranteeing the same measuring scale for all 3D models. In this case, the 3D models of the different devices can be directly aligned, e.g. by an ICP method.

On the other hand, several authors, especially Callieri and colleagues (2011), report of a very large effort to align all high resolution scans to the low resolution reference. For this project, this was not possible, because the laser scans were recorded several months after the high resolution scans, when those 3D models were already available.

For this reason, as an accompanying measure of quality assurance, around 75 measurement points were taken from photogrammetry and

used as a reference for the 3D model. The photogrammetric measurement has been carried out with an AICON DPA PRO system with a NIKON D3 camera. 35 of these index marks were additionally measured with a total station. The evaluation of all generated data sets resulted in a consistency of the 3D models within a range of just a few millimetres not only among each other but also in relation to the photogrammetric control measurement. Considering the fact that the measurements were taken in very fluctuating ambient temperature conditions (temperature variations of up to 20°C) this is an excellent match.

Data Processing and Data Fusion

After data capturing was complete, all single measurements recorded with the structured light scanning systems were registered into a common coordinate system on the basis of their 3D geometry. In the following stage, all these single scans were combined (merged) into a final 3D model.

In the same way all laser scanner panorama scans were pre-aligned manually with the targets identified during the scanning process, automatically fine-aligned by an ICP algorithm and merged into a common 3D model. Similar to the processing of the fringe projection scans, the amount of data posed difficulties for the majority of the software.

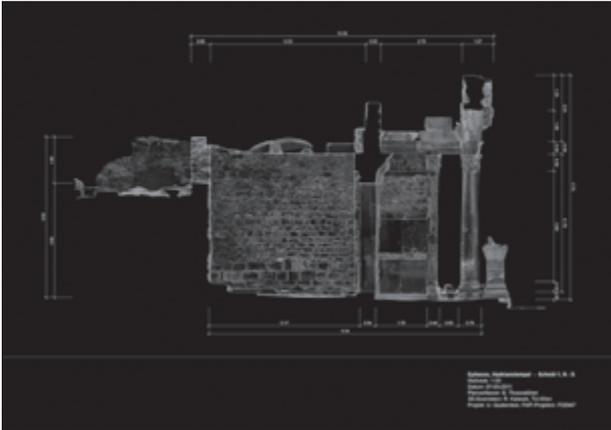


Figure 6. Section through the Temple with view to the east, based on laser scan data (© ÖAI).

After this first so-called data post-processing step, the results of both measuring methods differ in one essential feature (Quatember et al. 2011): while the procedural steps on the detailed model directly lead the raw data of the structured light scanner into flat polygonal objects, the data post-processing of the Z+F laser scanner measurements results in data point information in the form of so-called 3D point clouds.

In an ideal scenario, the polygonal structures (i.e. triangle meshes, see Fig. 4) completely cover the entire surface area of the captured objects. In other words, the objects are enveloped in a cover of a multitude of polygons. With this, the fundamental prerequisites for the three-dimensional representation of the objects are fulfilled – at this stage, the structural components are non-transparent.

By contrast, 3D point clouds are created from discrete points which are isolated from each other. Based on the results of the laser measurement, the location of each of these points entails relevant information such as its exact position in space, the signal intensity and – if required – the colour information. An area impression of the point cloud is created when the virtual viewer is located so far away from the object that the space between the points can no longer be identified. On the contrary, due to the absence of closed surface areas, the ‘principle of polygon coverage’ which is crucial for the visualisation of objects, is not applicable.

The transformation of such a point cloud into a closed polygonal surface model is a resource-intensive step. The necessary effort is to a significant degree determined by the intended resolution (i.e. number and size of the triangles) and completeness (i.e. surface without any gaps). It was therefore at this stage of the overall workflow that it had to be determined which type of final result was required and on the basis of which initial data sets this target was to be achieved.

While the documentation of the individual ashlar at a scale of 1:20 was mostly carried out by means of white-light fringe projection scans, the creation of plans and cross sections at a scale of 1:50 was accomplished with the use of laser scans (Fig. 6) (Quatember et al. 2011).

The complete three-dimensional model was achieved by a combination of data recordings resulting from both approaches (Figs 7 and 8).

Object	Number of triangles	Size of resulting PLY file	Remarks
Hadrian's Temple	~ 50 Mio.	~ 1.2 GB	
Postaments	~ 10–20 Mio. each	~ 200–400 MB	
Single blocks	~ 5–10 Mio. each	~ 100–200 MB	
Original Friezes	~ 20 Mio. each	~ 400 MB	Museum in Selçuk
Panorama scans	~ 15 Mio.	~ 300 MB	

Table 2. Summary of scans.



Figure 7. Combination of structured light scan data and laser scan data (© Breuckmann).

Table 2 gives an overview of the size of the triangulated polygonal models.

Because of the considerable amount of data to be processed as well as the different characteristics of the initial base data, the combination of the interim results of both kinds of “acquisition worlds” has turned out to be one of the “crunchpoints” of the post-processing tasks.

Firstly, the gaps in the database of the high-resolution 3D models of the Hadrian Temple, the pedestals as well as the original friezes captured in the museum had to be closed in an automated way. Simultaneously, the point clouds generated through the laser scans were prepared for the conversion into an intermeshed surface model. In order to achieve the pre-specified degree of detail, it was crucial at this point to selectively reduce the point density. While the tools available did provide the necessary technical support, the selection of individual partitions in line with the criteria of “relevance” and “visibility” had to be carried

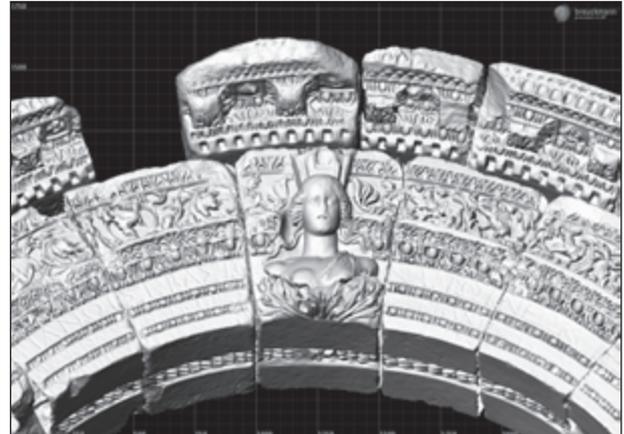


Figure 8. Details of structured light scan data (© Breuckmann).

out manually. The finishing step of this so-called intermeshing of the point cloud delivered an almost entirely closed surface model of all construction components of the temple as well as the adjacent areas which have been captured by means of a laser scanner.

In a subsequent phase, the high-resolution detail models of the marble construction components of the temple as well as the pedestals were integrated into the 3D model of the laser scans. The registration – i.e. the relevant adjustments with regard to the dimensions “orientation” and “scaling” – was carried out by reference to the 3D geometry of the laser scan models.

Lastly, in order to utilise the best possible resolution for each individual construction element, the laser scanned object parts captured at a lower resolution were replaced with the high-resolution 3D section models. With the same objective in mind the data sets of the two friezes captured on location were also replaced with the data recordings of the original friezes on display in the Museum in Selçuk (Quatember et al. 2011).

Figure 9 shows the final model of the Hadrian's Temple and related objects captured with Breuckmann structured light scanners and a Z+F time of flight laser scanner.



Figure 9. Final 3D model of the Hadrian's Temple (© ÖAI – R. Kalasek).

Summary

Hadrian's Temple project has shown that a combination of fringe projection and laser scanning techniques is ideally suited for digital architectural documentation of a complex building structure.

For the means of recording and post-processing it was of uttermost importance to choose the scanning method according to the desired resolution and accuracy. Otherwise, a needless amount of data would not only lead to extended computing time during post-processing, but would also require unnecessary time and effort during recording. Therefore, the different types of scanning technologies were assigned to capture the individual parts of the Temple.

Architectural blocks made out of marble with their high level of detail were captured with Breuckmann's structured light scanners; the phase shifting laser scanner IMAGER 5006i (company Zoller & Fröhlich) was used for creating area plans and large scale documentation, that means everywhere where a lower resolution was sufficient.

The main challenge during the post-processing that was carried out in Vienna

was the data volume of the high resolution fringe projection scans: Compiled from individual scans, the meshed model of the structure reached a size of up to several GB (Table 2). The majority of software tools still cannot cope with such an amount of data. Therefore, the ÖAI mostly worked with sections of the model in high resolution as well as with an overall model of the structure in lower resolution.

The 3D data of the final model does not only represent a tool for the detailed documentation of ancient monuments. It also provides information that forms the basis for answering the complex architectural questions concerning this building that could not be tackled otherwise.

The final three-dimensional model of Hadrian's Temple (Fig. 9) has been presented to the public for the first time on March 17th 2011 in the "Deep Space" of Ars Electronica Center in Linz, Austria.

For the time being, you can visit Hadrian's Temple there – projected onto a 16x9m screen by a total of eight special projectors – as part of guided tours.

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Büyükkolancı made the scanning of fragments possible that are now stored at the Basilica of St. John in Selçuk. F. Öztürk was an invaluable help for organisation, as well as the workmen Yusuf Turan and Mustafa Cobanoğlu and the foreman İbrahim Kınacı. Ch. Kurtze provided the necessary surveying data. We would also like to acknowledge TU Vienna/Department of Spatial Development, Infrastructure and Environmental Planning for infrastructure and IT support.

Bibliography

- Burrell, B. 2009. *Neokoroi. Greek Cities and Roman Emperors*. Leiden: Brill.
- Callieri, M., Chica, A., Dellepiane, M., Besora, I., Corsini, M., Moyés, J., Ranzuglia, G., Scopigno, R., and Brunet, P. 2011. "Multiscale Acquisition and Presentation of Very Large Artifacts: The Case of Portalada." *Journal on Computing and Cultural Heritage* 3 Article 3.
- Hueber, F. 1995. *Ephesos. Gebaute Geschichte*. Mainz: Zabern.
- Miltner, F. 1959. "XXII. Vorläufiger Bericht über die Ausgrabungen in Ephesos." *Jahreshefte des Österreichischen Archäologischen Instituts* 44:264–273.
- Otschar, U. 1999. "Zur Deutung des Hadrianstempels an der Kuretenstraße." In *100 Jahre österreichische Forschungen in Ephesos. Akten des Symposiums Wien 1995*, edited by H. Friesinger, and F. Krinzinger, 443–448. Vienna: Verlag der Österreichischen Akademie der Wissenschaften.
- Quatember, U. 2010. "The 'Temple of Hadrian' on Curetes Street in Ephesus: new research into its building history." *Journal of Roman Archaeology* 23:376–394.
- Quatember, U., Thuswaldner, B., Kalasek, R., Breuckmann, B., and Bathow, C. in press. "3-Dimensional Documentation of the Hadrian's Temple in Ephesus." *Proceedings VSMM in Heidelberg* 2009.
- Quatember, U., Kalasek, R., Breuckmann, B., and Bathow, C. 2010. "3-Dimensional Documentation of the Hadrian's Temple in Ephesus/Turkey." In *Proceedings CAA 2010 – Fusion of Cultures in Granada*, edited by F. Contreras and F. J. Melero (in press), 297–300.
- Quatember, U., Kalasek, R., Breuckmann, B., and Bathow, C. 2011. "Das 3D-Modell des sog. Hadrianstempels an der Kuretenstraße in Ephesos." *Forum Archaeologiae* 59/VI.
- Remondino, F. 2011. "Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning." *Remote Sensing* 3:1104–1138.
- Remondino, F., Stefano, G., Rizzi, A., and Gonzo, L. 2009. "3D Modeling of Complex and Detailed Cultural Heritage Using Multi-Resolution Data." *Journal on Computing and Cultural Heritage* 2 Article 2.
- Stumpf, J., Tchou, C., Hawkins, T., Martinez, P., Emerson, B., Brownlow, M., Jones, A., Yun, N., and Debrec, P. 2003. "Digital Reunification of the Parthenon and its Sculptures." In *4th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, edited by D. B. Arnold, A. Chalmers, and F. Niccolucci, 1–10. Brighton: Eurographics Association.
- Wörrle, M. 1973. "Zur Datierung des Hadrianstempels an der 'Kuretenstraße' in Ephesos." *Archäologischer Anzeiger* 1973:470–477.