Large Scale Angkor Style Reliefs: High Definition 3D Acquisition and Improved Visualization Using Local Feature Estimation

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Abstract:
It is the desire of stone conservators to preserve bas-reliefs endangered by acid rain, vandalism and structural instabilities. Documenting these bas-reliefs digitally will help minimizing the dangers of working on fragile structures while handling and analysing such large data sets is a new challenge for scientific computing in cultural heritage. From our experience in related research we developed a rapid workflow for 3D acquisition and visualization. It uses a close-range 3D scanner based on structured light and stereo vision. This paper shows the work done during our field trip in Banteay Chhmar, Cambodia where the temple complex is strongly endangered and large parts are already collapsed. The outcome of this digital documentation is a large collection of high-resolution 3D models each featuring a spatial resolution of 50-100µm. To extract more information about iconographic details we developed a new method of visualization using Multi Scale Integral Invariant surface filtering.

Key Words: *Archaeological Documentation, Close Range 3D Scanning, Pattern Recognition, Cambodia*

Introduction

The temple complex of Banteay Chhmar is one of the largest known Khmer temples as well as one of the largest temples known to man. It occupies an area of about nine square kilometres (Groslier 1937) and is located in the North-West of Cambodia close to the border with Thailand. King Jayavarman VII (AD 1181 - 1219) commissioned it at the end of the civil war to honour his son and four of his army generals who lost their lives while defending the Khmer empire against the Champa kingdom (Chandler 2008). The site features one main temple as well as eight satellite temples.

Climate, vegetation, acid rain as well as structural instabilities and severe looting has caused very

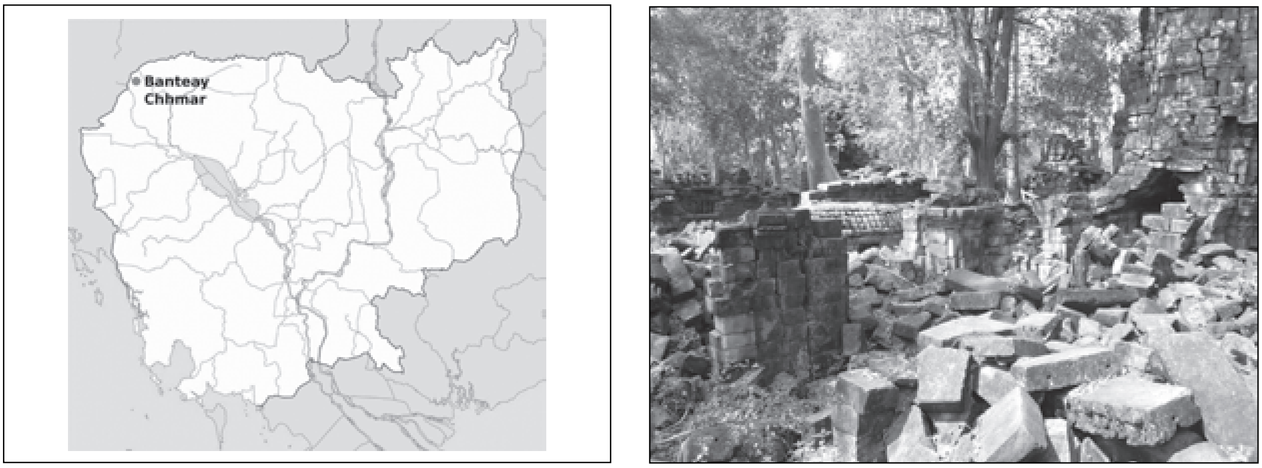


Figure 1. One of the largest known Khmer temples built by King Jayavarman VII is situated in Banteay Chhmar, Cambodia. The map of Cambodia (a) shows its location within the country close to the border with Thailand and (b) documents the state of deterioration inside the inner walls. Map source: Wikipedia.

serious destruction to the temple complex. Only about 20% of the main structures are still intact and most of these walls remain to be stabilized. The necessity to preserve the valuable carvings and structures was the motivation for our 3D acquisition campaign in Cambodia which took four months. In this paper, we present two parts of this larger project in more detail.

The map in figure 1a shows the location of the Banteay Chhmar temple and figure 1b documents its current state of deterioration.

Currently, the Global Heritage Fund is conducting a long-term preservation project divided into stone conservation and reconstruction. The eastern temple wall will collapse in the near future and needs foundations so parts of the wall were taken down and all the stones were numbered. Figure 2b shows the original state of the wall.

The first task of our project consisted of setting up a virtual reconstruction start-up by scanning about 200 of those dismantled and separated stones. So far, a manual reassembly has been performed but as this is dangerous for the workforce and accelerates the stones‘ deterioration, a virtual approach was suggested with the aim to solve a virtual 3D puzzle. Together with the knowledge of where the stones had been originally placed this will serve as a crosscheck for an automated reassembling algorithm that is in the process of being developed.

The second task was to document the well-known, still upright bas-relief featuring a

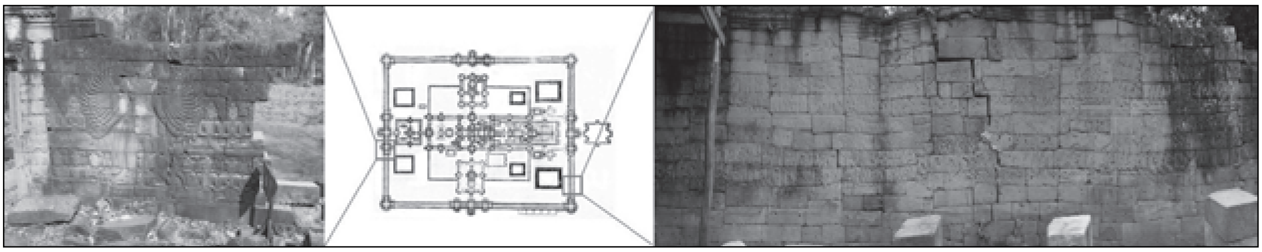


Figure 2. The floor plan in the middle shows a layout of the inner temple complex. The marked parts are where the first and second documentation objectives have taken place: (a) the Avalokeshvara, and (b) the eastern wall in its original state. Map source: (Groslier 1937). Picture Source: Dr. Pheakdey Nguonphan.

Figure 3. (a) and (b) show the two still standing Avalokeshvaras in the remains of the eastern temple wall. (c) is a view on the backside. The right part of (b) and (c) show what remains of altogether supposedly eight Avalokesharas. Picture Source: Dr. Pheakdey Nguonphan.

Buddhist multiarmed Bodhisattva (named Avalokeshvara, Fig. 2a). On the remaining parts of the eastern temple site this shows two Avalokeshvaras: the one presented here has 32 arms and the other has 22 arms. Those two are supposedly the remains of an original eight such Bodhisattva (Fig. 3).

Parts of the bas-relief features are deeply carved while others are very shallow. Over the centuries the stone gathered moss causing the majority of the wall to appear dark green to black in colour. Cleaning would be possible for the separate stones only but is not a practical solution in the long run because it takes too much time. The bas-relief itself could not be cleaned as there is not yet a reliable long term preservation method. Additional information for a complete virtual reconstruction of the temple is provided by the acquired data.

To compare and validate the whole process of documentation and visualization another relief has been documented using the 3D scanner, namely Sheshonk I, found in El-Hibe, Egypt. This relief is made from limestone and is on permanent exhibition in the Institute of Egyptology at Heidelberg University.

Developing 3D measurement techniques to acquire large-scale objects, Ikeuchi and Myazaki (2008) are doing related project work with a different focus. Our focus in using a 3D scanner in the field of cultural heritage lies in designing methods from algorithmic and numerical geometry and pattern recognition in order to analyse the data. One example of the use of this analysis is to enhance the readability of smallest details such as tool marks. For this reason adequate high resolution 3D data was gathered.

Figure 4. Setup of the 3D scanner for acquisition of the stones in (a) the tent with (b) the turn table and the ramp. Picture Source: Dr. Pheakdey Nguonphan.

Acquisition Workflow

From our experience in archaeological projects (compare e.g. (Mara et al. 2010) and like shown in (Quatember et al. 2009) where a whole temple has been scanned) we have chosen to use a 3D scanner based on the principles of structured light and stereo vision (Sablatnig and Menard 1992, 398–404) for documentation. After extensive tests, we decided on a Breuckmann smartSCAN-3D-HE because it features the highest spatial resolution together with colour information using two 5 megapixel colour cameras. Colour acquisition is very important in order to match broken tablets as well as for other related cultural heritage projects (Mara et al. 2009).

For the smartSCAN-3D-HE a wide range of different optics exists which are categorized by the range image diagonal – also known as Field of View (FOV) – and not by the focal length. The FOVs of 475, 600 and 1000mm are suitable if larger objects like reliefs and statues are acquired. The best choice for many archaeological findings has proven to be the FOV of 150mm to acquire small details such as fingerprints. In case objects contain even smaller details (e.g. tool marks) it is recommended to use the FOV with 60mm.

Being based on structured light (Fig. 5a) and therefore requiring a dark environment to operate at its best most of the actual scanning should preferably be done at night or indoors.

During our research campaign, however, it was not possible to pursue this approach for various reasons, e.g. dangerous animals around the temple site during night time. To be able to cope with the fact that the 3D data acquisition had to take place during daylight a solution had to be found. For the first objective – gaining 3D data of separate stones – a scanning tent was built especially for this task (Fig. 4a). This made it possible to obtain a considerable amount of data, about 200 stones with an average of 10 million faces each, and to darken the acquisition environment. This closed tent however, heated up while standing in bright sunlight. The heat posed problems for the project participants as well as for the computer hardware. The smartSCAN-3D-HE worked fine regardless of its inside temperatures of about 62° Celsius.

Acquisition workflow in Cambodia

Scanning individual stones turned out to be easier to move the object while taking the exposures rather than to move the scanner around the commodity. Therefore, a turn-

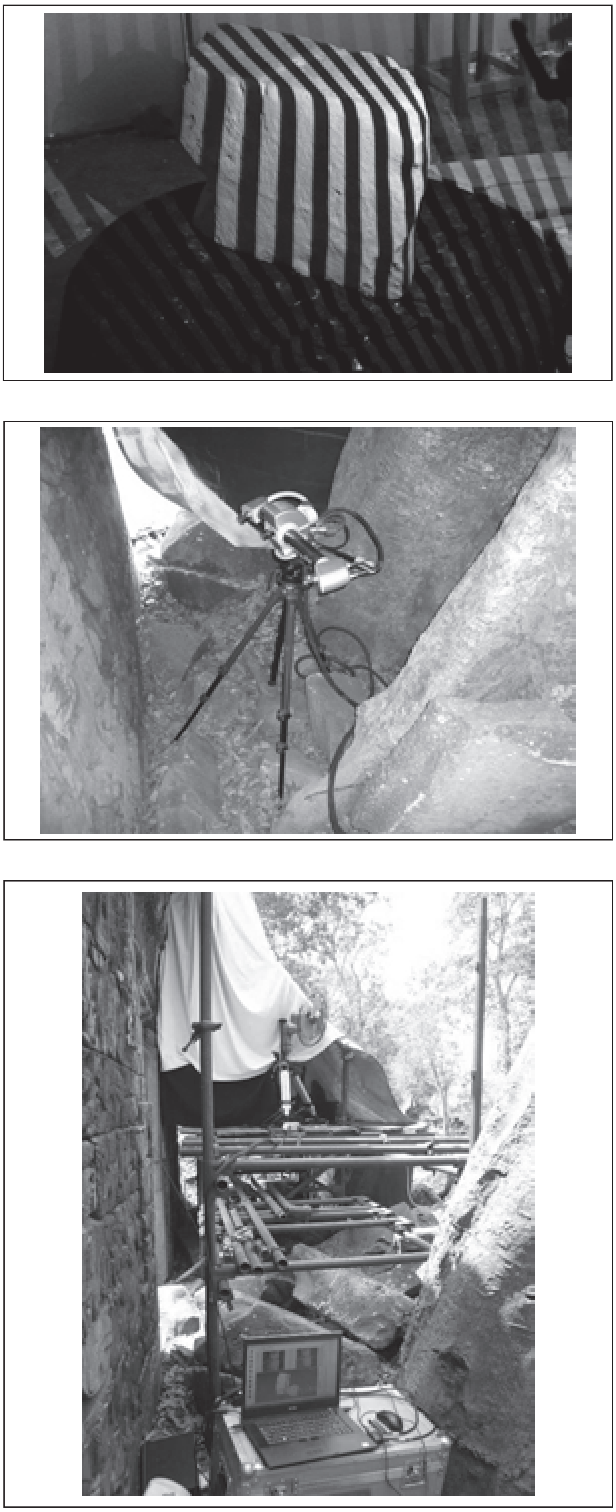


Figure 5. The structured light of the scanner (a) and the scanner between the bas-relief and a tree (b) and on the scaffolding (c).

table was designed made from steel to carry the stones' huge weight which ranged from 100kg to up to 1000kg. Additionally a ramp was appended to lift the stones up more easily (Fig. 4b). All stones were acquired using the 1000mm FOV.

Independent of the chosen optics a single 3D scan requires only a few seconds. For the first experiments with single stones the acquisition workflow took between 20 and 180 minutes depending on the size of a single stone as well as on its state of preservation, as the dark and weathered stones are difficult to acquire.

More precise data was necessary for the second objective – recording the Avalokeshvaras on the western wall – requiring the use of a smaller measuring field with a FOV of 475mm. The measuring field provides the necessary resolution crucial for the unique carvings. However, more than a thousand scans were required to cover the whole structure (Figs 3a and 3b).

The working conditions are highly influenced by the actual outdoor surroundings such as the ground surface or height of the structure: the ground surface was very rough because of fallen stone blocks. This hampered the positioning of the 3D scanner's tripod to comply with the compulsory fixed working distance of about 1–2m from the wall (Fig. 5b). Our scanning tent could not be used here so the sunlight was dimmed out by using multi-purpose plastic covers. In order to reach the upper parts of the bas-relief a scaffolding was installed (Fig. 5c).

Acquisition workflow in Germany

The acquisition of the relief of Sheshonk I. was less complicated and the FOV of 600mm has been used. This relief is on display in a specially purpose-built room at the Heidelberg University where the conditions, such as temperature, are irrelevant and light can be switched off or dimmed down. Although it was impossible to fully darken the room the acquisition conditions were advantageous compared to the campaign in Cambodia. An additional advantage was the plain floor and the possibility to build scaffolding-like structures very easily.

Data Processing

The software package Optocat supplied with the smartSCAN-3D-HE contains many features, e.g. it is possible to merge and reduce the data or its size. During data acquisition of the object the incoming 3D model is already obtained as a triangulated mesh. In this way the user does not need to define the adjacencies between the points themselves in contrast to Time-Of-Flight (TOF) 3D scanners (Rutzinger et al. 2008, 645–662; Siart et al. 2012).

Optocat offers different ways to add the latest scan to the previous recordings. We used a manual prealignment which only requires the operator to select several matching points between the current scan and the already processed parts of the object.

Processing the stones from Cambodia was done in at most one or two hours per piece. The Avalokeshvara had to be divided into several parts because there is currently no desktop computer with the memory able to store about 143 Gigabytes at once. The computer used to postprocess the data had an eight-core CPU with a speed of 2.6GHz and 12 gigabytes of RAM. The total amount of time necessary for post-processing the stones and the Avalokeshvara was 5 man-months.

Visualization Method

Having created these large-scale and high-resolution 3D models the next step is to generate a proper visualization. Similar to the data processing this can be done either in full resolution or on reduced data sets (Kobbelt et al. 1998) as for the Avalokeshvara.

For almost flat objects like the reliefs considered in this paper the 2D resolution unit Dots Per Inch (DPI) can be estimated by dividing the cardinality of the measuring points (vertices) by the acquired surface (in square inch) of the resulting 3D model. Having a 3D scanner based on 5.0 megapixel cameras we can achieve approximately 1000DPI for the FOV of 60mm, about 300DPI for the FOV of 150mm down to 100DPI for the larger FOVs.

It is acceptable to reduce the data for an overview of the Avalokeshvara as for example done for figure 7b. We reduced the data set to about 10 million vertices, which is a reduction from a density of 125DPI to 25DPI.

Figure 7b has a scale of 1:20 so when printed on DIN A4 we still achieve a printed visualization of 500DPI for the lower resolution. Additionally, this image and all other visualizations in this article are orthographic (parallel) projections. These are true to scale and in contrast to photographs allow precise measurements; furthermore, there are no lens distortions. Figure 8a shows the “little Buddha” next to the Avalokeshvara using the high resolution data at a scale of approximately 1:5, which equals a printing resolution of around 600DPI.

As shown in figure 3a, the relief is heavily darkened due to environmental conditions so it is difficult to see its actual structure. Removing the texture map and virtually illuminating the surface results in a much clearer image of the relief. Although the result appears to be appropriate there are details missing in particular no tool marks are shown. This is because virtual illumination is a global operation which leaves parts of the geometry in shadow. When confronted with a similar problem in a related project (Mara et al. 2010; Pottmann et al. 2009) we developed a local method for detecting man-made structures. These structures are typically characters for example on cuneiform tablets or medieval inscriptions which are often damaged by the same effects

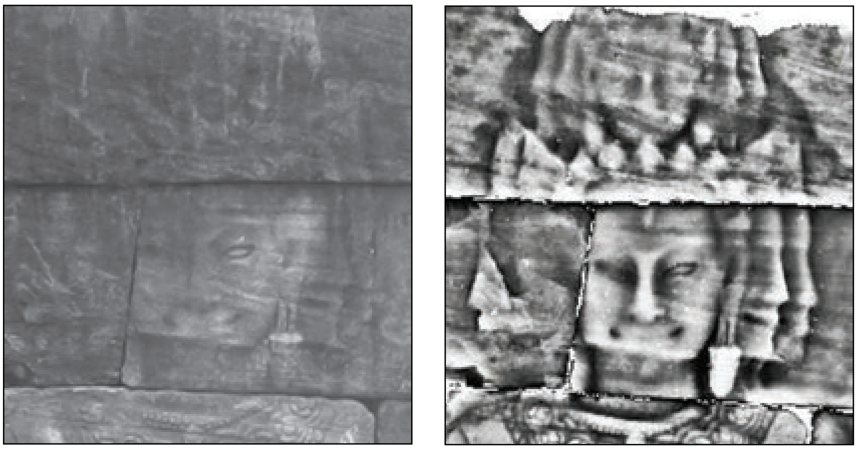
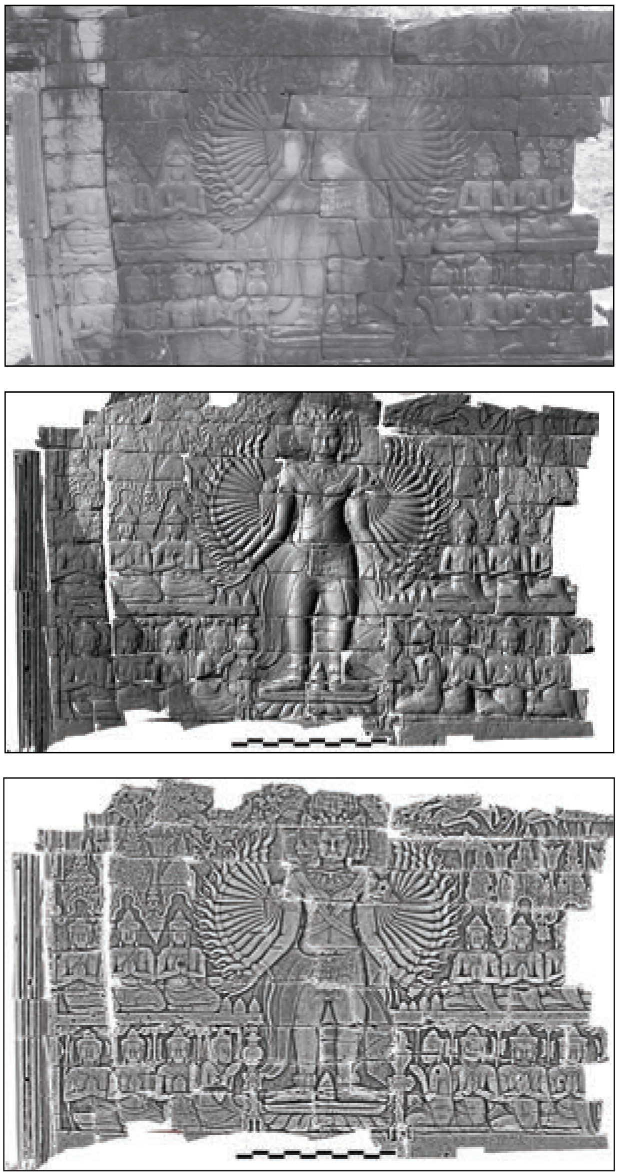


Figure 6. The many faces of the Avalokeshvara. (a) shows what is visible in-situ while (b) displays what can be seen in the acquired and visualized data.



as the stones of the temple. Therefore, the local method has to be robust against these distortions and measuring errors from the 3D scanner. The chosen method, developed in (Mara et al. 2010) uses a Multi-Scale Integral Invariant (MSII) filter to determine a feature vector for each vertex of the 3D-model, which is compared by correlation to a single vertex. The reference vertex is required to have a feature typical to the outline of the area of interest. Figure 7c shows man-made structures of the Avalokeshvara detected using this filter method.

Results

Seen with ambient light and light from the sun the shallow carvings of reliefs are invisible but the high precision 3D data and the possibility to adjust the light sources in the computer model reveals hidden information. So already the first results of the Avalokeshvara gave us more information about the carvings.

An important example is the faces of the Avalokeshvara. In a photograph or even in-situ it is not observable that this Bodhisattva

Figure 7. One picture and two visualizations of the Avalokeshvara on the right half of the temple wall. In (b) the texture map has been removed and the resulting image has been illuminated virtually. (c) shows a grey scale value for each vertex of the surface. The scale is 10cm with a total length of 1m.

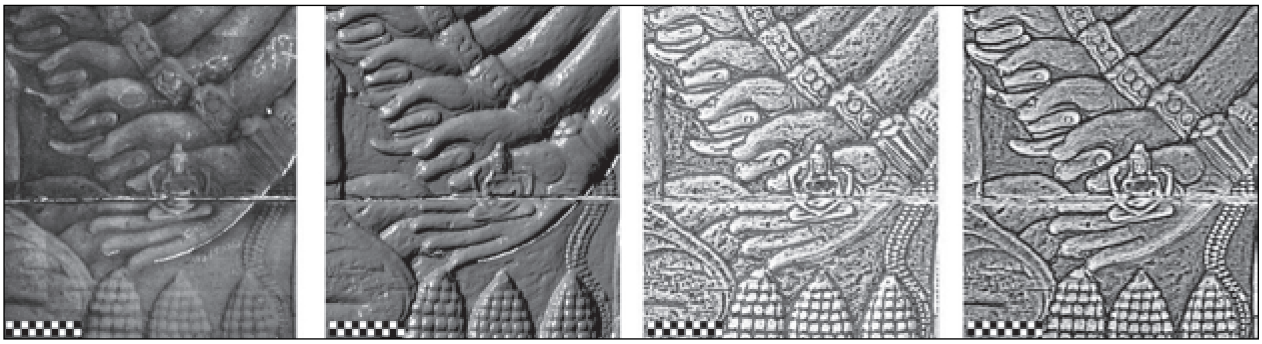


Figure 8. Detail of the Avalokeshvara: (a) acquired texture map, (b) illuminated 3D mesh, (c) coloured by autocorrelation of the MSII features, and (d) 3D mesh without illumination showing the MSII correlation of surface features as greyscale. A virtual scale with a length of 10cm is shown in the bottom of each image.

has more than one, yet the scan data and even clearer the visualized part show about five faces on the main head and five on top of them (Fig. 6).

Applying the MSII filter reveals more hidden details such as the aforementioned faces (compare figure 6a and figure 6b). It automatically emphasizes man-made structures and neglects misleading colour information or casted shadows as well as random noise. The detail of the Avalokeshvara in figure 8 has an absolute size of about 400 × 450mm and contains 4.4 million measuring points. The "little Buddha" in the open hand of the bas-relief can now easily be recognized and compared with other designs (Fig. 8).

The part of the Avalokeshvara that is still upright is supposed to be two of originally eight Botthisattvas. Therefore, we acquired Avalokeshvaras on display at the National Museum in Phnom Penh which are supposed to fit next to the ones still in Banteay Chhmar. Having obtained all existing and still upright reliefs they were virtually reassembled by hand to see whether they fit as expected. The result is shown in figure 11.

An overview of the amount of work needed to acquire different objects is shown in Table 1, information includes length of time for each acquisition, the number of scans needed and the resulting data size for the reliefs visualized in this paper. The whole bas-relief of the Avalokeshvara is about three times the size of what is shown in this work. To cover both of the still upright Avalokeshvaras including their back side took about 4 weeks and 1539 scans. The final 3D model contains approximately 1800 million vertices and 3600 million faces. The stones in comparison have been acquired during the course of 3.5 weeks. It took 8 - 20 scans for an average stone with about 7 million vertices and 13.6 million faces on average.

As a supplementary example figure 10 shows the 3D model of the relief of Sheshonk I. with false-

	Avalokeshvara	Avalokeshvara (detail)	Sheshonk
number of individual scans	250	9	20
number of vertices	170 million	4.4 million	22 million
number of faces	340 million	8.8 million	44 million
time needed for capture	3 days	20 minutes	43 minutes
dimensions of bounding box [mm]	3840 × 2870	392 × 445	2186 × 1561
Total acquired surface area	9.7m2	0.17m2	1.28m2

Table 1. Listing of the number of necessary scans, acquisition time and size of each object.

Figure 9. Computer-based manual reconstruction of the stone wall using the open-source software Blender (www.blender.org).

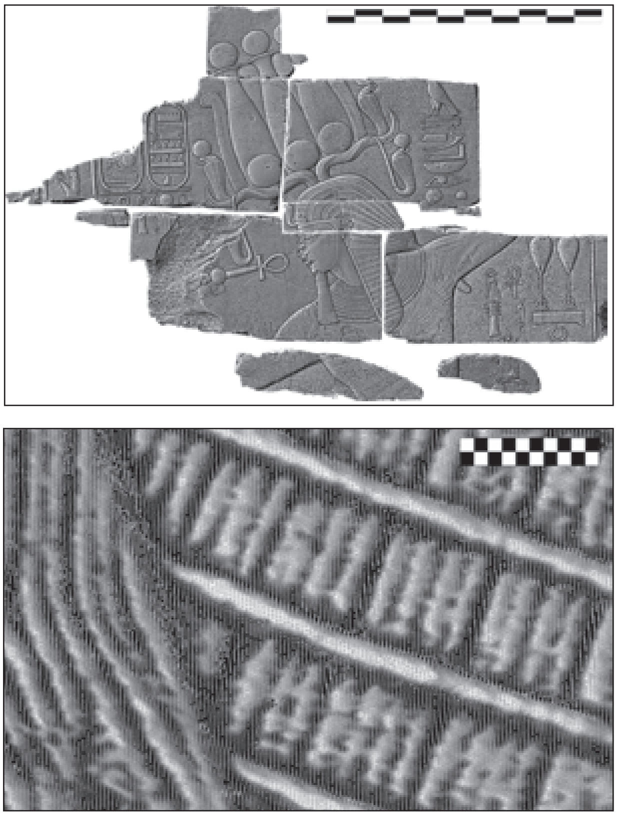


Figure 10. "Sheshonk I while striking dead his enemies". Visualization using MSII applied to the 3D model showing the filter response in false colours. The original which was found in El-Hibe, Egypt, is displayed in the collection of the institute of Egyptology of Heidelberg University. See (Feucht 1981) for more information.

colour based on MSII. At the bottom of figure 10 the measuring points are shown in green for the detail of the beard and the ornamentation of the garment of the Pharaoh (for full colour images please see the online version of this paper).

Summarizing the test cases for reliefs from the Middle East and Asia, we have successfully shown that the acquisition using a high-resolution close-range 3D scanner takes about 45 - 60 minutes per square meter.

This conforms to our experience for walls with frescoes, for which we estimated a duration of 20 minutes per square meter (Breuckmann et al. 2009). Post-processing can be prepared *in situ* in the evening while automated analysis can be done overnight if power supply is available. However the rule of thumb is that post-processing requires twice the time of acquisition. The manual work involved in the acquisition and post-processing has a steep learning curve for people working with the equipment, and with on-going software improvements guided by our own experience we have already halved the amount of man-hours spent on post-processing. Given the short development cycles in computer hardware we can safely assume that all the processing can be done on-site in the near future with one desktop computer, provided that a reasonable amount of memory is available. The same can be achieved already at the present day by dividing the work, using one or two additional computers close to the excavation site.

Concerning methodological advances in computational geometry, we showed the adoption of a novel approach from character extraction for cuneiform tablets as a local rendering method for large-scale high-resolution meshes. As the on-going development of this approach aims to determine

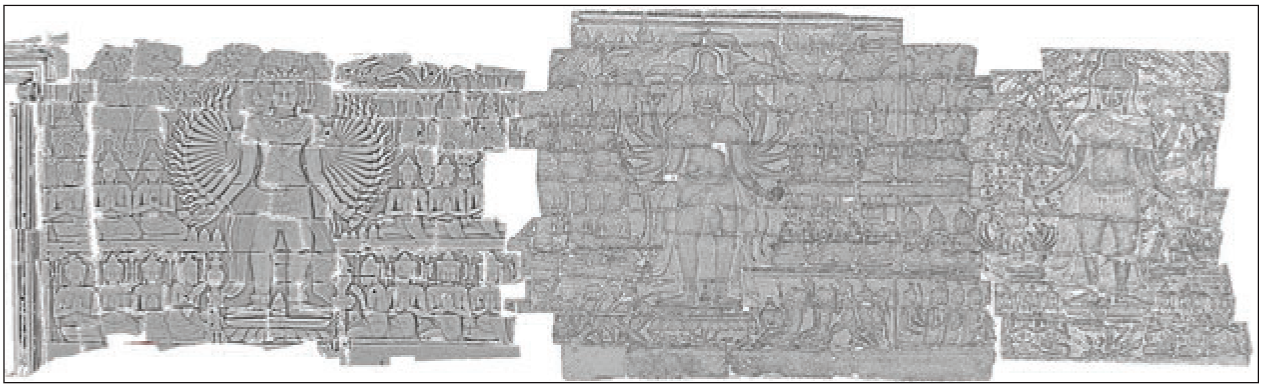


Figure 11. Proof of concept: The acquired Avalokeshvaras from the National Museum in Phnom Penh fit perfectly next to the ones acquired in-situ. They are shown on a grayscale texture map using MSII without virtual illumination. The scale shown is 1m.

vectorized drawings from 3D models, we expect to dramatically reduce the amount of data for further semi-automated research, e.g. the quantitative comparison of iconographic elements. In contrast to traditional methods from computer graphics we achieve an illumination independent virtual reproduction of ancient objects and their smallest details.

To conclude, we compared the manual task of a 3D puzzle with the virtual approach in which some clear advantages can be seen. First of all, it is the more efficient approach: it is known in advance that the stone will fit where it is supposed to fit, meaning a positive outcome is ensured. Secondly the 3D puzzles greatly improve security matters for the restoration personnel. Lastly, the workflow can be optimized by solving a "puzzle within the puzzle": first reassembling the broken stones, then reassembling the fallen wall. This is the challenging part leading to an optimization algorithm (Nocedal 2006). In conjunction with a combination of the still-standing bas-reliefs such as the Avalokeshvara the 3D puzzle will result in a virtually reconstructed model of the temple whose level of detail is comparable to the model achieved for Angkor Wat (Nguonphan 2009).

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