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Virtually reassembling Angkor-style Khmer temples

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ABSTRACT

Cambodian temples are severely damaged and their reconstruction is complex. Conservators are challenged by a magnitude of stones of unknown original position. Specialists resolve this large-scale puzzle by analyzing each stone, using their experience and knowledge of Khmer culture. Then a trial and error approach is applied which has disadvantages. The weight of the stones of up 1000 kg complicates their movement and opposes a safety hazard to workers. Additionally the stones' relocation should be reduced to a minimum as it promotes their deterioration. This motivated the development of a virtual approach, as computer algorithms lead to a potential solution in less time, thereby drastically reducing the amount of work. The basis for this virtual puzzle are high-resolution 3D models of 135 stones. These stones have an approximately cuboidal form and often feature indentations that are exploited by the algorithm to accelerate the matching process. The general idea is to (1) simplify the high-resolution models, (2) test all feasible combinations and (3) match best combinations and validate the results. Close collaboration with specialists on site ensures overall algorithmic correctness.

1. Introduction

The temple site of Banteay Chhmar is situated in the Northwest of Cambodia, about 15 km from the Thai border. It was built by king Jayavarman VII between 1180 and 1220 AD to honor his son and four of his army generals for defeating the neighboring Cham, an enemy civilization. The site exhibits many similarities to the better-known Bayon temple in the Angkor complex of the same period. The Banteay Chhmar complex is surrounded by a moat and a stone enclosure wall. Together with its eight satellite temples this sanctuary comprises an area of about 9 km^2 (Fig. 1).

The temple with its elaborate carvings is a valuable documentation of Khmer history and culture at the end of the 12th century. As a result of its remote location it was abandoned quite early in Cambodian history and is today highly deteriorated. Additionally, severe looting took place in the 1990s. Today only about 20% of the original structure are remaining and even these sections are in immediate danger of collapse. To ensure the temple's preservation, the *Global Heritage Fund* (GHF) started a long-term preservation project in 2008 that includes training locals in stone conservation and temple repair. A manual reconstruction of the temple is very difficult and complicated by the temple stones' weight of up to 1000 kg. The working conditions on site are unfavorable, both in terms of safety of the workers and in terms of conservation of the stones. Additionally, untrained workers can destroy the valuable carvings of the stones. Encouraged by the Ministry of Culture and Fine Arts, GHF and the *Interdisciplinary Center for Scientific Computing* (IWR) of Heidelberg University (IWR) have been working to develop appropriate technology to minimize the need to move the heavy sandstone blocks which threatens the safety of the local workers.

The digital reconstruction of the temple will help to minimize reconstruction costs and danger to the workers and the temple. The stones are digitized by the help of digital surface scanners. Their achieved resolution is within the range of micrometers and enables a detailed digital description of the stone's surface. The output of these scanners are triangulated surface meshes that perfectly reproduce irregularities in the stone and detailed reliefs. Still it is difficult to virtually reassemble the individual stones. In this paper a suitable workflow is introduced that is able to reconstruct the Khmer bas-relief walls.

Our contributions are:

- a new, simplified description of each stone block used to build the temple,
- a similarity analysis that indicates the probability of two matching stones,
- a complete workflow for the reassembly of digital bas-relief wall stones.

2. Related work

Approaches to find the correct placement of separate pieces are known as 3D puzzles. Numerous publications have appeared in this field in the last 15 years, such as e.g. Gomes et al. (2014), Willis

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and Cooper (2008), Kleber and Sablatnig (2009), Brown et al. (2012), Funkhouser et al. (2011), Toler-Franklin et al. (2010), Sonnemann et al. (2006), Huang et al. (2006), Reuter et al. (2007), and Winkelbach and Wahl (2008) or Papaodysseus et al. (2012). The approaches most relevant to our work are those of Huang et al. (2006), Reuter et al. (2007) and Winkelbach and Wahl (2008). The approach of Huang is the best known in this research area. Starting from a broken object, Huang et al. classify the surfaces of broken pieces either as fractured surfaces or as original surfaces. The former results from parts where the object broke apart and the latter from the exterior boundary surface of the undestroyed object. Based on integral invariants they identify fitting pieces of the available data set. Reuter et al. apply a different approach. They use a semi-automated algorithm that needs an expert user to appoint matching parts which are then subsequently merged using the *Iterative Closest Point algorithm* (ICP) (see Besl and McKay, 1992). This creates a new but larger puzzle piece and the process is repeated until the object is fully reassembled. Winkelbach and Wahl make use of cluster trees, i.e. special tree structures that enumerate all potential solutions. The various possible matches are enumerated in a tree and the algorithm checks the quality of a match by a depth-first search. Thus, the accuracy of the fit improves in each step or solutions are deemed unfit if they do not comply with the fitting criteria.

All approaches have the assumption in common that the broken pieces arise from the same object and permit a complete reconstruction (see Fig. 3). Fig. 4 exhibits this assumption in more detail: for every fragment there exists a complement, i.e. each indentation (female) complies with a fitting counter part (male). Such complements can also be found if the pieces are eroded. The assumption of fitting counter parts is opposed by Khmer temple stones, as such stones have been quarried out and the surfaces have been worked on by a chisel. Ergo, if Khmer unbroken temple stones are used as puzzle pieces no counter pieces can be found using the classical way. Yet, if one or several stones are broken, an algorithm such as the one proposed by Huang et al. (2006) needs to be applied beforehand. The dataset we are working on does not contain broken stones, which is why we skip this point from further consideration for the time being. The predominant feature of Khmer temple stones derives from the unusual way in which the temples were built (see Section 3). This feature implies that the vertical and horizontal joints of the stones fit together closely without any interlocking parts. A further disadvantage of existing 3D puzzling techniques is that they can only handle a limited amount of fragments – usually less than 50. Whereas more than hundred sandstone blocks have already been digitally acquired from Banteay Chhmar. This means, it is still possible to implement a brute-force algorithm to test all possible solutions. However, as the number of possibilities rises significantly along with the number of pieces this method is unsuitable for large-scale reconstructions, as the presented reconstruction problem of the Banteay Chhmar temple site. The numerous available algorithms for two-dimensional jigsaw puzzles are not suitable for 3D puzzles, as they rely on features that are not available in case of temple stones. Therefore a novel algorithm has been developed.

3. Khmer architecture

The eastern bas-relief wall enclosing the inner sanctuary of the Banteay Chhmar temple was in danger to collapse due to the lack of foundations. Fig. 2 shows the wall in its original state. To build new foundations, the wall had to be taken down, which gave a team of the IWR of Heidelberg University the opportunity to digitally acquire 135 of the stones using a high-resolution structured-light 3D scanner (Schäfer et al., 2011).

Prior to the disassembly of the wall the location of each stone was noted and the stones were labeled, such that the wall can easily be reassembled. Therefore the original position of each stone is known and the correct outcome of the virtual algorithm can be verified easily. Fig. 5 shows a sketch of this wall. All stones have a nearly rectangular block-shaped form. It is not a rectangle in a strictly mathematical sense meaning the angles vary between 80 and 100°. The red circle in the figure shows an additional idiosyncrasy: whenever a stone was to be placed but did not fit perfectly, an indentation was cut from the upper face from the underlying stone, which is illustrated by the accompanying video. The cutting was used as a classification of the temple stones as having either no indentation, one indentation or two indentations. Another characteristic feature is the tight joint in between the stones. The Khmer did not use mortar between the stones to fix them in one place, yet it is not fully resolved how they achieved this tight joint. One theory is that the stones have been rubbed together, the other one that the stones have been worked on until the perfect fit was created. For further information on both viewpoints, the reader is referred to Dumarcay (1973).

4. Manual virtual reconstruction

A first preprocessing step with regard to a 3D reconstruction was a manual reassembly on the computer. To better understand how to implement the stones' features into Khmer temple

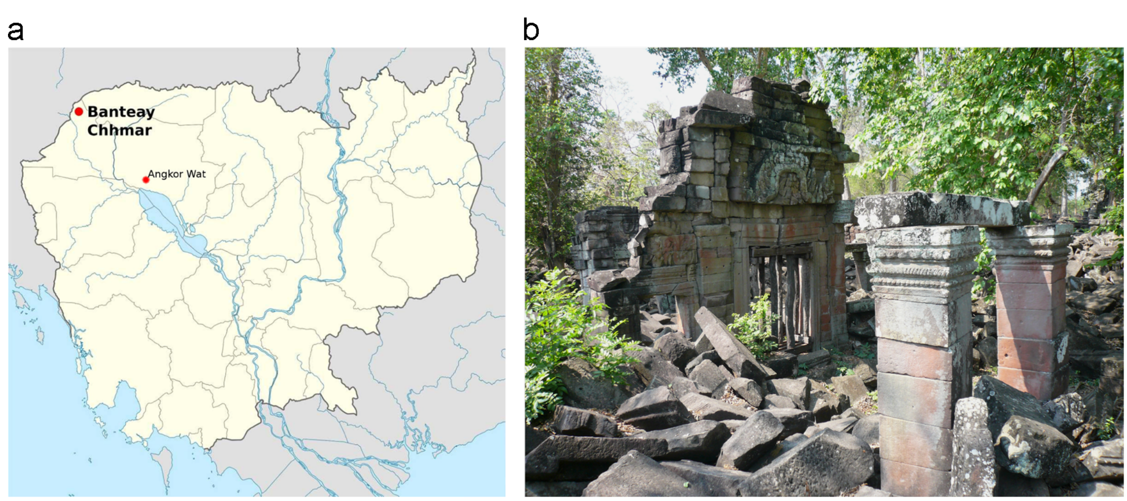

Fig. 1. A remarkable temple site, situated in the Northwest of Cambodia: Banteay Chhmar. The map of Cambodia (a) shows the location of Banteay Chhmar as well as that of Angkor Wat (Map source: de.wikipedia.org/cambodia). And (b) documents the state of deterioration inside the inner walls.