Clustering Bayon Face Towers Using Restored 3D Shape Models

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***Abstract*—Bayon, the well-known Khmer temple at Angkor in Cambodia, is famous for its numerous massive stone face towers. Researchers believe that these facial sculptures can be divided into several meaningful categories. Unlike previous studies, in this paper, each face tower is treated as a basic unit in the classification procedure, as we find that faces located on the same tower have a higher similarity value than those which belong to different ones. 3D replicas acquired by digital scanning are used and a restoration scheme based on the matrix recovery theory is adopted within each tower in order to eliminate the impact of data incompletion. Towers are represented by the average shapes of restored faces and hierarchically clustered based on their similarity values. The spatial distribution of the clustering result shows that there are some patterns among the structure of Bayon, which could be meaningful through further archaeological research.**

***Keywords*-clustering; shape analysis; restoration;**

I. Introduction

The Bayon, which was built in the late 12^{th} or early 13^{th} century, is a well-known Khmer temple at Angkor in Cambodia. Located in the center of Angkor Thom, the entire building is carefully designed, with rich and beautiful decorations. The most recognizable and distinctive symbol of this temple is the multitude of serene and massive stone faces on the many towers that jut out from the upper terrace and cluster around its central peak [1], as shown in Figure 1b. Containing about 200 gigantic faces, these mystical face towers never fail to fascinate archaeologists.

Among all mysteries of Bayon, one critical issue is: what is the significance of these smiling faces? Due to the similarity between these faces and other statues of Jayavarman VII, the Khmer emperor who actually built the Bayon and the city of Angkor Thom, many scholars accept that the faces are representations of the king himself. Others believe that these faces belong to the Bodhisattva of compassion called Avalokitesvara or Lokesvara [2]. Clearly, if these faces can be accurately divided into several meaningful groups, as many scholars believe, that will help to understand these relics better.

A pioneer study on Bayon face classification was done by the Japanese Government Team for Safeguarding Angkor (JSA) [4]. Based on the observation and analysis from experienced JSA experts, faces were roughly divided into three groups: *Deva*, *Devata*, and *Asura*, meaning *god*, *goddess*, and *devil* respectively. Figure 2 shows the typical faces of each group. Notice that this classification was obtained from subjective evaluation. Objective classification methods for comparison were proposed as well. For example, a framework for clustering images of face carvings at archaeological sites was presented by Klare et al. [5], where the pairwise similarities were computed from local facial features, such as eyes and nose. This method was effective when dealing with the Devata goddesses depicted in Angkor Wat.

(a) (b)

Figure 1. Images of Bayon, including an overview (a) and one face tower (b). The upper two are photographs, and the bottom ones are rendered images using 3D data acquired in the Bayon Digital Archival Project [3].

Currently, three-dimensional digital replicas have been playing an increasingly important role in the study of cultural heritage preservation and analysis. The geometric information of real-world objects can be accurately acquired using 3D scanning techniques and digital models can be used

(a) (b) (c)

Figure 2. Typical faces of the three categories in Bayon divided by JSA. (a): Deva (*No.* 51S), (b): Devata (*No.* 50E) and (c): Asura (*No.* 35N).

(a) (b)

Figure 3. Two rendered images of the same sculpture shown in Figure 1b from another viewpoint. (a): geometry only; (b): with color texture.

in a number of archaeological studies. In cooperation with JSA, the whole temple of Bayon was digitally archived by the Ikeuchi Laboratory at the University of Tokyo, known as the Bayon Digital Archival Project [3]. Here the non-photographic images shown in Figures 1, 2 and 3 are all rendered using the scanned 3D data from this project.

Using the acquired 3D data of Bayon, an objective classification analysis of these faces was given by Kamakura et al. [6]. In their study, 3D faces were first aligned and normalized using three anchor points; then, depth images were captured to represent faces for the further comparison. In the final shape analysis phase, both supervised and unsupervised classification methods were employed to classify the transformed input samples. Notice that the group label from JSA [4] was used in their supervised analysis procedure.

This paper concerns the Bayon face classification problem, using the same digitalized data from the Bayon Digital Archival Project [3]. Based on the fact proved in the previous work [6] that facial sculptures on the same tower are of a significant similarity, we present a hypothesis where each face tower is treated as an unit, and further modify the original goal to a face tower classification problem. Moreover, as 3D models are directly used in our method, in order to handle incomplete data, we adopt an example-based restoration procedure [7] within each tower. Besides, due to the unsupervised classification algorithm employed in our method, pre-labeled data, such as JSA's result, are no longer needed as input. Notice that our method is based on objective measurements and comparison as well.

The remainder of this paper is organized as follows: Section II introduces the preliminaries, including the face tower hypothesis, and the shape restoration scheme adopted in each tower using matrix recovery theory [8]. Section III presents the whole procedure of cluster analysis. The experimental results and discussion are presented in Section IV, with some preliminary findings and guesses based on our classification result. The last section gives a brief summary of this paper.

II. Face Tower Hypothesis and Restoration

A. *Face Tower Hypothesis*

The famous face towers are located on the upper terrace of the Bayon. Typically, each tower supports four huge smiling faces, as shown in Figure 1b. In the previous classification studies [4] and [6], faces were treated individually without considering the spatial connections. However, it is easy to see that faces on the same tower look more similar than those from different ones. See Figure 4 as an example. Based on this observation, we may assume that compared with considering every face separately, it is more reasonable to treat each face tower as a union, as it has a high shape similarity score within each tower. This speculation is also supported by the unsupervised clustering result in the previous work [6].

There are at least two advantages to consider each tower as a unit: first, the number of clustering units is reduced, making the result clear at a glance and therefore easy to discover the hidden regularities; second, a number of faces are only partially preserved, as shown in Figure 5, which makes the comparison inaccurate and inappropriate. If each tower is treated as a whole, other complete faces on the same tower can be used to help repairing the incomplete one, following the restoration scheme that will be introduced in the next subsection.

B. *Restoration within Towers*

As we mentioned in the introduction section, many facial sculptures in Bayon are partially damaged due to various reasons. In order to get a reasonable classification result, restoring incomplete faces to recover the original shapes

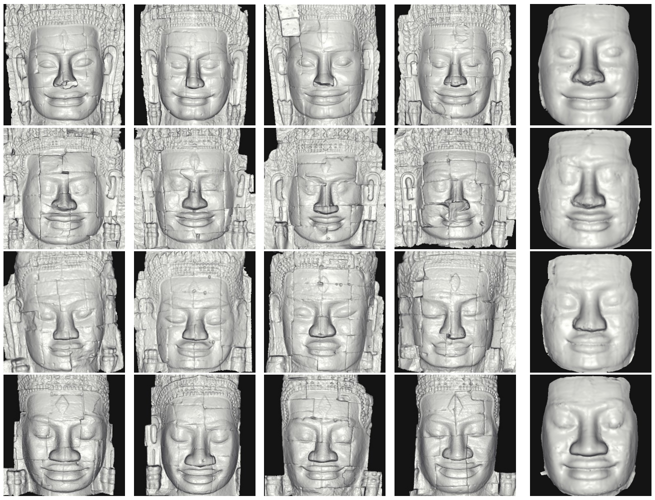


Figure 4. Similarities within towers. Each row corresponds to a certain face tower: from left to right, the first four items show the four facial sculptures on that tower, and the last one illustrates the tower's representative shape, using the processing scheme introduced in Section II-B.

Figure 5. Restoration examples of Bayon faces [7]. The upper row shows five partially preserved Bayon faces, and the bottom row is the corresponding restored outputs. Notice that these results were generated using the entire Bayon face database as similar shapes, not restoration within each tower.

when they were just completed becomes necessary. Here an example-based shape restoration method proposed by Lu et al. [7] is employed. Figure 6 shows its pipeline.

Suppose we are given a group of facial shapes from the same tower, and faces are represented as fixed-length vectors already, let $\{\mathbf{f}_i^0\}_{i=1}^n$ and $\{\mathbf{f}_i\}_{i=1}^n$ denote their original shapes when they were just completed and the corresponding observations, i.e., raw measured data in real world respectively. Typically, n equals 4 as there are usually four faces on each tower.

An assumption, that $\{\mathbf{f}_i^0\}_{i=1}^n$ are linearly correlated, is required as a premise. Let $span(\mathbf{f}_1^0, \dots, \mathbf{f}_n^0)$ denote the linear span of these original shapes, which is defined as

$$span(\mathbf{f}_1^0, \dots, \mathbf{f}_n^0) = \{\sum_{i=1}^{n} \alpha_i \mathbf{f}_i^0 | \alpha_1, \dots, \alpha_n \in \mathbb{R}\}, \quad (1)$$

meaning the intersection of all subspaces containing this set. The previous assumption means the dimension of this linear span should be much smaller compared with the

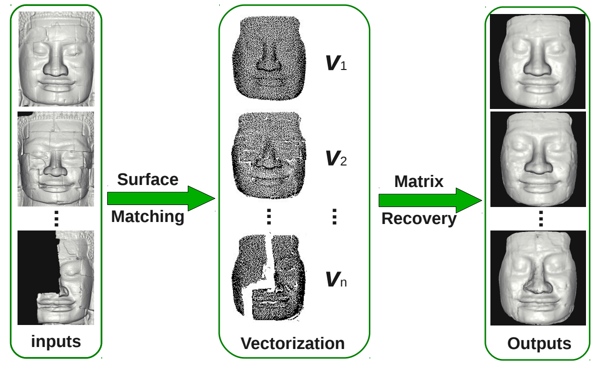


Figure 6. The pipeline of the employed restoration method [7].

superposition of *n* times the value of each sample. In other words, if vectors $\{\mathbf{f}_i^0\}_{i=1}^n$ form the columns of a matrix, denoted as *A*, the rank of this matrix should be less than the number of samples *n*. This means *A* is approximately a low-rank matrix.

Similarly, an observation data matrix *D* is formed by vectors $\{\mathbf{f}_i\}_{i=1}^n$. The difference between *A* and *D* corresponds to the corruption, which is denoted as matrix *E*. The observation can then be decomposed as:

$$D = A + E. \quad (2)$$

According to the former linear correlation assumption, this matrix *A* is approximately low-rank. As for the error matrix *E*, considering that usually the corruption is only partially existing, this matrix *E* should be sparse, which means most of its entries are zero. Therefore, the task of restoring a group of Bayon faces from a same tower turns into the form of a matrix recovery problem [8]:

$$\min_{A,E} \quad \|A\|_* + \lambda \|E\|_1, \quad s.t. \quad A + E = D. \quad (3)$$

Notice that here $\|A\|_*$ is the nuclear norm of matrix *A*, which is defined as the sum of its singular values: $\|A\|_* \doteq \sum_i \sigma_i(A)$, and $\|E\|_1$ refers to the L_1 norm of matrix *E*. This problem can be efficiently solved by convex optimization [9] and Figure 5 shows several restoration examples of the above method.

III. Tower Classification

A. Data Pre-processing

Before starting the cluster analysis, input 3D shapes have to be preprocessed. First, the outer parts, such as ears and headwear, are cropped. Next, by adopting a surface matching scheme [7], dense corresponding points are generated. Then we stack the (x, y, z) coordinates of these points, turning each face into a fixed-length vector to represent its geometry.

The next step is to adopt the shape restoration procedure introduced in Section II-B within each face tower, trying to handle the shape incompletion and make the similarity comparison more accurate. The average of repaired faces is used for representing the corresponding face tower. If no other than one face existed in a certain tower, which is really rare in the Bayon case, the restoration step would be skipped, keeping the original shape for further comparison.

B. Hierarchical Clustering

The final stage is to properly divide the data set into subsets so that face towers in the same cluster are similar in some sense. This is a typical task of cluster analysis, with several classical solutions, such as K-means [10]. Notice that for our problem, although we all believe these face towers should be classified, it is difficult to determine the exact number of how many clusters should they be divided into. Here the hierarchical clustering method [11] is chosen. Instead of generating a "flat" data description, like K-means, this method will lead to a hierarchical representation, where the relationship among all samples is clear at a glance and clusters can be chosen more flexibly.

Given pairwise similarity values of all samples, a hierarchy is built from the individual faces by progressively merging clusters. Ward's criterion [12] is used as the linkage criteria which determines the distance between pairs of clusters. The result is represented in a corresponding tree, called a dendrogram, as shown in Figure 9. Note that the similarity values, which correspond the height in the dendrogram, can be used to help determine whether groupings are natural or forced. For instance, if an unusually large gap between the similarity values of two neighboring levels is found, one can argue that here is a natural boundary to divide the dendrogram.

After the pre-processing explained in Section III-A, the similarity evaluation between a pair of towers becomes just measuring the distance between two points in a vector space for which we use the Euclidean norm.

IV. Experimental Results and Discussion

Currently, there are 154 facial models in the Bayon face database [3], coming from 46 different face towers. As mentioned earlier, many sculptures are incomplete or heavily damaged, making the following comparison phase difficult. Although the example-based restoration method described in Section II-B was adopted to overcome this problem, a few damaged towers were still not repaired, since each of them contained one face only, which did not meet the prerequisites of the restoration program. This was the case for most of the central towers, as shown in Figure 7, and they were not taken into consideration in our analysis.

In addition, notice that if incomplete faces were the majority on a certain tower, the restored output would not be satisfactory. Actually towers *No.* 22 and 24, as shown in Figure 8, were the only two unsatisfactory restoration results in our experiment, and they were shelved this time.

Figure 7. Faces from central towers. All were shelved in our experiment except *No.* 8, the second one from left to right in the bottom row.

Figure 8. The only two unsatisfactory results of shape restoration, towers *No.* 22 and 24. Similarly to Figure 4, each row corresponds to a certain tower. Both towers contain too many seriously incomplete faces, which led to poor restoration outputs.

After the proceedings described in Section III-A, a small data set containing the representative faces of 35 towers was built. Based on this data set, a hierarchy of face tower clusters was generated, as shown in Figure 9. The tree root refers to a single cluster containing all elements, and the leaves correspond to individual face towers. After setting a proper threshold value, the whole dendrogram was divided into three groups, labeled in different colors. Figure 10 shows the concrete result by clusters, with the average faces within each group as well. Figure 11 illustrates the distribution of clustering results on the plane figure of Bayon. Notice that tower *No.* 52 was included in none of the above three groups, because it was "far" from all the other towers, which means it had a notable difference from the rest. This was also confirmed by JSA experts. From their perspective, this tower seemed to be built later than the others, with a slightly worse sculpting skill compared with all the other towers.

After acquiring the above classification results, we tried to unscramble them from the perspective of culture and history, hoping to get some new findings of the ancient mystery.

First of all, our classification results are consistent with the three-type hypothesis of Bayon faces given by JSA [4]. The data set was roughly divided into three groups, as Figure 9 and 10 demonstrate. In particular, the second cluster, which is the green branch in Figure 9 and shown in Figure 10b as well, may be related to the "Devata" category in the JSA report. Since samples in this group look like females. As for the other two groups, although the averages seem to

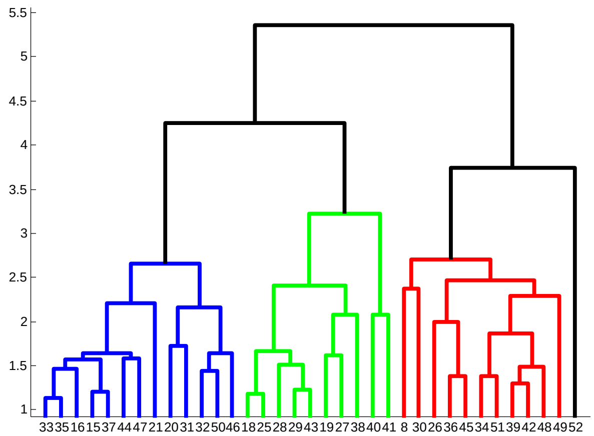
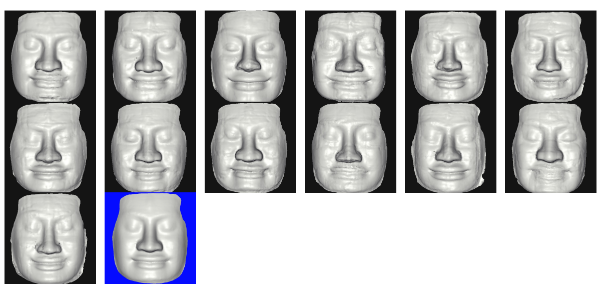


Figure 9. The hierarchy of face tower clusters. This dendrogram was divided into three groups, marked in different colors. The numbers on the bottom axis refer to the serial numbers of face towers. Notice that tower *No.* 52 was labeled as an outlier in this result.



(a)

(b)

(c)

Figure 10. The detailed clustering results of Bayon face towers. (a), (b), and (c) show the specific tower faces corresponding to the three groups in Figure 9 respectively, with the average shape within that particular cluster using the same color for labeling as background.

be similar at first glance, there are some slight differences actually. This indicates that there might be different sculpture teams who built the Bayon at the same time.

Second, it is interesting to find that the spatial distribution of our result shows a certain degree of structural information.

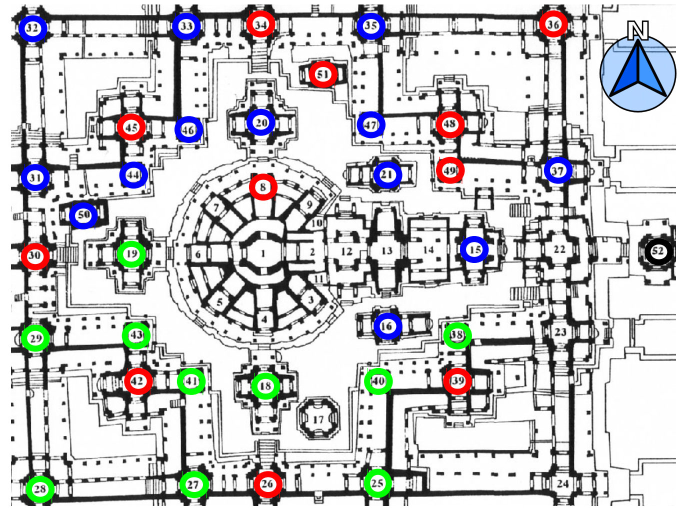


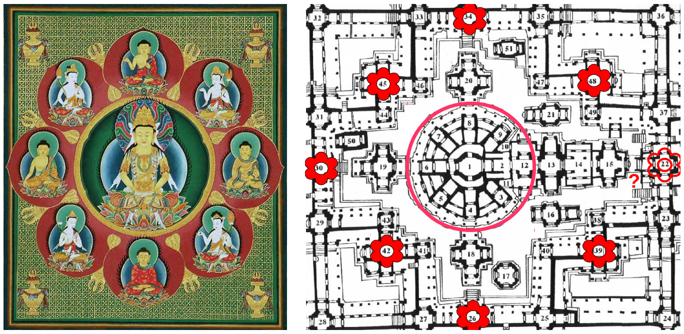
Figure 11. The distribution of our clustering result showed in Figure 9 on the plane of Bayon.

Let us focus on Figure 11. It seems that the blue and green groups are almost symmetrically distributed on both sides of the east-west axis of this temple. Moreover, except towers *No.* 8, 36, and 48, the rest samples in the red group are located on the symmetrical positions, as shown in Figure 12b. This figure resembles a meaningful structure called the "Mandala", which is widely used in the Hindu and Buddhist religious traditions for establishing a sacred space. This discovery confirmed our classification results to some extent.

Third, the clustering result may help us trace the sequence of construction. As large a project Bayon is, it is almost impossible to build all the face towers simultaneously. A previous research about this topic was done by Cunin [13]. Here we may reasonably speculate that after a certain tower was finished, it could be used as a reference for building the towers nearby, which led to the fact that these related towers have a larger chance of being included into the same group, as signified by our clustering process. Based on this assumption, we inferred the construction sequence of Bayon from the spatial distribution of our clustering results. The detailed order might be like this: the central peak first, then the four central high towers—*No.* 15, 18, 19, and 20, next the towers on the magenta cross strap marked in Figure 13, and finally the four corners. Most face towers on the central peak are heavily damaged and not taken into consideration in our cluster analysis. As many archaeologists believe they were built first, here we follow this assumption.

V. Summary

In this paper, we focused on the facial sculpture classification problems in Bayon. Based on the presented face tower hypothesis, faces on the same tower were treated as a basic unit in the clustering process. Data incompletion was han-



(a) (b)

Figure 12. Mandala. (a): A Mandala figure from a Japanese Buddhist temple; (b): The Mandala-like structure found in our clustering result.

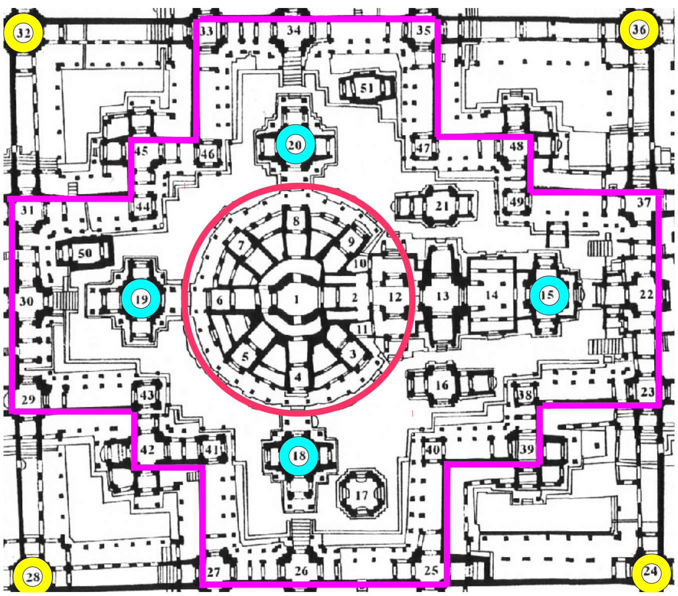


Figure 13. A possible sequence of construction we guessed. First, the central peak; next the four central high towers—*No.* 15, 18, 19, and 20, which are marked as cyan circles; then the towers on the magenta cross strap; and finally, the four corner towers that are marked in yellow.

dled by an example-based shape restoration processing and a hierarchical clustering scheme generated the final result. Several preliminary but interesting findings and guesses were acquired and they support the validity of our classification result.

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