Preah Vihear Project: Obtaining 3D point-cloud data and its application to spatial distribution analysis of Khmer temples

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Figure 1: An overview of the entire 3D point-cloud data of Preah Vihear Temple used in this paper.

ABSTRACT

Preah Vihear Temple, a Hindu temple located on the border between Cambodia and Thailand, is under the need of digitization mainly because of two reasons: possible destruction of the temple, and its unique characteristics. While most of the archaeological sites from the Angkor Dynasty, such as Angkor Wat Temple and Bayon Temple, are oriented in the east-west direction, Preah Vihear Temple is one of the few archaeological sites to be oriented in the north-south direction. The first half of this paper reports the digitization project of Preah Vihear Temple. While it is possible to acquire 3D digital data of tangible cultural heritage by using existing methods, the size and location of the temple, which resides near a cliff, inhibits us from directly applying existing methods. This causes the need to design methods that are applicable for these environments. For the first time in the world, we have succeeded in acquiring 3D digital data of the entire Preah Vihear Temple, by specially designing both hardware and software that is suitable for our task. We report details of our method and present visualizations of the obtained 3D point-cloud data. The second half of this paper provides an example of an application of this 3D point-cloud data. As an example, we determine the direction of the central axis of Preah Vihear Temple using the obtained 3D point-cloud data. We also provide a hypothesis for an interpretation of the direction of the central axis by examining a Khmer legend, using the results obtained from the 3D point-cloud data.

CCS CONCEPTS

• **Applied computing → Arts and humanities**; • **Computing methodologies →** *3D imaging*; • **Human-centered computing** → Geographic visualization.

KEYWORDS

e-heritage, point clouds, plane model segmentation

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(a) Data acquisition using a ground stationary range sensor. **(b) Data acquisition using a handcart type range sensor.** **(c) Data acquisition using a balloon range sensor.** **(d) Example of a GPS reference point in Preah Vihear Temple.**

Figure 2: Measurement scene at Preah Vihear Temple. Due to the wide temple grounds, sensors with different characteristics were used. Best viewed in color.

1 INTRODUCTION

Preah Vihear Temple is a Hindu temple, located on the border between Cambodia and Thailand. The construction began at the end of the 9th century by the Angkor Dynasty and is believed to have been completed by the 11th century. It is built on a cliff in the Dângrêk mountains, with a magnificent view of the Cambodian side to the south. The approach road extends from the Thailand side from the north to the south, going through the five *Gopuras*, each named from Gopura I to Gopura V, and finally through the main courtyard in Gopura I.

We, the University of Tokyo data-acquisition team, decided to obtain a 3D point-cloud data of this temple due to the following two reasons: possibility of destruction of the temple by international conflicts, and the uniqueness of the north-south main axial direction of the temple.

Preah Vihear Temple has the possibility of destruction due to international conflicts. As a matter of fact, there are bullet holes in the walls of Preah Vihear Temple from previous conflicts. We therefore consider it is worthwhile to obtain 3D point-cloud data of Preah Vihear Temple while the temple is still existing.

Preah Vihear Temple has a unique position among the Khmer temples built in the Angkor Dynasty. While most Khmer temples, including Angkor Wat Temple and Bayon Temple, are based on the east-west main axis, this temple is based on the north-south main axis. We conjecture that some intention has existed behind the construction of this temple along the north-south axis instead of popular east-west axis at that time. There is also an ancient legend that Preah Vihear Temple, with this north-south main axis, overlooks important Khmer temples, as the guardian temple of the Angkor dynasty. We use the 3D point-cloud data, as the obtained data may provide some clues to this conjecture and the legend.

In this paper, we first explain the method of the collection of the 3D point-cloud data of Preah Vihear Temple, and present visualizations of the obtained data. We then establish the method to determine the axis direction of Preah Vihear by using the 3D point-cloud data. Finally, we hypothesize two conjectures regarding the geographical relationship with other archaeological sites, and examine them based on the obtained main axial direction.

This paper is organized as follows. Section 2 describes the details of the digitization method and a visualization of the obtained 3D point-cloud data. Section 3 provides a method to transform the coordinate system of the 3D point-cloud data to the Universal Transverse Mercator (UTM) coordinate system. Section 4 explains the methodology of obtaining the axis direction in the UTM coordinate system. Section 5 examines archaeological conjectures based on the determined axes and locations archaeological sites. Finally, Section 6 concludes the paper.

2 DIGITIZING PREAH VIHEAR TEMPLE

The point-cloud data of Preah Vihear Temple was obtained by the data-acquisition team of University of Tokyo from 2012 through 2015, in cooperation with Japanese-Apsara safeguarding Angkor (JASA) team and Preah Vihear authority, by using laser range sensors developed by The University of Tokyo (UTokyo) as well as commercially available sensors with UTokyo-developed software. This section briefly describes these sensors and software, and presents a visualization of the obtained point-cloud data.

2.1 3D Laser Range Sensors

We used commercially available Imager5010c (manufactured by Z+F) and C10 (manufactured by Leica Geosystems) as shown in Figure 2(a). The maximum measurement distances of Imager5010c and C10 are 187m and 300m respectively. These sensors can obtain an omni-directional point-cloud data at one scan by emitting laser light along vertical directions while rotating the sensor-head horizontally.

Since Preah Vihear Temple is built on the ridge line of the Dângrêk mountains, it is also important to archive the terrains around the buildings to obtain the complete 3D point-cloud data that represents the entire temple. Unfortunately, the aforementioned sensors are not suitable for measuring wide areas since they must be fixed on the ground with a tripod, and requires too much time for scanning, as long as a few minutes. A commercially available mobile sensor such as Velodyne, has a much coarser resolution which is not suitable for our digital archiving purpose.

We have developed two types of mobile type sensors: a handcart type and a balloon type. In the handcart type [8] as shown in Figure2(b), we used the profile mode of the Imager5010C as the range measurement unit. The profiler mode does not rotate the head and can only measure one line, and needs to be moved forward or backward for area scanning. This forward (or backward) motion is realized by the handcart driven by humans. Because of the complex terrain around the temple adjacent to steep cliffs, the human driven method was inevitable. The sequential scan lines do not overlap with providing no positional information with each other scan lines. Thus, we need a method to estimate the motion of the sensor. We also develop the balloon type sensor as shown in Figure 2(c) [1]. We also use also Imager5010C as a range-measurement unit. In this case, we use the Imager5010C in omni-directional mode. However, due to balloon shaking during scanning, the obtained data is distorted. Again, we need a method to rectify the motion of the sensor.

In both the handcart and the balloon types, the motion is estimated by using images taken by the omni-directional camera, Labybug3 (Point Grey Research). Feature points in the images given by KLT tracker [5] are tracked through the sequential images. The motion and depths of the feature points are estimated from the tracked feature points. The depths obtained by the laser scanner and motion-depth information by the tracking are fused into accurate depth maps with absolute Euclidean measures. See [1] and [8] for more details.

2.2 Software Pipeline

When acquiring point-cloud data of an archaeological site, a single scan only provides partial data of the site due to occlusion and/or limitation of field of view of the sensor. Therefore, multiple iterations of partial scanning are conducted to produce a set of partial data that covers the entire surface of the site. The spatial relations among those data are then determined by using an alignment algorithm, such as the Iterative Closest Point algorithm [2]. Finally, the partial data are connected based on the obtained spatial relations into a whole point-cloud data.

The large scale of the temple prevented the use of existing algorithm pipelines. Since each ICP process provides a small error, by repeating ICP more than 10,000 times, the small errors accumulate gradually, creating a large gap between the first data and the last data by the time the alignment processes is finished. In order to avoid this accumulation error or the loop-closure issue, standard simultaneous alignment algorithms have been developed to load all the point-cloud data into the computer and consider all the possible combinations among the data for alignment. However, such standard simultaneous algorithms make memory overflow and combinatory explosion to handle the entire data set.

We developed two-step alignment algorithm. The first step is a GPU-based pairwise high-speed algorithm that roughly aligns the data obtained at the site [4, 6]. In particular, the GPU paining function is used for time-consuming point-correspondence search. One point-cloud data is converted to mesh data and each triangular mesh in the mesh data is colorized with a unique color by using the GPU painting function. This colorized mesh data is projected to the "image plane" as an index image, a perpendicular plane to the scanning direction of the second point-cloud data. Then, the second point-cloud data is projected on this index image and each point in the data is colorized based on the first mesh colors on the image plane. From the color information, we can obtain the correspondence between the first and the second point-cloud data. Based on the point-correspondence, we can determine the relative relation between two point-cloud data. These correspondences may contain small percentage of mis-correspondence due to occlusion but at this first step we ignore them because majority of the correspondences provides relatively accurate alignment result.

The second step of the alignment algorithm runs in parallel on a PC cluster [7]. Theoretically, from a given set of point-cloud data, simultaneous alignment algorithms have to consider all possible combinations of overlapping adjacent relations among all point-cloud data. Fortunately, the first step already establishes a rough alignment and provide adjacent relations. The second step makes it possible to accelerate computation time and reduce the amount of memory used by removing unnecessary relations and by clustering them into dependency groups. Since the alignment computation between two point-cloud data can be performed independently, each dependency group is assigned to each PC node. Because the computation time is proportional to the number of points assigned to each node, by forming those clusters so that the number of points computed is equal on each node, the load on each node is effectively distributed.

2.3 Obtained Point-cloud Data

We have obtained a complete 3D point-cloud data of Preah Vihear Temple. Figure 4 shows the data-acquisition results of Gopura I. As Gopura I has a main building surrounded by the corridors. We put the sensors inside of the building and on the roofs of the central courtyard and the corridors. Moreover, for the future virtual reconstruction purpose of the central sanctuary, we measured fallen stones as shown in Figure 4(b) As shown in Figure 4(c), we can easily generate orthogonal images of the buildings from the 3D point-cloud data. This orthogonal image is only possible from the 3D data because under traditional measurement methods, it is difficult to connect the parts of the same sea-level due to the elevation changes.

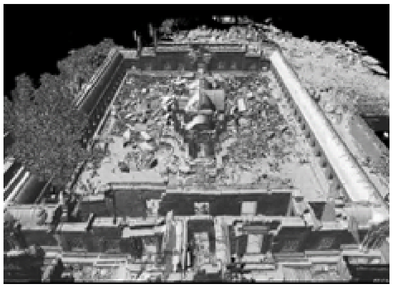
Figure 5 and Figure 6 show the 3D point-cloud data of the Gopura II and Gopura III, respectively. Figure 7 shows the 3D point-cloud data projected from the east, the west, the north and the south as well as the overview directions. Figure8 shows the 3D point-cloud data of Gopura V. Gopura V has a beautiful gate, and the platform of the building remains. But, unfortunately, most of the building have been collapsed. We measured the gate, fallen stones, and remained pillars from the ground, and the top of the pillars.

3 TRANSFORMATION OF COORDINATE SYSTEMS

The 3D point-cloud data is represented in a coordinate system different from the UTM coordinates, which we call the model coordinates. In order to analyze the spatial relationship among other Khmer temples, it is necessary to convert these coordinates into UTM coordinates. For this purpose, we use an affine transformation determined by the reference points of which UTM coordinates are known.

3.1 Affine Transformation from the Model Coordinates to UTM Coordinates

Let $\boldsymbol{x} \in \mathbb{R}^3$ be a point described in the model coordinates and $\boldsymbol{y} \in \mathbb{R}^3$ the same point described in UTM coordinates. We assume that

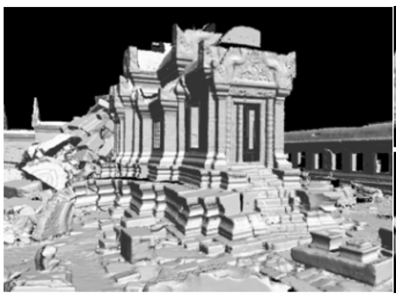


(a) Overview of Gopura 1.

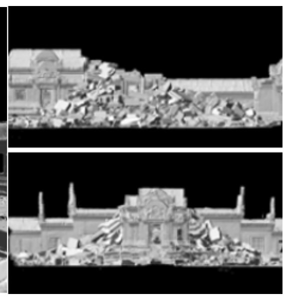
(b) North side of the courtyard of Gopura 1.

(c) West side of the courtyard of Gopura 2.

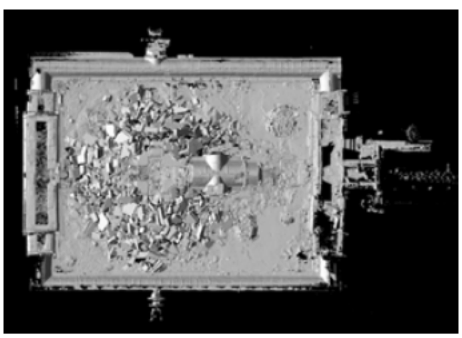
Figure 3: Example of 3D point-cloud data of Preah Vihear Temple used in this paper.



(a)



(b)



(c)

Figure 4: The 3D data of Gopura I. (a) the whole buildings of Gopura I. (b) the Central courtyard of Gopura I (c) the orthogonal image.

Figure 5: Point-cloud data of Gopura II.

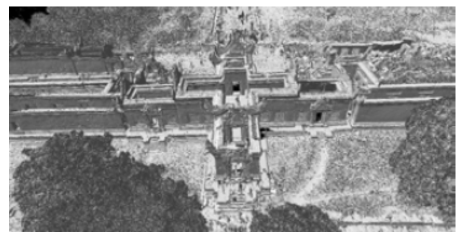


Figure 6: Point-cloud data of Gopura III.

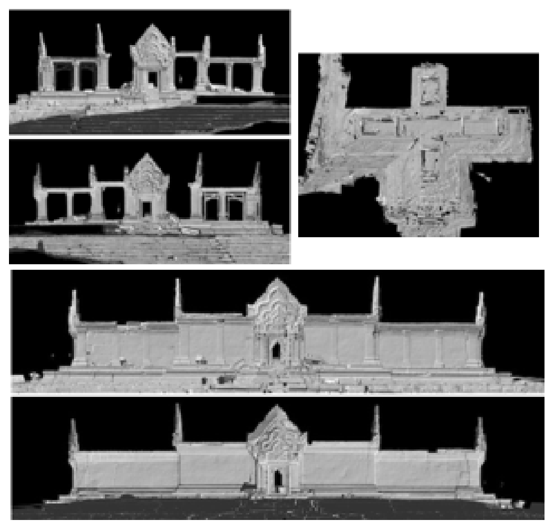


Figure 7: Point-cloud data of Gopura IV.

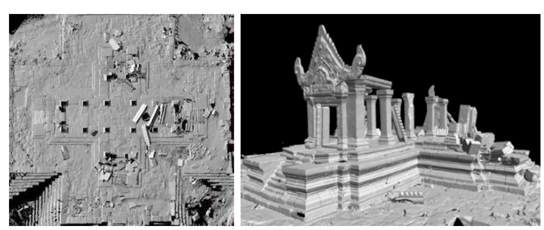


Figure 8: Point-cloud data of Gopura V.

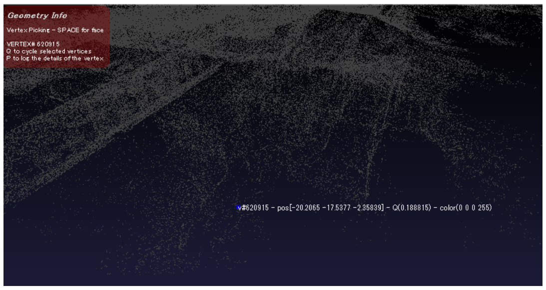


Figure 9: The user interface for selecting points in the 3D point-cloud data. We use Meshlab [3] for this purpose.

$\boldsymbol{y}$ can be obtained by an affine transformation of $\boldsymbol{x}$:

$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{b}, \tag{1}$$

where $\boldsymbol{A} \in \mathbb{R}^{3\times3}$ and $\boldsymbol{b} \in \mathbb{R}^3$ are the linear transformation component and the translation component of the affine transform, respectively.

In order to find $\boldsymbol{A}$ and $\boldsymbol{b}$, we need multiple pairs of model coordinates and GPS coordinates. When m data points are available, $\boldsymbol{A}$ and $\boldsymbol{b}$ in Eq. (1) is determined as

$$(\boldsymbol{A}, \boldsymbol{b}) = \underset{(\boldsymbol{A},\boldsymbol{b})}{\arg\min} \sum_{i=1}^{m} ||\boldsymbol{y}_i - \boldsymbol{A}\boldsymbol{x}_i - \boldsymbol{b}||. \tag{2}$$

3.2 Reference Points

In Preah Vihear Temple, seven PVG (Preah Vihear GPS) reference points and seventeen PVT (Preah Vihear Total station) reference points, are installed and measured by the JASA (Japanese-Apsara Safeguarding Angkor) team. PVG reference points are installed in well-viewed areas without any obstacles, and their UTM coordinates are obtained directly using the satellite GPS signals by observing GPS satellites for reasonable long observation periods.

PVT reference points are given by surveying multiple PVGs reference points by using a total station. Since all PVGs are located in well-viewed locations, they are located far away from the temple. In order to obtain key reference points near or inside of the temple, PVT reference points are introduced.

We then use Meshlab [3] as shown in Figure 9 to explore the model, and identify the reference points within the point-cloud data.

By substituting these UTM coordinates into $\boldsymbol{y}_i$ and the underlying model coordinates into $\boldsymbol{x}_i$ in Equation 1, we can obtain the affine coefficients, $(\boldsymbol{A}, \boldsymbol{b}$ to transform the model coordinates to the UTM coordinates.

We use the following coordinates pairs as shown in Table 1. The obtained parameters of the affine transform are as follows:

$$\boldsymbol{A} = \begin{bmatrix} -5.7546 \times 10^{-1} & -8.1775 \times 10^{-1} & 3.6220 \times 10^{-1} \\ 8.2985 \times 10^{-1} & -5.4907 \times 10^{-1} & -9.3693 \times 10^{-3} \\ 5.7153 \times 10^{-3} & 1.3311 \times 10^{-2} & 9.9203 \times 10^{-1} \end{bmatrix}$$

$$\boldsymbol{b} = \begin{bmatrix} 4.6553 \times 10^{5} \\ 1.5909 \times 10^{6} \\ 6.5291 \times 10^{2} \end{bmatrix}$$

3.3 Features to be Used for Determining the Direction of the Axis

One of the issues for determining the direction of the archaeological site is which feature to be employed for this purpose. This subsection considers several options.

One popular method in modern construction sites is to directly use reference points located on such sites for determining site directions. Such a method first sets reference points somewhere in the site and then measures the UTM coordinates of these reference points as was the case for PVGs and PVTs in the previous section. Then, based on these UTM coordinates, we can determine the direction of the site. However, this direct method is susceptible to errors, depending on where to put such reference points in the site. Modern construction sites, consisting fresh straight lines, provide ample candidate points. However, this method has a difficulty in handling an ancient stone building with swaying without any clear edges due to the decay.

The second possible method is to determine the contour lines of the site. This method is also often used in modern construction sites with clear boundaries. However, Preah Vihear Temple does not have any clear boundary lines, as some parts are half buried and other parts are deteriorated. Even if the point-cloud data is available, it is also difficult to extract clear boundaries directly from the entire point-cloud.

The third possibility is to determine the principal axis of the point-cloud data of the whole buildings. However, the axis direction obtained varies depending on how to segment the point-cloud data into buildings.

From these considerations, we have decided to extract the direction of the walls among the point-cloud data. Fortunately, the Preah Vihear Temple has a number of long walls either along the axis or perpendicular to the axis. Since the number of the points in the data is sufficiently large, the direction of the walls can be determined stably without depending on how much points we extract from the point-cloud data for this calculation once rough wall areas are manually extracted. Next section will explain this method in detail.

4 DETERMINING THE AXIS DIRECTION IN UTM COORDINATES

This section describes the method for determining the axis direction of an archaeological site. We conducted the following three steps for axis determination. In the first step, the walls to be used for determining the axis direction are manually segmented and their normal directions are obtained by applying Principal Component Analysis (PCA) to the point-cloud data of those segmented regions. We use Meshlab [3] for manual segmentation of the walls.

In the second step, the axis direction of the entire temple in the model coordinates is obtained from a weighted sum of these normals obtained from the point-cloud data of the walls. In the third step, the normal vector described in model coordinates is transformed into one in UTM coordinates by using the affine transformation obtained in the previous section.

Table 1: The model coordinates and UTM coordinates of the Reference points used for determining the affine transform.

Point name	Model Coordinates			UTM Coordinates		
	x	y	z	NORTH	EAST	HEIGHT
PVT9	-1.057816	-31.656767	-3.522477	465559.584	1590955.243	648.981
PVT11	-18.213732	-7.030200	-2.739809	465547.045	1590926.766	650.003
PVT13	10.3938	-7.90483	-2.14498	465533.762	1590951.014	650.444
PVT14	36.037498	-27.529705	-3.545917	465534.075	1590984.175	649.757
PVT15	51.491562	-40.020699	-2.877236	465534.390	1591002.463	649.675
PVT16	99.773567	-76.024345	-10.033089	465534.823	1591063.054	642.450
PVT17	122.412971	-93.022789	-10.074991	465534.978	1591091.278	642.363

4.1 Determining the Wall Normals

In this paper, we use PCA to determine the normal direction of the walls. When PCA is applied to a 3D point-cloud, three principal component directions are obtained as three eigenvectors corresponding three largest eigenvalues. When the point-cloud is distributed on an ideal plane, the first and second principal component directions, corresponding to the largest and the second largest eigenvalues, are contained within the plane, while the third principal component direction corresponds to the normal direction of the wall. Therefore, among the obtained principal component directions, the third principal component direction is taken as the normal direction of the wall.

Since some of the walls in the archaeological sites have decorations, walls that are as close to a flat surface and have few decorations were selected and their point-cloud data is used for this purpose. 7 walls were used for determining the central axis.

We determine the axis direction $\boldsymbol{c}_{\mathrm{Model}} \in \mathbb{R}^3$, written in model coordinates, as a weighted sum of the wall normal vectors $\boldsymbol{n}_i \in \mathbb{R}^3, i = 1, 2, \cdots, N_{\mathrm{walls}}$:

$$\boldsymbol{c}_{\mathrm{Model}} = \sum_{i=1}^{N_{\mathrm{walls}}} w_i \boldsymbol{n}_i, \tag{3}$$

where $w_i \in \mathbb{R}, i = 1, 2, \cdots, N_{\mathrm{walls}}$ are the weights for each normal vector, and N_{walls} is the number of walls.

We first align all of the normals in the north-south direction, by rotating the normals facing the east-west direction by 90 degrees. The weights w_i for each normal vector are determined by the area from each wall. We use the product of the largest eigenvalue and the second largest eigenvalue as the area of each wall.

Since $\boldsymbol{c}_{\mathrm{Model}}$ is described in the model coordinates, we must transform this vector into the UTM coordinates for localization purpose on the map.

Let $\boldsymbol{c}_{\mathrm{UTM}} \in \mathbb{R}^3$ be the centerline vector written in UTM coordinates, and $\boldsymbol{c}_{\mathrm{Model}} \in \mathbb{R}^3$ be the centerline vector written in model coordinates. Using the obtained affine transformation in the previous section, the relationship between $\boldsymbol{c}_{\mathrm{UTM}}$ and $\boldsymbol{c}_{\mathrm{Model}}$ can also be written as

$$\boldsymbol{c}_{\mathrm{UTM}} = \boldsymbol{A}\boldsymbol{c}_{\mathrm{Model}} + \boldsymbol{b}. \tag{4}$$

Finally, we define the angle of the axis direction θ_{center} with respect to the east direction in the UTM coordinates:

$$\theta_{\mathrm{center}} = \arctan(\boldsymbol{c}_{\mathrm{GPS},y} / \boldsymbol{c}_{\mathrm{GPS},x}), \tag{5}$$

where $\boldsymbol{c}_{\mathrm{UTM},x}$ and $\boldsymbol{c}_{\mathrm{UTM},y}$ are the horizontal and vertical components of $\boldsymbol{c}_{\mathrm{UTM}}$. The angle $\theta_{\mathrm{center}} = 0$ represents the east direction.

As a result, the direction of the central axis of Preah Vihear Temple determined to be tilted 3.9212 degrees to the western direction, compared to the true southern direction. The results of these calculations are summarized in Table 2.

4.2 Error Analysis

The affine transformation from the model coordinates to the UTM coordinates can be subject to the following errors: 1) uncertainty of the GPS measurement of reference points, and 2) uncertainty of the choice of the corresponding point in the 3D point-cloud model for the GPS measurement. We estimate that the accumulated error occurring from both of these sources are at an order of 0.1 meters.

We analyzed the impact of these errors on the axis directions. First, based on the estimation of the size of the errors, we added additive Gaussian noises $\boldsymbol{\delta}_{\mathrm{Model}} \sim \mathcal{N}(0, \sigma_{\mathrm{Model}})$ and $\boldsymbol{\delta}_{\mathrm{GPS}} \sim \mathcal{N}(0, \sigma_{\mathrm{UTM}})$ to the model coordinates and the GPS coordinates of the GPS data, respectively. Since both coordinates are described in meters and the error for both coordinates are estimated to be in the order of 0.1 meters, we have used $\sigma_{\mathrm{Model}} = \sigma_{\mathrm{GPS}} = 0.1$. We then calculate θ_{center} from $\boldsymbol{c}_{\mathrm{Model}}$ using the affine transformation obtained from the noisy data. We repeat this for 100 steps. Let $\theta_{\mathrm{center},i}, i = 1, 2, \cdots, N_{\mathrm{trials}}$ be the values of θ_{center} for each trial. We then evaluate the error of our method θerror by the standard deviation of θ_{center}:

$$\theta_{\mathrm{error}} := \sqrt{\sum_{i=1}^{N_{\mathrm{trials}}} (\theta_{\mathrm{center},i} - \bar{\theta}_{\mathrm{center}})^2} \tag{6}$$

$$\bar{\theta}_{\mathrm{center}} := \frac{1}{N_{\mathrm{trials}}} \sum_{i=1}^{N_{\mathrm{trials}}} \theta_{\mathrm{center},i} \tag{7}$$

As a result, the error θ_{error} for Preah Vihear Temple was calculated as 1.4 degrees.

5 DISCUSSIONS

In the previous section, we have determined the direction of the central axis of Preah Vihear Temple based on the point-cloud data and reference points. In this section, we will focus on Khmer temples mainly built during the Angkor Dynasty, and examine their locations and spatial relationships. Table 3 shows those temples considered in this section. These temples, all registered as the UNESCO world heritage sites, are now scattered around the Kingdom of Cambodia and Neighboring Laos, Thailand and Vietnam. Although their construction ages are roughly identified, we will not take into account of difference in construction durations, materials and architectural styles.

From the distribution of the direction of each temple wall, we have found that the Preah Vihear walls are tilted 3.9212 degrees with the error range of 1.4 degrees from the actual south direction. We consider the tilt to be within the range of technical errors at that time. Thus, we consider that the Preah Vihear Temple was built along the north-south line.

These results clearly reject the hypothesis that Preah Vihear Temple was built facing Angkor Wat Temple, since the line connecting to Angkor Wat Temple from Preah Vihear Temple has an angle of approximately 40 degrees from the north-south line.

Next, We will consider the spatial arrangement of Khmer temples based on this direction. We will consider two conjectures: lines drawn every 15 degrees and 40 degrees from the Preah Vihear Temple.

The first conjecture is for that the temples are located in 24 directions. The Chinese 24 solar term is a Chinese calendar to divide one year into 24 seasons according to positions of the sun. Figure 10a shows the results of the case that lines drawn radially every 15 degrees, thus dividing the plane into 24 angular directions, from the Preah Vihear Temple as the center based on its axial direction. Markers indicate the locations of important Khmer temples. Only some important Khmer temples are located on these lines.

Another conjecture is to draw nine lines around the temple. The line connecting Preah Vihear Temple and Angkor Wat Temple, the most important temple of the Angkor Dynasty form 40 degree with respect to Preah Vihear main north-south axis. Dividing 360 degrees by 40 degrees is nine. Figure 10 shows these nine lines. Again, only some important Khmer temples are located on these lines.

Table 4 summarizes the angular displacement of the actual spatial distributions from these radial lines drawn from the Preah Vihear Temple. The "closest axis" column shows the radial line that has the smallest angular displacement from the temple. The central axis of Preah Vihear has index zero, and the indices for the lines on the clockwise direction are decremented by 1, and the indices for the lines on the counterclockwise direction are incremented by 1.

6 CONCLUSION

This paper has described the point-cloud data of Preah Vihear Temple as well as the details of the methods used for data collection. While it is possible to acquire 3D digital data of tangible cultural properties by using existing sensors and software, for large buildings such as Preah Vihear Temple, which is located near a cliff, there are locations where these existing methods are difficult to apply directly, arising the need for various specialized schemes for this task. For the first time in the world, we have succeeded in acquiring 3D digital data of the entire Preah Vihear Temple through research and development from both hardware and software perspectives. As an example of the application of the obtained 3D data, we have examined a Cambodian legend that Preah Vihear Temple was built as the guardian temple of Angkor dynasty, facing important temples of Angkor Dynasty, in particular Angkor Wat. In order to determine the axis direction of this temple, we analyzed the point-cloud data and GPS measurement data. From the results of the analysis, we have found that the axis direction of Preah Vihear is not facing the Angkor Wat within the bounds of the construction skills of that era. We have also provided a hypothetical interpretation that the underlying intention of the orientation of Preah Vihear Temple may be based on the positional relationship between the archaeological sites near Cambodia.

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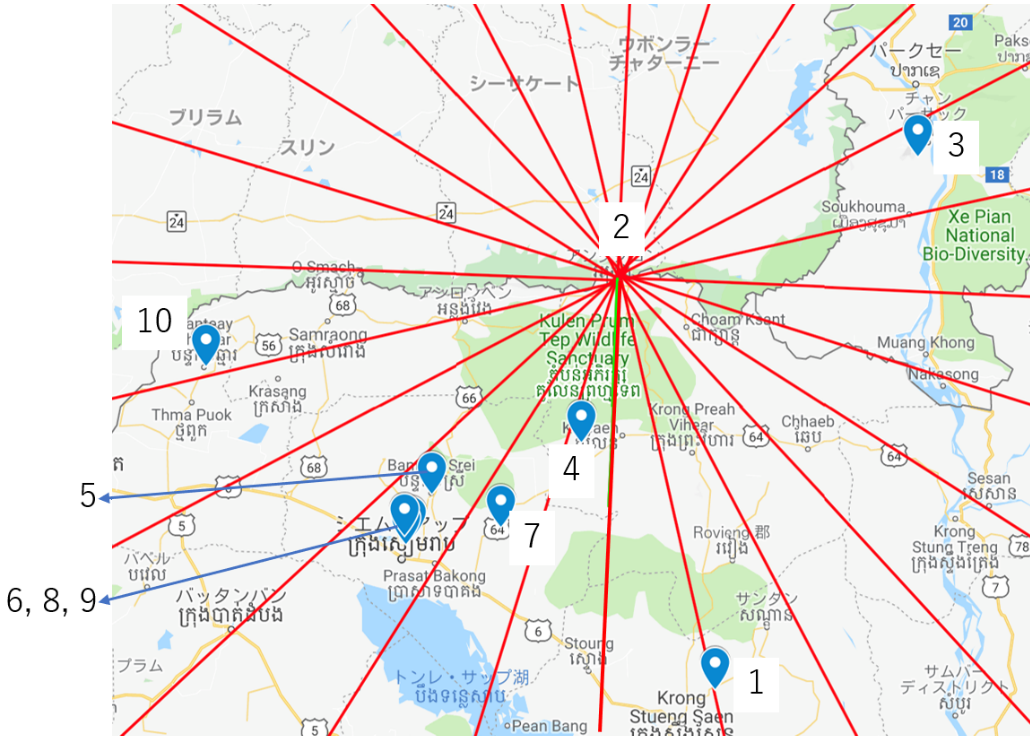
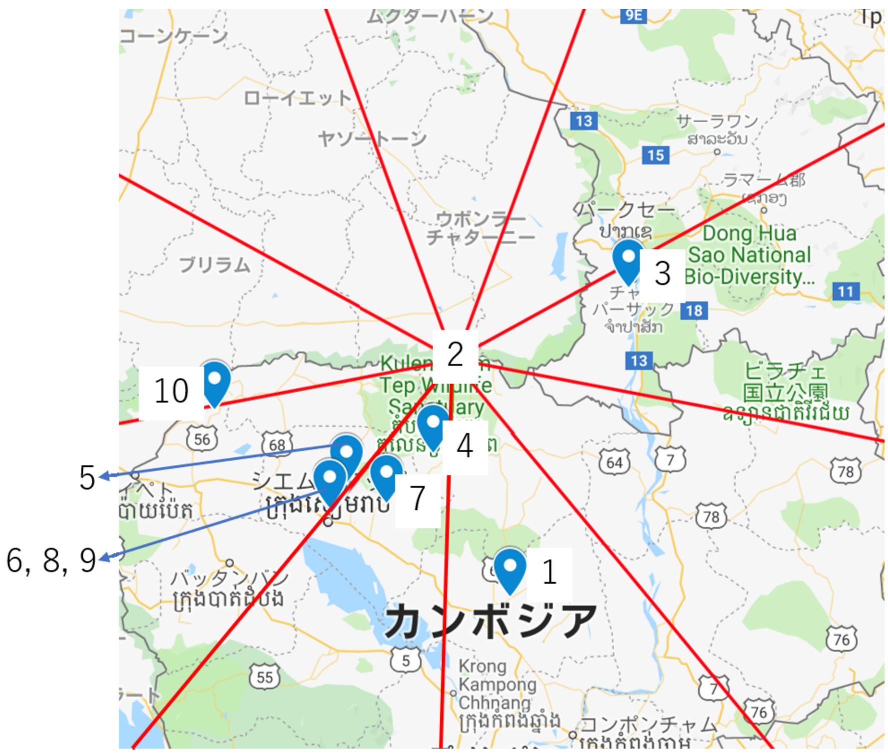


(a) A hypothetical interpretation of the spatial arrangement of the archaeological sites, with 24 divisions. Map referenced from Google My Maps. Best viewed in color.



(b) A hypothetical interpretation of the spatial arrangement of the archaeological sites, with 9 divisions. Map referenced from Google My Maps. Best viewed in color.

Figure 10: A hypothetical interpretation of the spatial arrangement of the archaeological sites, with 18 divisions and 24 divisions. Map referenced from Google My Maps. Best viewed in color.

Table 2: The normal directions and weights of each walls, determined from PCA. The "Displacement" column shows the displacement from the true southern direction in degrees.

Wall Number	Normal Direction (Model Coordinates)			Weights	Displacement (deg.)
	x	y	z		
1	0.60951	0.79278	-0.00232	115.26	-3.6153
2	0.59604	0.76775	-0.23516	116.97	-4.5044
3	0.60198	0.79841	-0.01299	48.656	-3.1161
4	0.61445	0.78856	-0.02497	60.161	-4.0434
5	-0.73963	0.58107	0.33957	1.4112	-3.1176
Weighted Average					-3.9212

Table 3: A list of temples that were considered in this paper. All the temples are UNESCO's World Heritage sites.

ID	Temple Name	Construction Period	Dynasty	Note
1	Sambor Prei Kuk	600-	Isanavarman I	The oldest site with an octagonal hall
2	Preah Vihear	890-1150	Suryavarman I/Suryavarman II	Has a north-south axis
3	Vat Phou	900-	Yasovarman I	Located in the southern area of Laos
4	Koh Ker	921-944	Jayavarman IV	Pyramid style
5	Banteay Srei	967-	Rajendravarman II/Jayavarman V	Oriental Mona Lisa
6	Bayon	1100-	Jayavarman VII	Referred to as the center of the universe
7	Beng Mealea	1100-	Suryavarman II	Referred to as East Angkor Wat
8	Angkor Wat	1113-1145	Suryavarman VII	The symbol of Cambodia
9	Ta Prohm	1186	Jarvarman VII	Buddhism to Hinduism, entangled by big trees
10	Banteay Chhmar	1100-1200	Jarvarman VII	Near the border of Thailand, thousand-armed Avalokiteshvara

Table 4: The list of displacements of each temple for each hypothetical interpretation. The "Angle" column shows the angle measured from the center line of Preah Vihear Temple, in degrees.

ID	Temple Name	Angle (deg.)	24 Divisions		9 Divisions	
			Displacement (deg.)	Closest Axis	Displacement (deg.)	Closest Axis
1	Sambor Prie Kuk	-74.671	0.32867	-5	5.3287	-2
3	Wat Phou	-35.696	5.6956	-2	4.3044	-1
4	Koh Ker	-9.6297	5.3703	-1	9.6297	0
5	Banteay Srei	-35.829	5.8287	-2	4.1713	-1
6	Bayon	17.367	2.367	1	17.367	0
7	Beng Mealiea	115.81	4.1859	8	4.1859	3
8	Angkor Wat	-22.344	7.3441	-1	17.656	-1
9	Ta Prohm	-38.266	6.7341	-3	1.7341	-1
10	Banteay Chhmar	-36.953	6.9526	-2	3.0474	-1
	Average displacement(deg.)		4.9785		6.2351	