Acquisition Evaluation on Outdoor Scanning for Archaeological Artifact Digitalization

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Abstract: Archaeological archives are important assets because they provide primary information resources for research, mainly digital archives that not degraded. Instead of directly visiting a site, an archaeologist can examine and manipulate the data without harming the real object. However, choosing an efficient scanning scheme with detailed results is a challenging task. In this work, we present new sculpture models obtained in three different ways and assess it in two comparison approaches: A quantitative and qualitative assessment. The quantitative comparison architecture provides a detailed assessment of three different scanning mechanisms in two stages: point cloud and mesh comparison. This evaluation is purposed to describe the differences between unmodified data. Finally, a qualitative evaluation is performed by an expert and practitioner to explain the difference based on four different produced models to help their needs in the real application.

1 INTRODUCTION

Archaeological archives should represent a real condition of the artifact, and it is a researchable resource generated by archaeological investigations. These archives are also the primary source of information to understanding any interpretations of published results. Furthermore, the data collection related to the records of all archaeological remains must be updated periodically(CIFA, 2014). Instead of a direct visit to sites, an archaeologist can examine the digital infrastructure from the data and manipulate it without harming the real object. However, the reconstruction becomes challenging due to environmental conditions, especially for artifacts located in an outdoor environment.

In the indoor environment, the lighting condition can be controlled to meet particular requirements. In the Michelangelo project (Levoy et al., 2000), the lighting from various directions around the statue is in the fixed distance. These setups are possible because the indoor environment usually is reachable and can be manipulated based on the requirement. On the other hand, several outdoor scanning approaches have been created to solve the reconstruction problem, such as Photogrammetry (Boehler and Marbs, 2004), Structured Light (Georgopoulos et al., 2010), and low-cost scanner (Gonzalez et al., 2013). However, these works are only focused on their specific problems.

Figure 1: Sculpture object.

We made a detailed comparison on point clouds, geometry, and completeness to understand the difference between the processes. Hence, several results

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from four different methods without any modifications (such as noise reduction, smoother, and hole filling) are used to keep their originality. The contribution of this paper is two-fold: First, a scanning of Indonesian sculptures in an outdoor environment that can be used by other archaeologists or scientists to study Indonesian culture to acknowledge the complexity of Indonesian sculptures. Second, a comparison of various ways of reconstruction, *i.e*., Photogrammetry, ASUS XTION, AICON Primescan Structural light scanner, and Single Image Reconstruction (SIR) to investigate the characteristics of the surface results in outdoor sculptures. In the final part, these results are given to an Indonesian archaeologist and qualitatively assessed based on the requirement on the real application.

2 RELATED WORKS

With the increasing demand for 3D spatial information in cultural heritage documentation, the techniques of obtaining it have been increasingly important. In particular, a point clouds with high accuracy and density are demanded to describe the detail information of object components (Lee et al., 2015). Many different devices have been used to build 3D models, with each system coming with its limitations, advantages, and costs. It should be noted that many restrictions are due to the properties of the various objects that are to be digitized. Between all the available sensors, methods, and platforms, the most suitable ones based on expert requirements should be chosen carefully(Remondino and Rizzi, 2010).

Figure 2: The outdoor scanning process of Structured Light Scanner to capture the sculpture.

In cultural heritage preservation, Photogrammetry and laser scanning have long played an essential role in archaeological research (Remondino and Rizzi, 2010). Photogrammetry, *i.e*., extracting information from a series of images, has long been used to record, measure, and model archaeological structures of different-size artifacts. An alternative to the most known and market-dominating laser scanners is Structured Light (Georgopoulos et al., 2010). A Structured Light 3D scanner projects a pattern of light on the object and detects the deformation of the pattern on it. The scanners are non-contact optical systems, similar to Photogrammetry; they transform image pairs to surface information. The main advantage of using this scanner is the faster speed compared to a typical laser scanner (Georgopoulos et al., 2010). However, a problem arises when the location of the sculpture is in an area that lacks electricity and unobstructed sunlight. Direct sunlight intensity has 2-5 orders of magnitude brighter than the projected structured light (Gupta et al., 2013), and it makes a distortion on the result. Therefore, the structured light method is rarely used for outdoor scanning. In Gupta's works (Gupta et al., 2013), they show that the reconstruction quality of an object placed outdoors degrades under intense ambient illumination, even when spectral filtering is used. However, the content of the artifact can still be seen, including the engraving reliefs in the objects. Based on this evidence, we include the Structured light method into one of our compared methods. On the other hand, a new approach called Single Image Reconstruction (SIR) recovering the geometric information from a single photograph or synthetic image. This method tried to infer the 3D shape of complex objects, given from one picture. Recent work in cultural heritage application, Pan *et al.* (Pan et al., 2018) uses Deep Learning to predict the depths in the relief images from Borobudur temple. However, the real problem with SIR in full 3D reconstruction remains the same, as it is shown from the one perspective.

3 DATA PREPARATION

Firstly, we investigate 3D data obtained from several scanning processes. This process is divided into two parts, which are quantitative and qualitative evaluations. Quantitative evaluation measures unprocessed data by finding the distance and differences. On the other hand, qualitative evaluation measures the effectiveness of the results on user experience. The qualitative and quantitative evaluation is described in the next subsection.

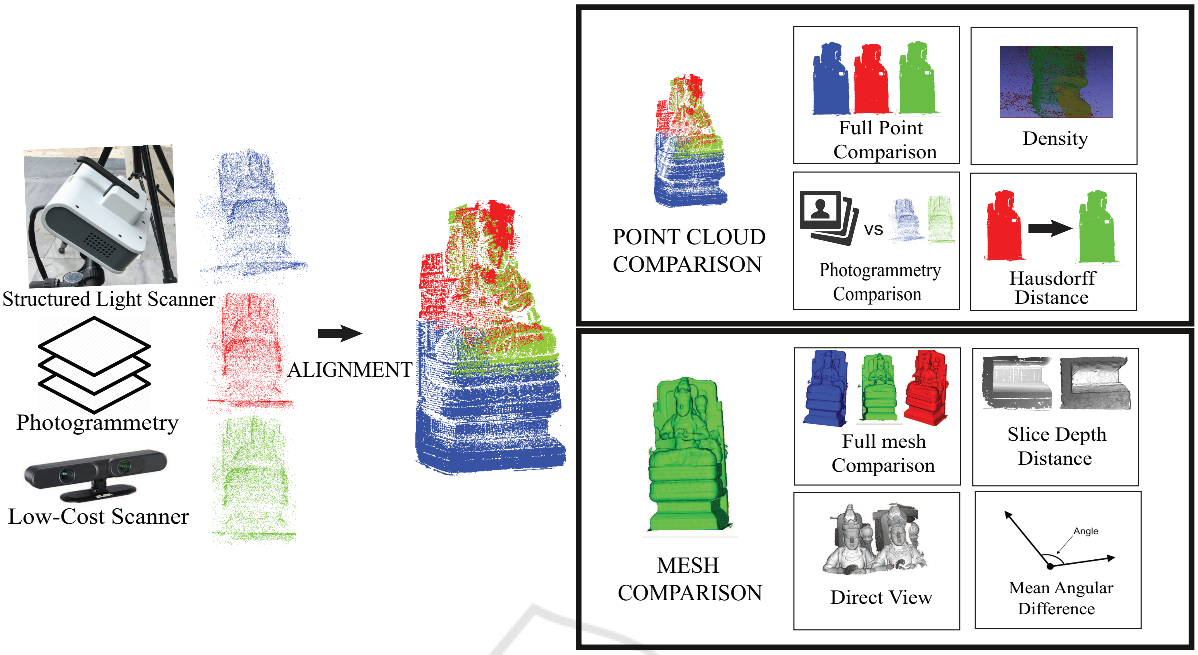

Figure 3: Quantitative Evaluation scheme.

3.1 Quantitative Evaluation

The sculpture scanned in this paper is an Indonesian Sculpture replica of Prajnaparamita Sculpture made from Candi Stone and located in the outdoor environment (see Figure 1). Candi stone, also known as Black Lava Stone, is a type of black basalt quarried in Indonesia. The scanning is done under direct sunlight, without a cloud, between 50.000 and 100.000 lux in illuminance. The four different processes used the following configuration:

- Structured Light Scanner. The scanner used is AICON Primescan with 2 x 8 Megapixel camera resolution, 28 Megapixel projection resolution, and a fixed 50 mm field of view. The distance between the object and the scanner is one meter, but the angle is variance. The whole process consisted of forty times of scanning from different angles (see Figure 2). After that, these chunks of scans are manually registered to obtain the complete point cloud of the statue.
- Photogrammetry. In this method, 48 RGB pictures with 3.024 x 4.032 resolution are taken from iPhone 7, covering all the sides of the statue. The pictures are taken randomly from different angles, yet still covering all areas of the statue (Figure 4). The photogrammetry process is performed using Agisoft using a high-density option. In qualitative evaluation, we used three different resolutions, i.e., 1.280 x 720 (720p), 1.920 x 1.080 (1080p), and 3.024 x 4.032 (4K).

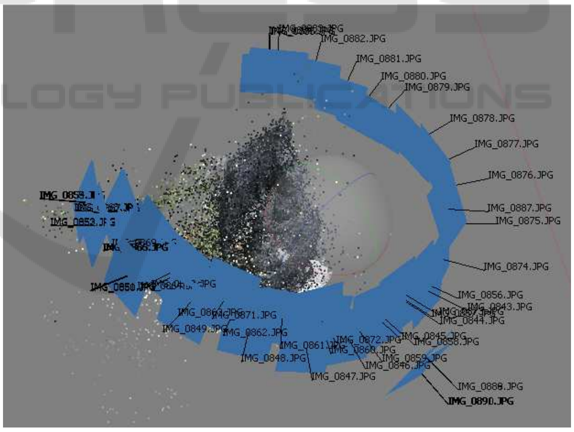

Figure 4: Photogrammetry setup of 48 images.

- Low-Cost Scanner. The low-cost scanner used in this paper is ASUS XTION Primesense. Based on Gonzalez's (Gonzalez et al., 2013) accuracy test, to get a 15mm accuracy, the distance between the scanning device and the object should be maintained in one meter. In this work, we follow the configuration on Gonzalez work, starting from one meter using freehand scanning. The process tried to capture a whole sculpture while maintaining the distance. The scanning process is performed in the Skanect application.

- Single Image Reconstruction. Single Image Reconstruction (SIR) approach used in this paper is a method in Pan *et al.*'s (Pan et al., 2018) with input 720p from frontal image data. Next, a pre-trained model from Eigen work (Eigen et al., 2014) is used to obtain the depth and point clouds. The number of the point cloud is the same number with a number of pixels in the depth image. Furthermore, the stochastic point-based rendering method is used to reconstructed point clouds to obtain the 3D model.

To be able to compare 3D models, the aligning process is needed. One of the most common ways to align 3D data onto one another is the Iterative Closest Point (ICP) algorithm by Besl and McKay in (Besl and McKay, 1992). This method minimizes the difference between two-point clouds by decreasing distances between them in every iteration. ICP algorithm is a widely popular solution and has been improved several times. The algorithm keeps iterating until it finds the minimum Mean Square Difference (MSD) while we fixed the iterative count parameter steadily at 100.

After the point clouds are aligned, it converted into a mesh using Poisson Reconstruction (Kazhdan et al., 2006). Poisson reconstruction is chosen because of the detailed result by combining the benefits of both global and local fitting schemes. The purpose of this conversion is to investigate the surface produced from point cloud by each method. Since this part of the work is focusing on investigating the surface alone, the comparison is only made to the scanned surface, ignoring the hole. There are three methods used in this paper to evaluate the quality of the surface: Visual, Depth Distance, and Mean Angular Difference. Different parts of the statue give different errors and complexity. Therefore, in order to achieve a fair comparison, the sculpture is sliced into eleven smaller pieces (see Figure 5), and the differences between each part are investigated separately.

Different level of depth is a problem, especially when comparing the 3D models from different scanning processes. To overcome that problem, In Figure 6, it can be seen that a ground plane is used as a basis for zero values depth, where the camera direction is orthogonal from the surface of this plane. Based on the visual result, it is decided to use a structured light mesh model to find the plane, and the other meshes (Photogrammetry and Low-cost scanner) are aligned to this chosen one. This plane is obtained by performing RANSAC shape finder from (Yang and Förstner, 2010). After all meshes are aligned, then the depth value is measured. Using this obtained depth value, we obtained the surface normal by calculating the normal using the basis plane. Afterward, based on Ackermann and Goesele's work,(Ackermann and Goesele, 2015), the Mean Angular Difference (MAD) is calculated by finding the mean difference value. In the next section, a result comparison of three different meshes, *i.e.* Structured Light Scanner (SLS), Photogrammetry(PH), and Low-cost Scanner(LC) are presented.

Figure 5: Slice configuration. The orange line is the border of a slice, thin box in the right and left means it is the right and left side of the mesh.

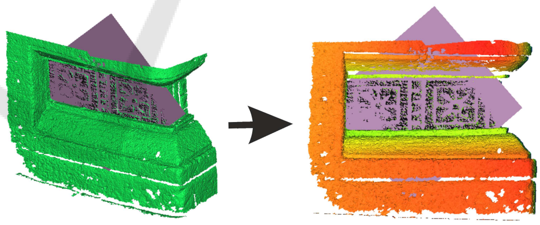

Figure 6: Left image: Mesh with with basis plane (rectangle) from RANSAC shape detector, Right image: Aligned mesh.

3.2 Qualitative Evaluation

In this section, the qualitative measure shows the difference of quality impact on archaeologist's works. Two parts of the evaluation process are conducted, which are the reconstruction process and result. Both the reconstruction process and the mesh model of six different results are randomly given to ten archaeologists and conduct a direct interview to assess it. The final result of this assessment is adaptability, flexibility, efficiency, and post-processing. From these examiners, five of them are an expert, and the others are practitioner and student. The expert consisted of lecturers at universities who deepened their knowledge about Indonesian artifacts and experts from Indonesian artifact observation centers. Also, the practitioner is field staff from the observation center and master students from the archaeologist department.

4 RESULTS

Based on Figure 3, the comparison step mainly consists of two parts: point clouds and mesh comparison. The point clouds comparison process mainly used the full, unprocessed point cloud and compared the results between them. There are four steps included in point cloud comparison, *i.e.*, full point cloud comparison, direct view, two-pair Photogrammetry, and Hausdorff distance. In mesh comparison, there are two parts of the process, full and slices comparison. The full-size part, there is a direct full mesh comparison using a direct view, slices direct view, slice depth distance, and mean angular difference. In the next section, all the results in each process is explained more detail.

4.1 Point Cloud Comparison

In our first investigation, we determine how well the Photogrammetry worked, including the minimum requirements for the photogrammetry algorithm. The data consists of 48 images, and neighboring pairs of images are created. We perform Photogrammetry on these pairs to obtaining the points clouds. From 48 images, we created eight neighboring image pairs and an 8-point cloud to be compared with structured light mesh and low-cost scanner results. The numbers in each pair name are the image numbers; for example, pair1-2 refers to the pairing of images 1 and 2. In this experiment, pair1-2 and pair3-4 are used for the bottom-left side of the statue, pair3-4 is used for the upper-left side, pair14-15 and pair15-16 are used to check the bottom-front side, pair17-18 is used to check the upper-front side, pair33-34 is used to check the bottom-right side, and pair34-35 is used to check the upper-right side. In other words, two models are in close proximity by hand, then registered using ICP. Finally, all 48 images are aligned and compared with structured light and low-cost mesh. It can be seen in Table 1, that pair15-16 gives the highest Mean Squared Difference(MSD) and variance rather than the other. It can be concluded that the comparison at the top front part of the statue performs worse and more complicated surface than the other part.

Table 1: MSD two-pair point cloud of photogrammetry compared with SLS and LC in millimeter.

Config. Model	PH vs SLS (a)	PH vs LC (b)	Variance (a) || (b)
pair1-2	42.23	35.34	5.25||4.32
pair2-3	41.54	33.65	4.32||5.25
pair3-4	40.34	35.45	4.45||6.23
pair14-15	45.88	38.32	18.1||8.45
pair15-16	52.56	44.78	15.5||12.4
pair17-18	44.50	39.67	19.4||11.5
pair33-34	42.30	34.85	4.37||5.68
pair34-35	41.68	33.87	6.61||3.46
Max. Dist.	68.76	51.48	-
Average	43.88	36.99	-

Next, We perform Hausdorff distance comparison to determine the distance between point clouds. Table 2 shows the Hausdorff distance and MSD between three full sculpture point clouds. Based on this result, the distance between ST and LC is higher than the other. It proves that the gap between this performance is quite low compared with others. Another factor is because both methods directly scan the object; the noise produces in both processes is minimum. On the other hand, PH, have a noise from the background, which is not included in the other approaches. Because of that, it can be seen that both results in two comparison processes with PH is higher than SLS vs. LC.

Table 2: Comparison results of Hausdorff Distance (H) and MSD in full point cloud against Structured Light Scanner (SLS) in millimeter.

Configuration	SLS vs. LC	SLS vs. PH
Full(H)	4.88	28.7
Full(MSD)	2.41	16.0
Variance (MSD)	0.32	6.85
Max. Dist. (MSD)	2.71	18.3

In density comparison, two sets of point clouds have a close Hausdorff distance if every point of each set is proximate to the other set. Differences in density are depicted in Figure 7, where the structured light shows the highest density compared to the other two. On the other hand, because of the usage of background in the image, the Photogrammetry's point clouds is sparser than other results.

4.2 Mesh Comparison

In this section, fully connected point clouds, called meshes, are used for comparison. Connecting point clouds using Poisson Reconstruction created these

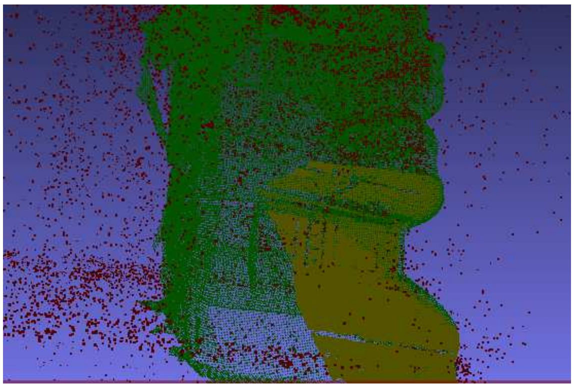

Figure 7: Point cloud density comparison. Red is Photogrametry, Green is Low-cost scanner, and Yellow is Structured light scanner.

meshes. The result of surface reconstruction can be seen in Figure 8. Structured light gives the highest level of detail, followed by Photogrammetry with 4k resolution and low-cost scanner.

Figure 8: Direct view comparison of three different mesh. Left: low-cost scanner, middle: photogrammetry, right: structured light.

In the next experiment, to know the distance between the two depth images, Euclidean Distance is used to measure the performance. As shown in Table 2, Slice 5 has a higher value than average in all distance comparisons. However, some have more difference values than others because of the different levels of difficulty in reconstructing each part of the statue. The geometrical quality of the mesh can change the DD and MAD results. It is proved that different parts can produce different performance results based on how detailed the meshes are.

4.3 Qualitative Result

In this section, all the processes are evaluated based on two parts. First is the effectiveness of the scanning process, and the second is the quality of the results. For the effectiveness, we implement a parameter for the adaptability, flexibility, time efficiency (Georgopoulos and Stathopoulou, 2017), in the assessment. For the result, examiners are invited to fill the evaluation. The variation engraved in the sculpture surface itself plays a significant role for the archaeologist to understand the content in a 3D surface engraved in the sculpture. Especially in Indonesian sculpture, the usage of specific parts, i. e. crown, necklace, and other accessories can determine the story or even the construction time of the reliefs. On the Barcelo work (Barceló, 2014), to understand the surface characteristic, several parameters need to be seen in the surface model, i.e., roughness, shape, and waviness.

Table 3: Results of Depth Distance (DD) using Euclidean Distance and Mean Angular Difference (MAD) from three different comparisons : SLS , PH, and LC using eleven slices (in mm).

Configuration	ST vs. LC	ST vs. PH
Slice1 (DD)	215.66	266.34
Slice2 (DD)	273.32	417.50
Slice3 (DD)	326.59	398.09
Slice4 (DD)	309.37	399.09
Slice5 (DD)	339.75	435.78
Slice6 (DD)	274.37	283.49
Slice7 (DD)	202.09	273.68
Slice8 (DD)	220.56	621.74
Slice9 (DD)	194.29	304.04
Slice10 (DD)	201.43	319.68
Slice11 (DD)	295.71	352.04
Slice1(MAD)	29.57	12.43
Slice2(MAD)	27.34	10.71
Slice3(MAD)	30.79	10.77
Slice4(MAD)	45.92	19.36
Slice5(MAD)	24.96	9.56
Slice6(MAD)	22.33	9.51
Slice7(MAD)	22.13	8.76
Slice8(MAD)	24.36	9.91
Slice9(MAD)	23.84	10.65
Slice10(MAD)	23.30	10.71
Slice11(MAD)	28.24	13.92
Variance(MAD)	2.35	4.32
Max. Dist.(MAD)	29.54	13.43

Overall, based on Table 4, the Photogrammetry gives enough adaptability, flexibility to be established in an outdoor area. The problem in using Photogrammetry is the homogeneous object with minimum variation in color and shape. Based on the obtained model, the photogrammetry result has all the major components, such as the body, hand, crown, and necklace. Based on that, the style of the sculpture can be determined. Furthermore, the main shape of the accessories, the action of the sculpture, can be seen clearly. The relief detail on the surface cannot be used to determine the material due to the lack of roughness, but the waviness can is depicted on the surface. Based on that observation, it is best to use Photogrammetry on outdoor artifact at noontime based on the adapt-

Table 4: Qualitative Evaluation. Higher ✓means is better choice (Adaptability, Flexibility, Efficiency, and Post-processing) and easy to determine the main feature of the object(Main parts and Relief detail).

Scanning method	Adaptability	Flexibility	Efficiency	Post-Processing	Main parts	Relief detail
PH(720p)	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓✓	✓✓✓
PH (1080p)	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓✓	✓✓✓
PH (4k)	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓✓	✓✓✓✓
SL	✓	✓	✓✓	✓✓	✓✓✓✓✓	✓✓✓✓✓
LS	✓✓✓	✓✓✓✓	✓✓✓✓	-	✓✓✓✓	✓✓
SIR	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	-	✓✓	✓✓

ability, flexibility, and efficiency results. Also, it can be seen that a higher resolution on the input gives better performance on detail reconstruction.

On the other hand, Structured Light Scanner lacks adaptability, flexibility, and efficiency. Based on Georgopoulos's review, (Georgopoulos et al., 2010), they show the difficulties to set up the laser scanner because of the need of AC electricity, the flexibility is limited by the power source and cable length. This scanner is also sensitive to light. Because of that, positioning from the object, and the direction of scan taking are very much considered. There are 40 scans done in the sculpture, and after that, manual registering is needed to complete the model. Contrary to the scanning process, which is rather complicated, the result of SLS gives promising detail in the surface models. The surface has the roughness from the material and the waviness of the depth. This method is fit to be used in the adequate size of an artifact with a power source nearby. This scanning process is also proven to be used in an outdoor environment at noontime with excellent results. The third acquisition process is a low-cost scanning. Different from SLS, the ASUS XTION scanner requires power from the USB port directly from the computer. The process of scanning is almost real-time and gives output directly. Because of the portability, this scanner is easy to use in the outdoor environment. Regarding the results, it lacks the roughness, and waviness makes the detail on the crown and necklace cannot be examined. In this quality level, based on (Zatzarinni et al., 2009), (Tal, 2014), also with an observation on the model from the examiner, this quality can be used as a base surface besides of textured 2D images to understand the surface detail. The last reconstruction method is SIR applied from (Eigen et al., 2014). The input is sliced into a 304x228 resolution patch and trained using registered image and depth from one perspective. Based on the examiner, the adaptability and flexibility using this method are better than any other methods. Similar to the Low-Cost Scanner result, the depth information obtained from SIR can help to determine the shape and pose. The major drawback of using SIR is created from one perspective. Hence, this approach is the best to be used for 2.5D plane artifacts, such as relief in-wall.

5 CONCLUSION

A comparison of scanning models using three different acquisition methods for quantitative evaluation and four methods for qualitative evaluation is presented. In this paper, the acquisition process, efficiency, and the perspective from the user perspective are assesed. Firstly, quantitative measurement is conducted. Two sub-architectures are established to know the differences in point cloud obtained and mesh model. However, most data preparation are needed to be completed using a manual approach. Moreover, after the data are collected, the post-processing of structured light registration is done by the human hand. After the data are ready, they are compared to know the quality of the result between three different scanning processes. Using these results of the comparison, archaeologists can understand differences in performance and use this as the basis for choosing the best method. On the other acquisition, Photogrammetry gives an excellent performance; however, much noise is produced through the process. It is because the background is not removed. It is also possible that the shape complexity and the position where the data is taken can disrupt the scanning process. Because of that, it makes the preparation must be prepared carefully. Based on our investigation, this problem can be solved by taking close-range Photogrammetry. In the third approach, the result of a low-cost scanner is presented. Overall, these results give the best efficiency, and it can be used to reconstruct 2.5D models. This reconstruction can be used on Indonesian sculpture, relief, and temple since all of them have similar shape properties. What makes it different between them is the number of scans or data used to create the models.

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