Historical Building 3D Reconstruction for a Virtual Reality-based Documentation

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***Abstract*—An innovative preservation approach was proposed to document historical buildings in 3D model, and to present it virtually. The approach was applied to the Lawang Sewu building, one of the architectural masterpieces that is part of Indonesian history. Virtual Reality (VR) technology was used to create a Lawang Sewu VR application program that allows users to virtually walk around the building. A new method for 3D reconstruction was proposed, where data of photo, video and miniature documentation, as well as notes collected from observations were used as the main reference. Meanwhile, architectural record data was used in cases where information cannot be obtained through the main reference. The proposed method focuses on traditional techniques, both at the data acquisition and 3D modelling stages. Poly modelling techniques were chosen for 3D reconstruction. The poly modelling technique was chosen based on its ease and flexibility in controlling the number of polys in 3D models, and was suitable to be applied for repetitive spatial typologies, such as the Lawang Sewu building. After given textures, the 3D model was sent to the VR editor. In addition of running on the desktop platform, Head Mounted Device (HMD) that supports the creation of an immersive experience, was also chosen to run the Lawang Sewu VR. The evaluation carried out to measure the level of similarity of the 3D model to the original building and the sensation of an immersive experience felt by the user shows good achievements.**

Keywords*—Virtual reality; immersive presentation; 3D reconstruction; historical heritage building preservation

I. Introduction

Lawang Sewu is a historic building that became one of the markers of the city of Semarang, Central Java, Indonesia. This building is the work of the famous Dutch architect, C. Citroen from the J.F. Firm. Klinkhamer and B.J. Quendag in 1903 and completed in 1907 for the headquarters of the Dutch colonial railway company, or Nederlandsch Indishe Spoorweg Naatschappij. The Lawang Sewu building was designed to have a lot of windows and doors as an air circulation system, and this is where the term Lawang Sewu, which in Javanese means a thousand doors, came from. The Lawang Sewu complex which stands on an area of about 18,232 square meters consists of five buildings, which are buildings A, B, C, D, E, and lavatory. Fig. 1 shows the photo collection of the Lawang Sewu building.

An innovative approach was proposed to support the preservation of the Lawang Sewu building as an architectural masterpiece which is currently functioning as a tourist destination. The proposed approach allows users who have not had the opportunity to visit the Lawang Sewu building can see the architectural details of the building virtually. VR technology based on 3D reconstruction was proposed to create a Virtual Lawang Sewu program application that can document architectural details of buildings in 3D format. Therefore, users can walk around the building virtually. VR is an immersive technology that allows users to interact subjectively with the virtual world so that they can feel the sensation of their physical present. VR is an environment that is displayed in the form of media that is able to create a sensation for users who seem to be physically in their surroundings [1], and 3D reconstruction techniques are developing rapidly to meet the needs of geometric 3D models for the film, game and virtual environment industries, such as works [2-5]. In this study, for the purpose of the documentation and virtual presentation, the Lawang Sewu building was reconstructed into a 3D model to be applied to VR applications that can be run in the desktop and HMD platforms. The main problem was to reconstruct the building into a 3D model as precisely as possible. In order to maintain the number of polys in the 3D model, traditional 3D modelling techniques was chosen to create the 3D model. The technique has consequences for the process of selecting data sources and analyzing them, which are also carried out manually, such as carrying out careful photography sessions to obtain information from the building profile, or measuring every detail of the building profile directly or other approaches. After that, carry out an analysis of the information obtained to calculate the shape and size of the building. The proposed traditional 3D modeling technique can be used to reconstruct buildings into 3D models with precision.

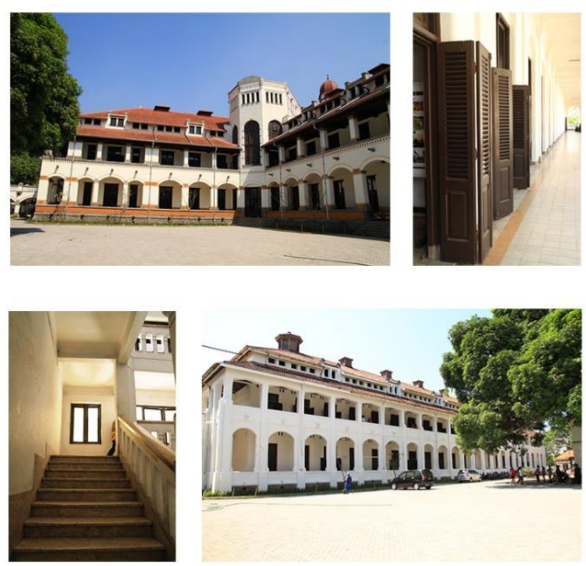

Fig. 1. The Lawang Sewu building.

The remainder of this paper is organized as follows: Section II discusses a review of some related work, Section III describes the proposed methodology which includes techniques in the data collection, techniques in the 3D reconstruction and 3D model texturing, VR programming, and evaluation. Section IV analyzes results. Section V covers the conclusion.

II. Related Work

There are various types of sensations of user presence in a virtual world (immersion), which are tactical to feel experience in carrying out tactical operations that require skill, strategic to feel mental challenges, narrative to feel being in a story, spatial to feel being in the real world, psychological to feel anxiety over the game with real life, and sensory to feel being in a unity of time and place based on the virtual environment [6]. VR consists of hardware components including computer sets, sensor embodiments (head mounted displays, binocular omni-orientation monitors, and monitors), process acceleration cards, tracking systems, input devices, and software components including 3D modelling software, graphics, audio, and virtual reality simulation [7].

3D reconstruction is one of the challenges in developing VR applications. The challenge in 3D reconstruction is to formulate the right method in creating a 3D model that is as close as possible to the original object [8]. 3D reconstruction research was conducted for building objects [9-10], underwater environments [1, 5], small objects [11], and other objects. 3D reconstruction can be grouped by time (time-based reconstruction). For example, 3D reconstruction that aims to visualize objects based on their current construction such as works [2-3, 12-15], and 3D reconstructions that aim to visualize objects that have been damaged into their intact form such as works [16]. Research on 3D reconstruction for the Coliseum building in Rome, Italy, was carried out by [17], and the Great Wall in China by [18]. Both studies used tourism photo data from the www.flikcr.com site. The Coliseum building model was generated from 2106 photos, while the Great Wall model was generated from 120 photos. Further, it was explained that the challenge of this research is matching and 3D reconstruction of information from hundreds or thousands of photos consisting of variations in perspective, illumination, weather, resolution, and others that have the potential for clutter and outliers. The real-time room environment reconstruction technique uses an octre-based surface representation for Kinect Fusion, where the space is represented as a signed distance function and stored as a uniform grid of voxels [18].

Technological developments have enabled VR application programs to be presented through stationary displays (desktop-VR or CAVE), head-based displays (HMD-VR or smartphone-VR), and Hand-based displays (Handheld VR) [9]. This supports the so-called Second Chance Tourism that utilizes digital technology, such as VR technology, which allows tourists to get the experience of visiting tourist sites without physically having to be on site [4]. On the other hand, the appearance of an attractive 3D model is one aspect of building the absorptive experience that the user gets, and the absorptive experience has an influence on the level of immersive felt by the user in a virtual environment [19]. Therefore, the use of VR technology for the preservation of cultural heritage needs to consider the design of attractive 3D models. Meanwhile, multi-experiential which includes learning and educational experiences, including emotional experiences, has become part of the existence of cultural heritage preservation [20]. Therefore, VR application programs also need to be designed to be able to provide various experiences for users while in a virtual environment.

III. Methodology

Workflow used in this study was designed based on eight challenges in developing the model of tangible 3D-based cultural heritage preservation identified by [8], which are time-based 3D reconstruction, typology, 3D reconstruction method, application category, research objective, data management, presentation method and research evaluation. Based on the time, there are two types of time in the 3D based preservation of historical objects, which are 3D reconstruction based on the current environment that uses data from the current condition of historical objects, and based on the past environment that uses data from historical objects that have been damaged, even extinct [8]. The proposed 3D reconstruction for the Lawang Sewu building referred to the current physical condition of the building, where the current physical data of the building was analyzed for use in its 3D modelling. Typological analysis was carried out to design data collection techniques based on the detailed characteristics of the building. Data was collected through: 1) direct observation by documenting the architectural details of the Lawang Sewu building in records, photos and videos; 2) the building miniature observation; 3) the building blueprint analysis. After determining the time-based 3D reconstruction method and performing typological analysis, the data management stage was carried out to design the data flow for the process before, after and during the 3D reconstruction. Based on the chosen time-based 3D Reconstruction, typology analysis, and data management design, traditional 3D modelling techniques was chosen to create the Lawang Sewu 3D model. The technique was chosen based on its ease and flexibility in controlling the number of polys in 3D modelling to reconstruct buildings with repetitive spatial typologies, such as the Lawang Sewu building.

In addition to measuring the physical building, a new method proposed to measure the area of the building in 3D reconstruction is to use the size of one of small elements of the building, and then count the number of the chosen element in a room. For example, given a tile chosen for the element to measure area of a room with a size of 30 x 30 cm; the length and width of the room uses 10 tiles; and the area of the room is 900 x 900 cm. The tile order index is also used to identify the position of other elements, such as doors, windows, poles. For example, given the door in a room, the door is in the order of tiles 4 to 7, so the door size is around 120 cm. The proposed method uses calculations based on the size of the element of the building that is the reference for measurement and its number. Moreover, the proposed method can facilitate texturing work, where the texturing process for building elements, such as tiles, can be appropriate based on the number of elements. On the other hand, there are building elements that still require size data based on architectural records, such as building height, or building elements that require physical measurements for comparison data or because their position is disconnected from the elements used as measurement references, such as poles in the building yard.

Accurate building size is not the target, because this 3D reconstruction project aims to document historical buildings for virtual presentation purposes. Therefore, visual similarity is the target, and not the accuracy of the building's size. Later, evaluation results show that this method is effective for 3D reconstruction which can create 3D objects with a size scale that is close to real objects. The workflow of the Lawang Sewu VR development consists of five stages, which are data collection, 3D reconstruction, 3D texturing, VR programming, and evaluation.

A. Data Collection

In addition to direct observation to the location of the Lawang Sewu building, the data sources used include a collection of photos, videos, miniatures and blueprints of the building. First of all, direct observation to the location was conducted in order to get a general picture of the environment, such as the layout, shape and structure of the building. Furthermore, an analysis of the building blueprint was carried out to sharpen the understanding of the building information from an architectural perspective. The building blueprint is displayed in one of the rooms used as a museum in the Lawang Sewu building. The building miniature which is also displayed in the museum was a medium to better understand the layout, shape, and structure of the building in a 3D perspective. Furthermore, photo and video sessions were conducted on every detail of the building, including physical measurements of the building. Physical measurements of buildings were not carried out on all building constructions, but on certain parts, such as doors, windows, stairs, tiles, and several other parts. Fig. 2 shows some blueprints of the Lawang Sewu building, while Fig. 3 shows the illustration of the miniature buildings.

All data sources were treated like puzzles in working on 3D reconstruction, where data serve to complement each other. The data acquisition method in 3D reconstruction proposed in this study adopts a puzzle game.

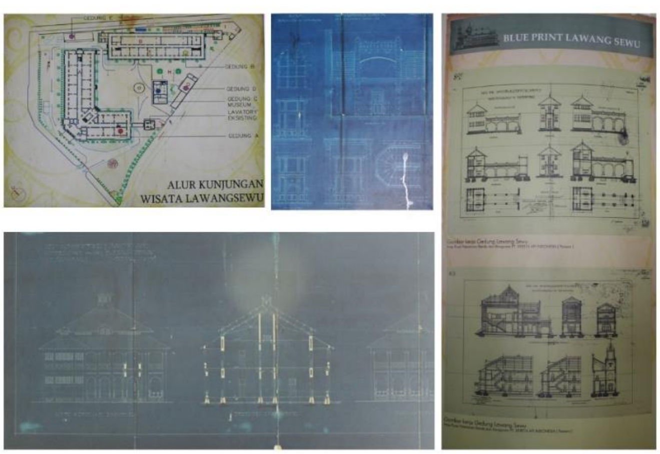

Fig. 2. Example of the blueprint of the Lawang Sewu building

Fig. 3. Example of the blueprint of the Lawang Sewu building

B. 3D Reconstruction

The Lawang Sewu building consists of buildings A, B, C, D, and E, including the basement which is located under building B. In this study, 3D reconstruction was targeted at the two main buildings, which are building A and B, including the Lavatory connected by a bridge to building A. The 3D reconstruction phase started from building B, continued with building A and Lavatory including the connecting bridge between them. Fig. 4 shows the layout of the Lawang Sewu building based on its blue print.

**the term GEDUNG in Indonesia means BUILDING,*

Fig. 4. The blueprint of the buildings.

Building B has a size of 22x77 m2 or an area of 4,145.21 m² with two main floors and one roof space. 3D reconstruction begun by identifying the size of the one room at the very end. The design of building B has a repeating pattern of rooms with almost all rooms being the same size. There are different sized rooms that are twice the size of the other rooms. The 3D reconstruction process in building B which consists of three floors was started from the first floor by identifying the size of the tiles and counting their number like cells in a matrix, where the number of cells in a row represents the width of the room, and the number of cells in a column represents the length of the room. Furthermore, as long as it is still accessible by hand, physical measurements of building elements were also carried out, such as the thickness of walls, the size of doors, windows, poles and stairs. In order to reduce the amount of poly, the ceiling of the room was not 3D reconstructed, but created using image textures from the original photo. Meanwhile, the height of the room was identified using architectural records data. After one room at the very end has been reconstructed in 3D, the process continues with the next room, and so on until the room at the other end. The method was also applied to obtain size, shape and layout data of other objects in the building. Fig. 5 shows illustration of using the size and number of tiles to identify the area of the room and the position of elements in it, while Fig. 6 shows example of an object that require physical measurement.

Fig. 5. Illustration of using the size and number of tiles to determine the area of the room and the position of the profiles in it.

Fig. 6. Example of an object that require physical measurement.

After obtaining the data and information of building B, the process continued with the creation of a 3D model of the building using the 3Ds Max application program. Stages in the process of making 3D models were carried out as in the stage of data acquisition for buildings. Starting from the very end of the room, then it was duplicated to complete the design of the first floor of building B, and continued with corridors and terraces. Other editing, such as merging two rooms into one room, and making stairs objects were carried out with the support of photo documentation data. After the first floor was completed, the 3D reconstruction was continued to the second and third floors using the same methods and techniques. Meanwhile the 3D reconstruction for the roof of the building was carried out using data obtained based on observations and analysis on the miniature building. Next was applying a cleaning process to remove unnecessary vertices and polygons.

Fig. 7. The comparison illustration between the original photo of building B and the 3D model of building B.

The cleaning process was performed to maintain the number of vertices and polys in the 3D model for its size does not swell and the application program can be lighter when being played. The cleaning process produced a 3D model of building B with a total of 75,209 polygons and a total of 107,619 vertices. Fig. 7 shows a comparison illustration between the original photo of building B and the 3D model of building B. Further, the 3D model of building B was used as a reference in the 3D reconstruction of building A.

Building B has a size of 22x77 m2 or an area of 4,145.21 m² with two main floors and one roof space. Building A is a three-story main building that has a shape like the letter L with an area of 5,473.28 m², and the floor of the office and lobby is tiled with a size of 16x16 m2. Meanwhile, the 2-story Lavatory has an area of 242.60 m². The same methods and techniques were applied in the 3D reconstruction of building A. The 3D reconstruction of the bridge connecting building A and Lavatory was carried out by continuing, or embedding, in the 3D model of building A. The wall of building B which is at the end of the building that connects to building A was used as the starting point.

Fig. 8. Comparison illustration between the original photo of building A and the 3D model of building A.

The cleaning process produced a 3D model of building A and the lavatory with a total of 67.068 polys and a total of 100.712 vertices. Fig. 8 shows a comparison illustration between the original photo of building B and the 3D model of building B. The 3D model of the Lawang Sewu building consisting of buildings A, B, and Lavatory produced has a poly count of 142,227 and a vertex of 208,331. Fig. 9 shows an illustration of the results of making the model.

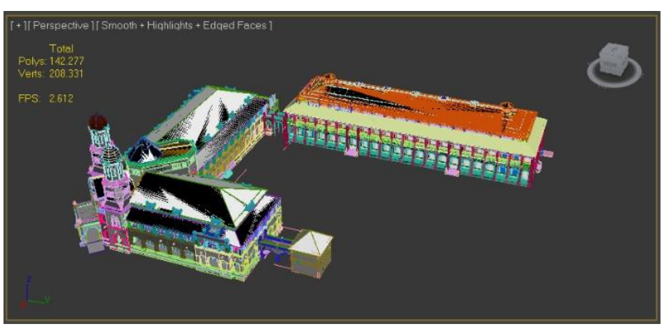

Fig. 9. A Results of the 3D model of the Lawang Sewu building consisting of buildings A, B, and Lavatory.

C. Texturing

The 3D texturing process was carried out using the Unwrap UVW modifier tool in 3Ds Max. The tool is for applying and controlling more than one texture on various parts of the object. First of all, the details of the surface of the real object were photographed. Furthermore, the 3D object is applied with the unwarp technique to produce a pattern of parts of the object in the form of an outline. The pattern image is saved in PNG format and sent to the Adobe Photoshop application program to be textured using a warp technique based on the photo details of the real object. Fig. 10 shows an illustration of an unwarp image resulted from the 3Ds Max application program which was then applied to the warp technique in the Adobe Photoshop application program using photo details of the real object.

The 3D texturing process was also carried out using the image texture mapping technique. This technique can keep the number of polygons from swelling in making 3D models more realistic and attractive, in which 3D objects are applied with color patterns [21]. Some objects, such as doors and windows, were manipulated using the image texture bump mapping technique. 3D models for doors and windows were formed using boxes, a primitive shape type, consisting of six polygons and eight vertices. Details of the original object profile were photographed, then edited using an image editor application program, Adobe Photoshop. Image of the object profile, then used to give texture to the object. Fig. 11 shows an illustration of the application of the image texture mapping technique to create a 3D door model. Details of the door profile, including the surface look realistic although it is built from a 3D box object consisting of a small number of polygons and vertices with a flat surface.

Fig. 10. Illustration of an unwarp image resulted from the 3Ds Max application program which was then applied to the warp technique in the Adobe Photoshop application program (a) using photo details of the real object (b).

Fig. 11. Illustrations of (a) that is the door profile image used in the image texture mapping implementation for a 3D box object (b).

D. VR Programming

The Lawang Sewu VR computer program was developed to run on the desktop and the HMD platforms with a consideration that desktop applications are still popular and widely used by users, while HMD-VR applications, although currently gaining popularity, not many users have the devices. A teleportation feature that allows users to change locations from building A to building B, or vice versa, including building floor selection is added to the Lawang Sewu VR. This feature makes it easy for users to get around the building virtually. The challenge in implementing 3D assets into the virtual environment presented through HMD is determining the proportion of users and 3D objects. The traditional technique was used by comparing the proportions of humans and objects in the real environment with the proportions of avatars and objects in the virtual environment through certain poses.

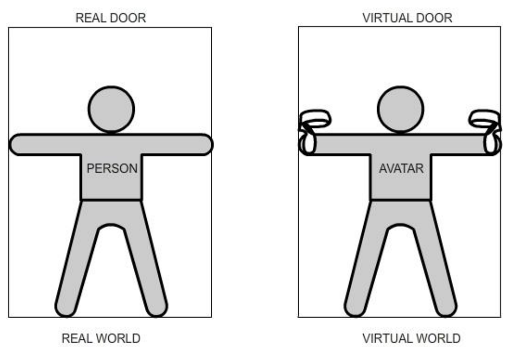

Fig. 12. Illustration of setting a 3D model scale to make it proportional to the original object.

In this case, a person was asked to pose with his arms stretched out in a door of the Lawang Sewu building in the real environment, and the pose was documented through photographs. After that, the person was asked to play Lawang Sewu VR using Oculus Quest 2, and pose in the same location as in the real world. Comparison of photos in the real environment and visualization of user games through casting were the benchmarks in scaling the 3D model so that it is proportional. Fig. 12 shows an illustration of setting a 3D model scale to make it proportional to the original object. Fig. 13 shows user's activities in playing the program using Oculus Quest 2.0, while Fig. 14 shows screenshots of the Lawang Sewu VR played in the desktop platform.

Fig. 13. Illustration of user's activities in playing the Lawang Sewu VR using Oculus Quest 2 HMD.

Fig. 14. Screenshots of the Lawang Sewu VR for desktop.

E. Evaluation

User acceptance test was carried out to measure the achievement of the goal of developing the Lawang Sewu VR computer program, which are documenting historical buildings and presenting them virtually using VR technology. The performance of the Lawang Sewu run in desktop-VR and HMD-VR platforms was measured by evaluating the level of visual similarity and the level of area proportionality between the 3D model of buildings and the original objects. An additional evaluation was carried out on the Lawang Sewu HMD-VR which was the level of immersion evaluation in order to measure the sensation of the user presence in the virtual environment of the Lawang Sewu building.

Respondents who work as tour guides were selected based on their profession in taking tourists every day to tour the Lawang Sewu building. They were assumed to have knowledge of the physics of the Lawang Sewu building. The other 15 respondents were those who had visited the Lawang Sewu building in the past month. Out of 30 respondents, 12 of them were women, and the rest were men. The youngest respondent was 11 years old and the oldest was 51 years old. Respondents were asked to rate the performance of the Lawang Sewu VR by providing opinions.

Results of the user acceptance test for each the Lawang Sewu run in desktop-VR and HMD-VR platforms were measured using the Mean Opinion Score (MOS) technique with the following formula, where R is the individual rating for the stimulus given by subject N:

$$\mathrm{MOS} = \frac{\sum_{n=1}^{N} R_n}{N} \quad (1)$$

Results of the calculation of the MOS value were converted to a range of values 0 - 1 representing bad performance, 1.1 - 2.4 representing poor performance, 2.5-3.4 representing good performance, and 3.5-4 representing excellent performance. The following are statements (S) judged for gaining opinions of users:

- S1: The 3D model of the Lawang Sewu building has a high level of visual similarity to the original building.
- S2: The 3D model of the Lawang Sewu building has a high degree of similarity in size proportion to the original building.
- S3: The sensation of being in the virtual environment of the Lawang Sewu building really feels like being in the original environment.

The user acceptance test was carried out in two sessions, where the first and second sessions were to provide opinions on the Lawang Sewu desktop-VR, and the Lawang Sewu HMD-VR, respectively. In the first session, each respondent was guided in playing the Lawang Sewu desktop-VR. After getting used to playing the application, each respondent was asked to play it by walking along the usual route for an unlimited duration. After the respondent completes the usual route taken virtually, respondents were asked to provide an opinion on the S1 and S2 statements in the range of values of 1-4 which represent Strongly Disagree, Disagree, Agree and Strongly Agree, on each statement based on their experience when playing the application. Meanwhile, the second session took place the next day. The evaluation mechanism was the same as in the first session, but in this session the respondents used the HMD device. In this session, respondents were asked to provide an opinion on the S1, S2, and S3 statements.

Evaluation in the first session that measured the Lawang Sewu desktop-VR performance resulted that out of 30 respondents, MOS scores for the statement S1 and S2 were 3.5, and 3.3. Meanwhile, evaluation in the second session that measured the Lawang Sewu HMD-VR performance resulted that out of 30 respondents, MOS scores for the statement S1, S2, and S3 were 3.5, 3.2, and 3.6, respectively. Table I and Table II show MOS results of the performance of the Lawang Sewu run in desktop-VR and HMD-VR, respectively.

TABLE I. MOS RESULTS OF THE LAWANG SEWU DESKTOP-VR

Statements	**Opinion Score**				**MOS Score**	
	1	**2**	**3**	**4**		
Visual Similarity (S1)	0	0	14	16	3.5	Good
Size Proportionality (S2)	0	0	22	8	3.3	Good

TABLE II. MOS RESULTS OF THE LAWANG SEWU HMD-VR

Statements	**Opinion Score**				**MOS Score**	
	1	**2**	**3**	**4**		
Visual Similarity (S1)	0	1	14	15	3.5	Excellent
Size Proportionality (S2)	2	3	13	12	3.2	Good
Immersion Level (S3)	0	1	11	18	3.6	Excellent

IV. RESULTS AND DISCUSSION

An application program based on VR technology was developed to document historical buildings and present them virtually. The application program called The Lawang Sewu VR documents the historic Lawang Sewu building located in Indonesia by reconstructing the building into a 3D model and providing a texture similar to the current condition of the building. Furthermore, the Lawang Sewu 3D Model was sent to the game engine editor to be developed into a VR-based application program that allows users to go around the Lawang Sewu building environment virtually. Desktop and HMD platforms were the targets for running The Lawang Sewu VR, considering that many users already have devices to play desktop-based applications, while HMD-based applications provide a strong immersive sensation.

Based on the typology of buildings that have repetitive patterns, data acquisition and 3D reconstruction were more focused on the use of traditional methods and poly modeling techniques. Photo and video data including architectural records obtained through direct observation were used as references for 3D reconstruction. Some of the data that cannot be obtained through observation were collected through the blue print of the building. The solution in the use of the poly modelling technique was proven to be able to control the number of polys and vertices in the details of the curve of the building in the 3D model of the Lawang Sewu building which includes buildings A, B and Lavatory. The development of the Lawang Sewu VR application program lasted three months which was divided into one month for data acquisition, one and a half months for 3D reconstruction, and half a month for VR programming. The 3D reconstruction phase involves the most human resources. Ten students from Universitas Dian Nuswantoro, were involved in this stage.

The achievement of the goal of documenting the Lawang Sewu building and presenting it virtually was measured based on the visual similarity and size proportionality of the 3D model to the real building. The traditional 3D modelling technique was conducted based on information obtained from carrying out careful photography sessions, measuring every detail of the building profile directly and the building blueprint analysis. The proposed 3D reconstruction technique is appropriate for building objects with profile and visual characteristics that have symmetry patterns that can be easily identified and measured, such as having tiles of the same size, the same distance between building pillars, or others. The proposed 3D modeling technique is proven to be able to appropriately reconstruct buildings with repetitive spatial typologies, such as the Lawang Sewu building. The user acceptance test measured using the MOS technique on the Lawang Sewu desktop-VR shows that both visual similarity and size proportionality reach a good level. Meanwhile, the visual similarity in the Lawang Sewu HMD-VR reached an excellent level, and size proportionality reached a good level. This achievement shows that the documentation of the Lawang Sewu building into a 3D model format with visuals and sizes that are close to real objects can be carried out well, and VR technology that supports users around the location virtually can perform well. Especially in the Lawang Sewu HMD-VR, the measurement of the immersive level, the sensation of the user's presence in the virtual world, can achieve an excellent MOS score. Although it still requires further testing, it can be assumed that in 3D reconstruction of historic buildings as assets in HMD-based VR application programs, the relationship between visual similarity and size proportionality has a significant role on the level of immersive perceived by the user. Through some light discussions after trying the Lawang Sewu HMD-VR, some users tried to compare the visuals and sizes of several building elements in a 3D model with real objects, such as doors, windows, stairs and others.

V. Conclusion and Future Work

The 3D reconstruction method and the use of VR technology proposed in this study are proven to be able to document historic buildings in 3D model format and present them virtually and interactively. However, the 3D reconstruction technique used in this research is appropriate for building objects with profile and visual characteristics that have repetitive spatial typologies, such as the Lawang Sewu building.

At this time, the functionality of the Lawang Sewu VR is still limited to documentation and virtual presentation of the physical building based on its current condition. The story telling functionality that is able to visualize the physical and historical conditions in the past is the target for further development, including the addition of a multi-user feature that allows more than one user to interact in a virtual Lawang Sewu environment.

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