3D RECONSTRUCTION OF THE FORT SANTIAGO DUNGEONS USING HANDHELD LASER SCANNING METHOD

P. L. Borrega*, Y. A. Felisilda, C. J. Sarmiento, A. Tamondong

Department of Geodetic Engineering, University of the Philippines Diliman, Quezon City, Philippines - (pmborrega, yefelisilda, cssarmiento, amtamondong)@up.edu.ph

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ABSTRACT:

The preservation of Cultural Heritage sites is an inherent responsibility of the citizens of a country. To this end, developments in digitization serve as a permanent way of preserving a site at its optimum state, and the creation of accurate 3D models becomes a repository of measurements for future reconstruction. Thus, in this study, the Fort Santiago Dungeons, a popular Cultural Heritage site in the Philippines, was 3D-reconstructed using the GeoSLAM ZEB Revo RT, a handheld Light Detection and Ranging (LiDAR) scanner that uses a Simultaneous Localization and Mapping (SLAM) Algorithm. With it, dense point clouds were produced with acceptable results in terms of colorization using the ZEB-CAM accessory, completeness, and measurement noise. This trend extended to quantitative evaluations of the dense point clouds of different formats (LAS and PLY) and colorization settings, as the Root Mean Square Errors (RMSE) against corresponding ground measurements were 0.734cm and 0.739cm for the Non-colorized, and 1.308cm and 1.312cm for Colorized, respectively. Likewise, the derived mesh files gave similar RMSEs with the Non-colorized at 1.044cm (LAS) and 0.999cm (PLY); and with the Colorized at 1.339cm (LAS) and 1.326cm (PLY). Overall, results showed that the mesh file derived from PLY dense point cloud exceeded the other format - as the dungeon's interior was better represented. Nonetheless, even though there were differences in the RMSEs of the measurements, due to factors such as the number of points and the processing itself, all are within the 5cm threshold to be considered useful in the event of reconstruction.

1. INTRODUCTION

1.Background

Cultural Heritage (CH) consists of tangible artifacts, and intangible attributes of a group or culture, that have been passed down through the years, safeguarded in the present, and entrusted to future generations (UNESCO Framework for Cultural Statistics, 2009). As of 2020, the National Historical Commission of the Philippines (NHCP) listed a total of 202 sites and structures declared as National Historical Landmarks, Shrines, Monuments, Heritage Zone/Centers, and Heritage Houses (Philippine National Volunteer Service Coordinating Agency, 2020). Among these is Fort Santiago located in Intramuros, Manila which served as the administrative hub of the colonial government during the Spanish Period (1521-1898). One notable facility of this fort is its dungeons which was first constructed in 1592 to originally house weapons during the Spanish conquest. Eventually, a new artillery storage location was built, and this chamber was converted into jail cells (Limos ,2020). In the aftermath of World War 2, Cruz (2022) described that an estimated 600 corpses were found inside it when the Japanese occupation ended.

Historical sites such as this deserve to be protected because they represent significant moments in our history that shaped the country and influenced where it is headed today (Korostelina, 2019; Nilson & Thorell, 2018). Conservation has however proven to be a challenge as the Philippines is susceptible to natural disasters such as typhoons, earthquakes, and volcanic eruptions (Miller, 2021). An example of this was the magnitude 7.3 earthquake that struck Northern Luzon last July 27, 2022, that damaged the facade of the UNESCO World Heritage-listed Vigan Cathedral, and the structure of the Bantay Bell Tower, which showed the vulnerability of CH sites to both outdoor and indoor damages (Sadongdong, 2022).

* Corresponding author

To this end, the utilization of 3D Digital Modeling techniques provides a compelling solution for recording their geometric information (Pepe et al., 2022). As for the specific methods to be used, the conventional static Terrestrial Laser Scanner (TLS) has its limitations as it is not efficient for every setting such as mapping indoor environments. Thus, promising alternatives that emerged in recent years such as Mobile Mapping Systems (MMS) that utilize a Simultaneous Localization and Mapping (SLAM) algorithm (Maboudi et al., 2018) can be used.

1.2. Rationale

This research focused on the testing of the GeoSLAM Zeb Revo RT, a handheld MMS (that utilizes SLAM), to obtain data for the creation of a 3D model of the Fort Santiago Dungeons, a popular Cultural Heritage site in the country. The findings of this study may then provide a good benchmark for modern Landmark Conservation and may serve as a reference for future researchers who aims to expand the use and scope of using 3D scanning methods to further similar objectives.

1.3. Research Objectives

The main goal of this study is to analyze, both quantitatively and qualitatively, the 3D Indoor Reconstruction of a Cultural Heritage Site using Handheld Laser Scanning Method. Specifically, it aimed to:

a) To reconstruct the Fort Santiago Dungeons using Simultaneous Localization and Mapping (SLAM) and compare the eventual 3D models created.
b) To evaluate the quality of the Dense Point Cloud in terms of colorization using the ZEB-CAM accessory, completeness, and measurement noise in consideration of the conditions of the dungeons.

c) To assess the accuracy of the dimensions of the Dense Point Cloud and 3D models against discrete ground measurements such as room dimensions and wall thickness.

1.4. Scope and Limitations

The output 3D scans are dependent on the specifications of the GeoSLAM ZEB Revo RT 2017 and the ZEB-CAM accessory used. Additionally, the succeeding products were subjected to Model-based evaluations instead of the conventional cloud-to-cloud comparison, as reference data from static lidar instruments would be unavailable as they are impractical to use considering the layout of the site.

2. METHODOLOGY

2.1 Study Site Preliminary Survey

The study area, officially named the Dungeon of Baluarte de Santa Barbara, is located inside Fort Santiago at Intramuros, Manila (as seen in Figure 1). This fort is located along Pasig River and near the opening to Manila Bay.

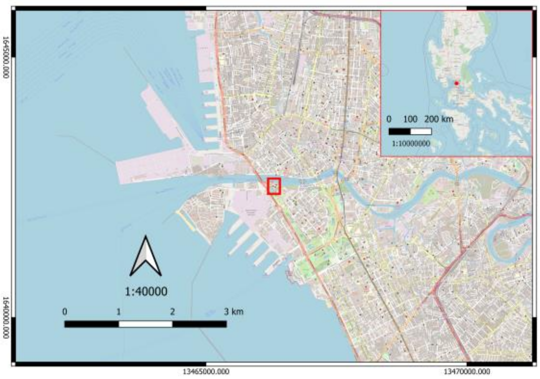

Figure 1. Inset map of Fort Santiago at Intramuros, Manila

In recent years, the dungeons have been accessible to the public as a tourist attraction (Limos, 2020) that is accessed via the entrance shown in Figure 2.

Figure 2. Dungeon Entrance

The exploration of the interior of the study area led to the creation of an initial trajectory map that is aligned with the requirements of using SLAM, as shown in Figure 3.

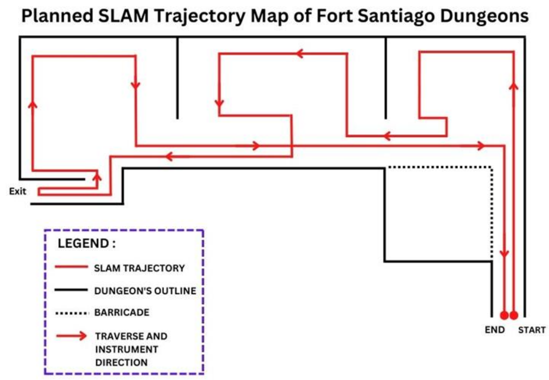

Figure 3. Initial Trajectory

Sammartano and Spanò (2018) noted that the local environment setup should be considered while planning the trajectory and loops, as the SLAM system was centered on the iterative alignment of extracted profiles based on the space's distinguishing properties. Thus, it can be noticed that there are several loops included in the plan to maximize exposure of the surfaces and that the overall path starts and ends at the same spot.

2.2 Instrument Preparation

The equipment used to acquire 3D information on the study area was the 2017 GeoSLAM ZEB-REVO. The setup mainly involves connecting the ZEB-REVO handheld laser scanner to the ZEB-DL2600 data logger using the provided main cable as shown in Figure 4. This also serves as a connection to the power source.

Figure 4. GeoSLAM ZEB-REVO & ZEB-CAM set-up for data acquisition

The ZEB-REVO (left of the set-up) is equipped with a 2D time-of-flight laser range scanner that is connected to an Inertial Measurement Unit (IMU) and is mounted on a motor drive. At the start of data acquisition, the motor would spin providing the third dimension needed to acquire 3D information.

Included in the data collected were the laser scan data and IMU data that served as the input for GeoSLAM's algorithm which generated the 3D point cloud. The specifications of the laser as indicated in its manual are shown in Table 1.

Maximum range	Up to 30m in optimal conditions Typical max range 15-20m
Points per scan line	432 (0.625o interval)
Field of view	270° x 360°
Scan rate	100 lines/s 43200 points/s
Scan range noise	±30mm
Laser safety classification	CLASS I Laser Product (21 CFR 1040.10 and 1040.11)
Laser wavelength	905nm
Operating conditions	Temperature 0° C to +50° C Humidity <85% RH
Power supply	12VDC ±10% approx. 1.5A
Weight	Scanning head 1.0kg Carry case and contents 4.1kg
Dimensions	Scanning head 80 x 113 x 140mm (287mm inch handle) Carry case and contents 470x220x180mm
Battery life	Approximately 4 hours of continuous use

Table 1. Specifications of GeoSLAM ZEB-Revo (GeoSLAM Ltd, 2017b)

An accessory device called ZEB-CAM was also included to the set-up as seen in Figure 4. Specifications are listed in Table 2.

Camera Type	GoPro Hero Session
Mode	Video
Video Resolution	1440p
Frames per Second	30
Image Resolution	1920 x 1440
Field of View	Ultra-wide (~120°x 90°)
Logging Medium	Internal SD card
Power Supply	Internal Battery
Battery Life	2 hours of continuous use
Image Syncing	Optical flow using integrated inertial sensor

Table 2. Specifications of GeoSLAM ZEB-CAM (GeoSLAM Ltd, 2017a)

This camera is located below the motor drive which allows the capture of a video in the same direction as the field of view of the laser during the acquisition process. By doing this, the video can be used to radiometrically colorize the point cloud to produce to a more realistic model of the dungeons.

2.3 Data Acquisition

Permission to conduct the scan was first secured from the Intramuros Administration (IA) so the scan would not be interrupted during its duration. This is important as possible errors may occur if there are moving objects present.

During the scan, the walking pace was kept slow and accompanied with the subtle movements of the scanner along the horizontal axis. Multiple trials were conducted, and each was eventually pre-processed but only the most complete point cloud was selected for further processing.

2.4 Field Measurements

After obtaining the 3D point cloud data, ground measurements of distinguishable features (that was later used for accuracy assessment) were taken using steel tape. These measurements were used as one of the bases for accuracy assessment as it was later compared with the corresponding measurements that were taken from the 3D products.

2.5 Point Cloud Assessment

Four dense point clouds were eventually exported after the pre-processing of the raw ZIP file in GeoSLAM hub which is a software that allows the importing, examining, and analyzing of data from any GeoSLAM device (GeoSLAM, n.d.).

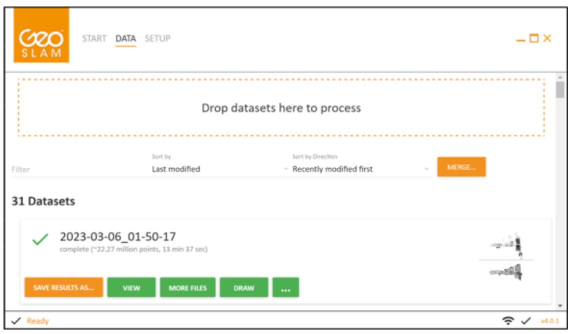

Figure 5. GeoSLAM Hub v.4.0.1 Data Page

Using its interface, the specifications of the output file can be set in the outputs dialogue; of which, notably, the file format and the colorization can be varied.

By default, GeoSLAM Hub prompts the creation of a LASer (LAS) and Polygon File Format (PLY) as they are each compatible with one subfunction of the software. One key difference between the two is the availability of the normals computation for the PLY format but not for LAS. With this, further assessments were done between the two file formats for both Colorized and Non-colorized Point Clouds. The properties of which can be seen in Figure 6.

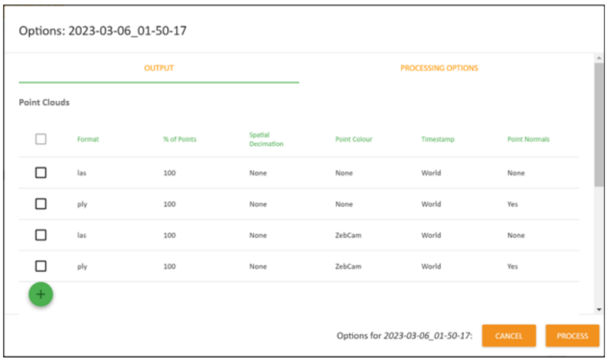

Figure 6. GeoSLAM Hub Options Dialogue with the output file formats to be used for further assessment and their properties.

For the point cloud assessment itself, a Colorized and a Non-colorized Dense Point Cloud were exported in GeoSLAM Hub and processed in CloudCompare to count the number of points. The percentage of Colorized against Non-colorized was calculated.

The latter was further tested on its completeness using the "Compute geometric features" function which quantified the concentration of points in the dense cloud. Among the variables checked are the number of neighbors for each point, surface density, and volume density in a local neighborhood radius of 0.5 meters.

To check for measurement noise, a flat section of the floor in the second chamber was sampled as seen in Figure 7.

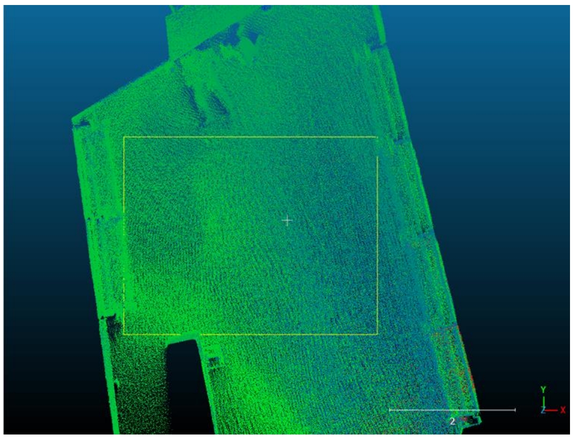

Figure 7. Sampled flat section from the Dungeon's second chamber.

Here, the Random sample consensus (RANSAC) Shape Detection function was used to fit a plane into the sampled section. Next was the Compute Cloud/Mesh distance functions to obtain the mean and standard deviation of the distances of the points that did not coincide with the said plane.

2.6 3D Reconstruction

Further processing was done in CloudCompare where the dense point clouds underwent cleaning as seen in Figure 8; accuracy assessment against corresponding ground measurements; normals calculation for the LAS files; and mesh generation using Poisson Surface Reconstruction at Octree depth 11.

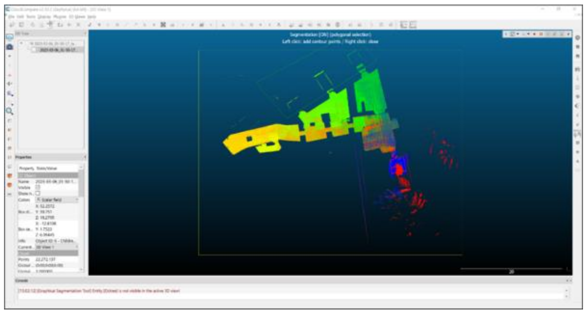

Figure 8. Point Cloud Cleaning in CloudCompare.

2.7 Model-based Evaluation

In line with the objective of finding which format presented the more accurate model, visual inspection was first done as a qualitative check on how well the elements of the dungeons were rendered. Both the exterior and interior of the model were checked, and points of difference were noted.

For the quantitative side, measurements from the rendered 3D model as seen in Figure 9 were compared with the corresponding ground measurements (Maboudi et al., 2018).

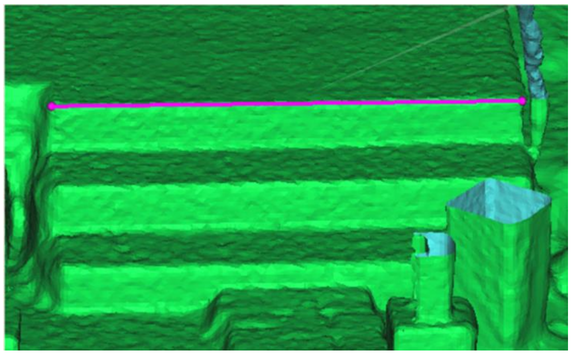

Figure 9. Acquisition of Measurements using the Point Picking Tool in CloudCompare

3. RESULTS AND DISCUSSION

The GeoSLAM Viewer that can be accessed in the GeoSLAM Hub Data Page allows the exploration of the point cloud in 2D and 3D views. Here, the actual trajectory taken during the scan is overlayed with the 2D top view of the dungeons along with the thumbnails of extracted images from the ZEBCAM (as seen in Figure 10).

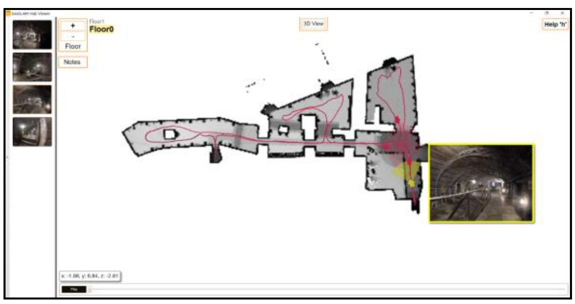

Figure 10. 2D exploration of the dungeons using images that are synced with the actual survey trajectory.

Comparing the Colorized and the Non-colorized Dense Point Clouds in CloudCompare, it was determined that the ZEB-CAM was able to colorize 74.85% of the dungeons. This is expected as the field of view of the scanner is greater than the field of view of the ZEB-CAM.

As for the completeness, it was found out that the trajectory of the scan itself affected the concentration of points throughout the dungeons in several ways, as illustrated in Figure 11.

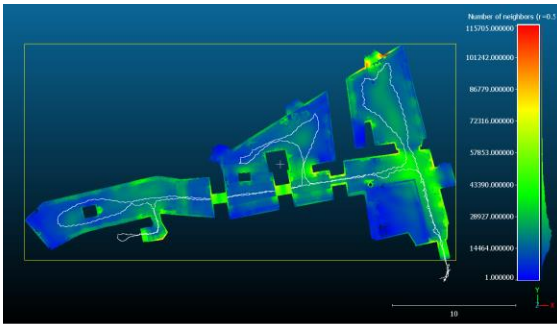

Figure 11. Cross section of a dense point cloud visualized using the Number of Neighbors for each point and overlaid with the survey trajectory.

Other factors include the varying exposure time, the proximity of the scanner to the objects of interest which was affected by the layout of the dungeons itself, and the height of the instrument during the scan. Nevertheless, the concentration of the points still had a mean of 30,000 with a standard deviation of 20,000 points as seen in Figure 12.

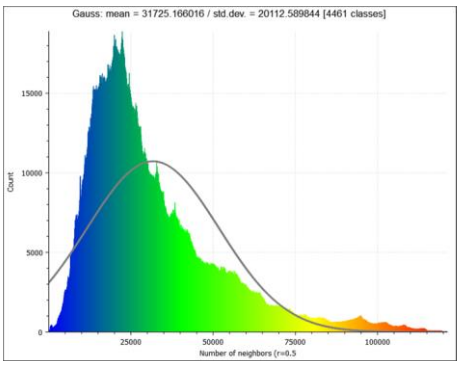

Figure 12. Histogram of the Number of Neighbors showing a left-leaning bell curve

As for the measurement noise, a section of the dense cloud was fitted with a plane and the approximate distance of extraneous points were determined to have a mean of 0.0006m and standard deviation of 0.0073m as seen in Figure 13.

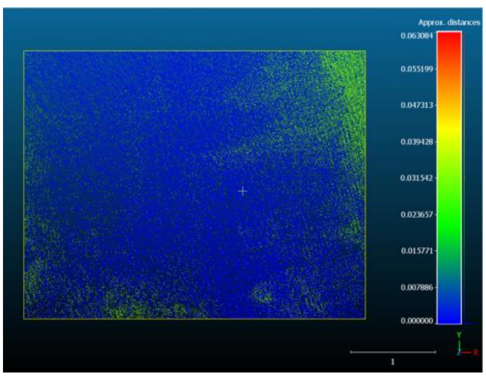

Figure 13. Histogram of the Number of Neighbors showing a left-leaning bell curve

Continuing with the construction of the 3D models, the Dense Point Clouds were first subjected to accuracy assessment by comparing measurements from the point cloud to corresponding ground measurements. The RMSEs obtained against corresponding ground measurements is summarized in Table 3.

Dense point cloud	Root Mean Square Error
Non-colorized LAS	0.734cm
Non-colorized PLY	0.739cm
Colorized LAS	1.308cm
Colorized PLY	1.312cm

Table 3. Summary of Accuracies of generated dense point clouds

As for the Poisson Surface Reconstruction, increasing the octree depth showed the most visible improvements in the quality of the output 3D model but this was at the expense of processing time. Multiple trials then showed that setting the octree at 11 gave the best compromise in terms of the mentioned factors.

The generated mesh files showed that there is little difference in the render of the exterior of the 3D models except for the texture of the roof/ceiling as shown in Figures 14 and 15.

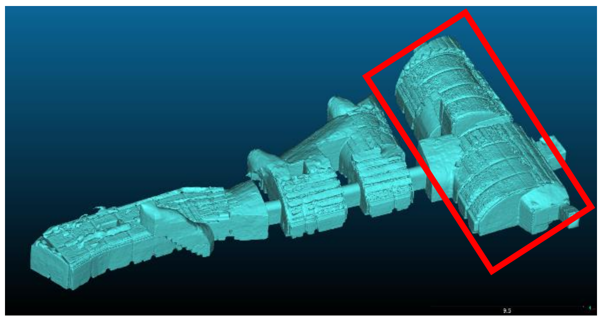

Figure 14. Isometric view of the 3D models rendered using the Non-colorized LAS file.

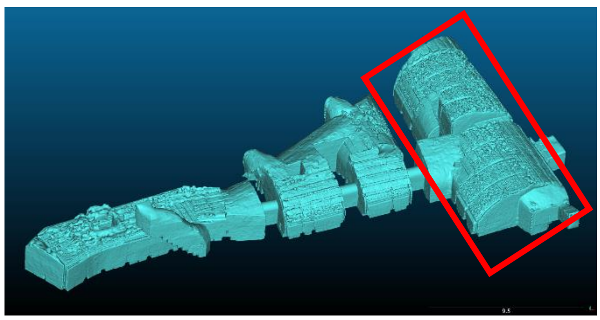

Figure 15. Isometric view of the 3D models rendered using the Non-colorized PLY file.

However, if we take a closer look at the interior, we can find that the render from the PLY file was of better detail when it comes to objects that are comparatively small against the whole dungeon. This distinction among the two is evident in the railings as seen in Figures 16 and 17.

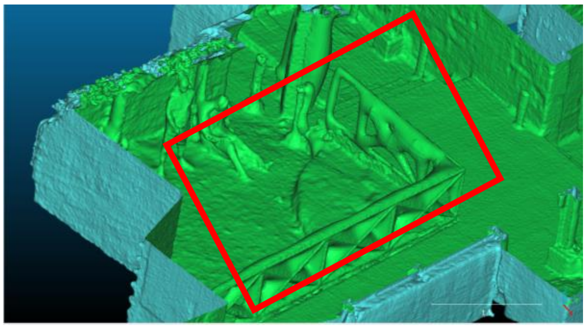

Figure 16. Rendered railings using the Non-colorized LAS file

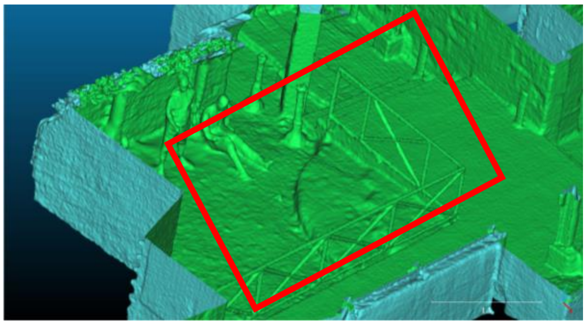

Figure 17. Rendered railings using the Non-colorized PLY file

This trend is consistent for the other parts of the generated meshes such as that of the figurines, beams, and support structures.

As for the colorized Mesh files, it is more difficult to discern the details of the dungeons but the same trends in the previous mesh files can still be observed as seen in Figures 18 to 21.

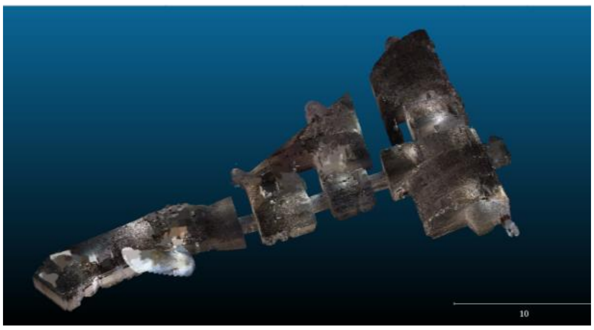

Figure 18. Isometric view of the 3D models rendered using the Colorized LAS file.

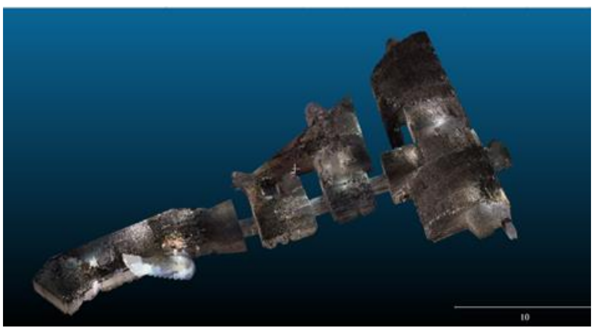

Figure 19. Isometric view of the 3D models rendered using the Colorized PLY file

Figure 20. Rendered railings using the Colorized LAS file

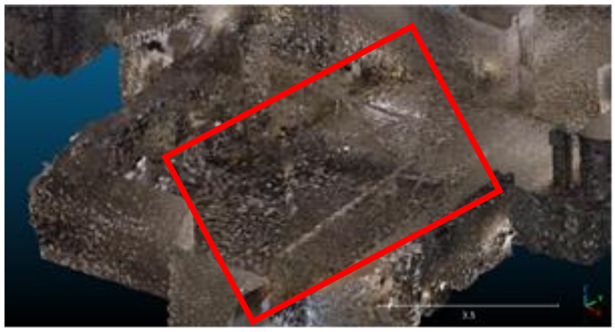

Figure 21. Rendered railings using the Colorized PLY file

Nonetheless, the derived mesh files gave similar results for the RMSE as summarized in Table 4.

Mesh file	Root Mean Square Error
Non-colorized LAS	1.044cm
Non-colorized PLY	0.999cm
Colorized LAS	1.339cm
Colorized PLY	1.326cm

Table 4. Summary of Accuracies of generated mesh files

These values are well within the 5cm threshold for measurements to be viable as a reference length in the event of reconstruction (Pepe et.al, 2022).

4. CONCLUSION

In this study, a dense point cloud of the interior of Fort Santiago was successfully made and evaluations on colorization, completeness, density, and measurement noise were satisfactory.

Even though there were differences in the RMSEs of the measurements, due to factors such as the number of points and the processing itself, all of them are still within the 5cm threshold to be considered useful in the event of a reconstruction.

But overall, the analysis showed that the Dense Point Cloud derived from PLY rendered a better 3D model - as the dungeon's interior was better represented.

5. RECOMMENDATION

Given enough time to remove the points representing the structural supports and light sources, it is viable to create a 3D mesh representing a more unaltered environment of the dungeons. Additionally, by selecting viable points that could be assigned coordinates, the entire point cloud then be georeferenced which could further improve its usability. The use of ZEB-CAM to colorize the point still holds great potential but only if the factors identified in the results are addressed.

Since only model-based evaluations were done to check for the accuracy in this study, further studies may use data from a Terrestrial Laser Scanner (TLS) and perform cloud-to-cloud comparison for better accuracy assessment.

The GeoSLAM Draw, which is the accompanying application of the GeoSLAM hub, could also be explored for more products. Given the accuracy that was obtained, the scan can be converted into a usable floorplan fit for architectural archiving and presentation. Thus, we strongly recommend the acquisition of a license for the use of this subprogram.

Various combinations of settings and parameters in GeoSLAM Hub and CloudCompare could likewise be investigated to generate better 3D point clouds and models. Lastly, the latest versions and models of handheld laser scanners could be assessed and researched in the same or similar indoor environments, such as caves and underground domains.

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