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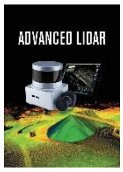

Deviation Analysis of Historical Building Based on Terrestrial Laser Scanner Data and 3D Mesh Model

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Keywords
Cultural Heritage,
Deviation Analysis,
Point Cloud,
Terrestrial Laser Scanning.

ABSTRACT
The use of Terrestrial Laser Scanner (TLS) technologies in cultural heritage studies has become more common day by day. In addition to documenting a historical building with high accuracy, TLS technologies can obtain detailed data about the structure being studied by analyzing point cloud. Laser scanning data is seen as a non-contact and effective analysis method in determining the formal deformations that occur due to various reasons, especially in historical buildings. With this method, it is possible to determine how much the object deviates from a reference 3D model or plane and with this analysis, deformation maps can be prepared. With the help of these maps, intervention decisions can be made. Within the scope of the article, laser scanning data of Selime Sultan Tomb located in Güzelyurt Selime Town in Türkiye, one of the important settlements of Cappadocia, were acquired. By comparing the 3D mesh model prepared with base on point data, the morphological differences and deviations of the tomb were determined and mapped.

1. INTRODUCTION

In the last 20 years, laser scanning technologies have brought new initiatives to cultural heritage studies. Laser scanning data is used to define the structural safety of historical buildings and to determine their formal anomalies. Laser scanning technology collects highly accurate 3D data to provide conceptual understanding of the historic building (Lindenbergh, R., & Pietrzyk, P. 2015). By analyzing the laser scanning data, information of the possible behavior of the buildings could be obtained. (Fregonese et al., 2013; Kaartinen, 2022; Alptekin and Yakar., 2020, Alptekin et al., 2019a, Alptekin et al., 2019b). Moreover, using these data, the application errors related to construction period of historical building could be analyzed. Beside these, the formal deformations exposed to any reason could be determined. In addition, material properties of the building, deformations caused by the ground and the damages caused by the earthquake could be analyzed. While these analyzes are carried out in classical methods by directly contacting the surface and by establishing a scaffold, thanks to laser scanning data similar analyzes could be performed without contacting these surfaces. However, it can be said that the analyzes made with the classical methods are more subjective than the laser scanning data (Pesci et al. 2011; Altuntas et al., 2007; Ulvi and Yakar, 2014, Ulvi et al., 2014).

In recent years, quality controls could be made by using point cloud data at different stages of all production sectors. Thanks to software using point cloud data in different sectors, quality controls could be made by comparing the current sample with a reference product. Due to the benefits of this technique, different software have tried to produce solutions for the subject. In general, commercial (Geomagic, Cyclone, PolyWorks 3DReshaper etc.) and opensource software such as CloudCompare can perform these analyzes in a qualified manner.

Besides regular contact and contactless structural analysis, deviation analysis method can provide some data about the structural problems of the building and can detect the error and error resources in modelling process. Different deviation pattern could be correlated with different type of errors and deviation patterns facilitate identifying of error resources.

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2. DEVIATION ANALYSIS

The term deviation, which is used by different disciplines, is a method of determining differences and anomalies by making comparisons from a plane or object at a certain time or periodically in production or construction industry. According to Anil et. al. (2013) TLS data base analyses 6 times more sensitive than eye-contact observations.

These analyses techniques could be carried out by different data or 3D model for different purpose:

- *Comparison of two point clouds at different times:* Generally, this comparison purposes as an observation of building Deviations from the reference point cloud by comparing point clouds measured at different times (Scaioni, 2013; Wunderlich, 2016). Similarly, point clouds from different sources could be compared (Ahmad Fuad,2018; Vanneschi et. all, 2017; Yakar et al., 2009, Yakar et al., 2014, Yılmaz and Yakar., 2006a). These sources can be photogrammetric data and TLS data or point clouds could be obtained with different devices. In this technique, the main challenge is how to efficiently and precisely identify the correspondences points between the compared objects.

- *Deviation analysis of building with respect to orthogonal planes:* They are widely used for vertical deviations of tall buildings or for deformation mapping of surfaces. Thanks to laser scanner data some deformations could be measured about the historical buildings like overhanging of some part of building, progressive changes of inclinations, differential movement of structure (Castagnetti et.al. 2012). Deviations have been defined by carrying out a detailed analysis of deflection from verticality with respect to orthogonal plane that is perpendicular position of the inclination direction. Vertically analysis of high buildings can be carried out by cutting point cloud or mesh models and obtained sections. (Bertacchini et. al.2010). This method can provide data local leaning and tapering angle, radius, local deviations from local curvatures (Teza and Pesci 2013). Similarly, deformation maps can be created on large surfaces by measuring their distances relative to a reference coordinate system or reference plane. The main difficulty in this method is how to create and determine the reference plane and the location related to the building. Essentially, a point on a building that is assumed to remain unchanged over time can form the reference point of the reference plane.

-*Surface analysis of building with best-fit cone and cylinder or 3D Model:* Some software packages are optimized for analysis of mesh and point cloud data as a reliable tool for shape analysis with respect to planer, spherical, cylinder and cone reference objects. (Korumaz et. al, 2017; Yang, 2017, Bruno, 2018). The computation of the distance field between the point cloud or mesh model and reference shapes provides local deviations from the expected shape

The error map-based approach can be carried out with standard tools for point cloud inspection. In many case examples, geometries that are not cones or cylinders cannot be analyzed because a single suitable geometry cannot be created for the entire object, and sometimes a different reference geometry must be created for each part of the building.

-*Point cloud versus mesh model comparisons for the whole structure:* It is the comparison of the prepared mesh model with the point cloud data of the structure (Nguyen,2018). This technique could be used in reverse engineering applications for comparing deformation of final product and prepared mesh model. In addition, by comparing an idealized mesh model with a point cloud, the deviations of the structure from this model can be measured and comments on the deviation could be made.

Deviation analysis consists of four stages:

a. Determination of deviation analysis techniques according to features of the building. The deviation analysis technique is determined according to the nature of the surface or all building to be analyzed. Comparison of different point clouds, reference plane, best fit cone or cylinder, or 3D mesh model comparisons are selected based on analysis.

It is observed in the literature that the analyzes of a tall building are mainly for deviation from the vertical plane (Schneider, 2006; Yılmaz and Yakar., 2006b). Similarly, in high-rise buildings, a reference cone, cylindrical or prismatic geometry that best overlaps with the point cloud can be compared to the whole or part of the building. More complex forms can be compared with prepared 3D models and differences could be obtained.

b. Mapping of Deviations: Thematic expression of deviations is a mapping method that the best overlapping segments are marked as green (0 and close to zero value) and positive and negative differences as from red to blue. Map colors may change according to the determination of threshold values. The smaller threshold value ranges in mapping, the more precise the damage can be expressed. As the threshold values increase, the content of the map becomes more general.

c. Deviation analysis and determination deviations' reasons: The main purpose of damage detection in cultural heritage studies is to find the source of this anomalies. Prepared deformation maps give a preliminary idea of damages (Neuner et. All, 2016; Holst, 2017). Vertical distortions, ground strength problems, anomalies on the walls, color differences, vegetation on the surface can be given as examples (Hsieh, 2012). After these determinations, the laser scanning data may not be sufficient and the causes of the deformations can be determined by using different techniques.

d. Generating intervention decisions: Intervention decisions related to cultural heritage can only be developed based on highly accurate documentation and analysis methods. One of the most important criteria for its interventions are the correct determination of the problems. Intervention decisions can be made based on these correct determinations. Structural interventions could be made according to the size of the deformation in the historical building. Soil reinforcement can be applied for ground settlements. Preventive measures for cracks, deformations and spills on flat surfaces could be made in line with the analysis.

3. METHOD

The methodology of the study consists of two parts. In the first part, the point cloud model of the Tomb is created using TLS data. The second part consists of comparing the point cloud with the idealized 3D mesh model produced with reference to the point cloud and the creation of the deformation maps. FaroS120 was used to obtain the point cloud, and post-process applications were produced in Faro Scene software. SketchUp was used for creating 3D Cad model and UNDET software was used to import the point cloud to Sketchup. Cloud Compare opensource software was used for point cloud comparison and deformation maps with produced 3d model (Figure 1).

Field of View (FOV), Topographic Measurement

TLS, Data Acquisition (Point Cloud)

Data Preparation (Remove Noise, Cleaning)

Export to SketchUp with Undet

mport 3d Cad Model and Point Cloud to CloudCompare

Compare Cad model and Point Cloud

Obtain Deformation Maps and Results

Figure 1. Workflow of Study

Figure 2. Current Images of Tomb

Figure 3. Entrance of Tomb and Brick Array

4. DATA AQUSITION, POST PROCESSING and DEVIATION ANALYSIS OF HISTIRICAL TOMB

4.1. Short History of Tomb

The tomb is in the borders of the Cappadocia region within Aksaray province in Turkey. It is mentioned as Ali Pasha Tomb (Konyalı, 1975), Anonymous Tomb (Bakırer, 1981), Selime Hatun Tomb (Anonymous, 1995), Selime Sultan Tomb (Önkal, 1996) in researches and various publications (Figure 2,3). Although the exact date of construction of the tomb is not known, researchers generally dated its construction period as XIII century. The building was abandoned for many years and its restoration was carried out in 1996. The building consists of two floors. The burial space is located in the basement level and there are symbolic mausoleums in the upper part.

It is observed that it was exposed to severe deformations with examination of old pictures of the building (Figure 4-5). Major interventions or repairs were made in restoration process in 1996. The tomb has an octagonal plan scheme. This octagonal plan narrows towards the upper levels and the surfaces are inclined. Constructing this geometry requires very careful craftsmanship. Within the scope of the article, analyzes were made to determine whether this geometry was restored properly or not.

Figure 4. Old images of Tomb before 60's.

Figure 5. Structural deformations of Tomb around 60's.

4.2. Data Acquisition

Data acquired with Terrestrial Laser Scanner (Faro S120 Laser Scanner) were transferred and aligned with Faro Scene software. All alignment, flittering, cleaning works carried out in Scene software. The building was scanned in the form of two intertwined circular path. While the far scans measure the cone section of the tomb, the scans in the inner circle are close to the octagonal façade of the tomb and intensive measurements were made. During the scanning, positions were chosen providing a perpendicular angle to the surface for reducing distorted number of the points. In the post-processing stage, a more homogeneous point cloud was obtained by cleaning and filtering of the dataset separately for each scan. After this stage, approximately 22 thousand points remain after filtering and subsampling (Figure 6).

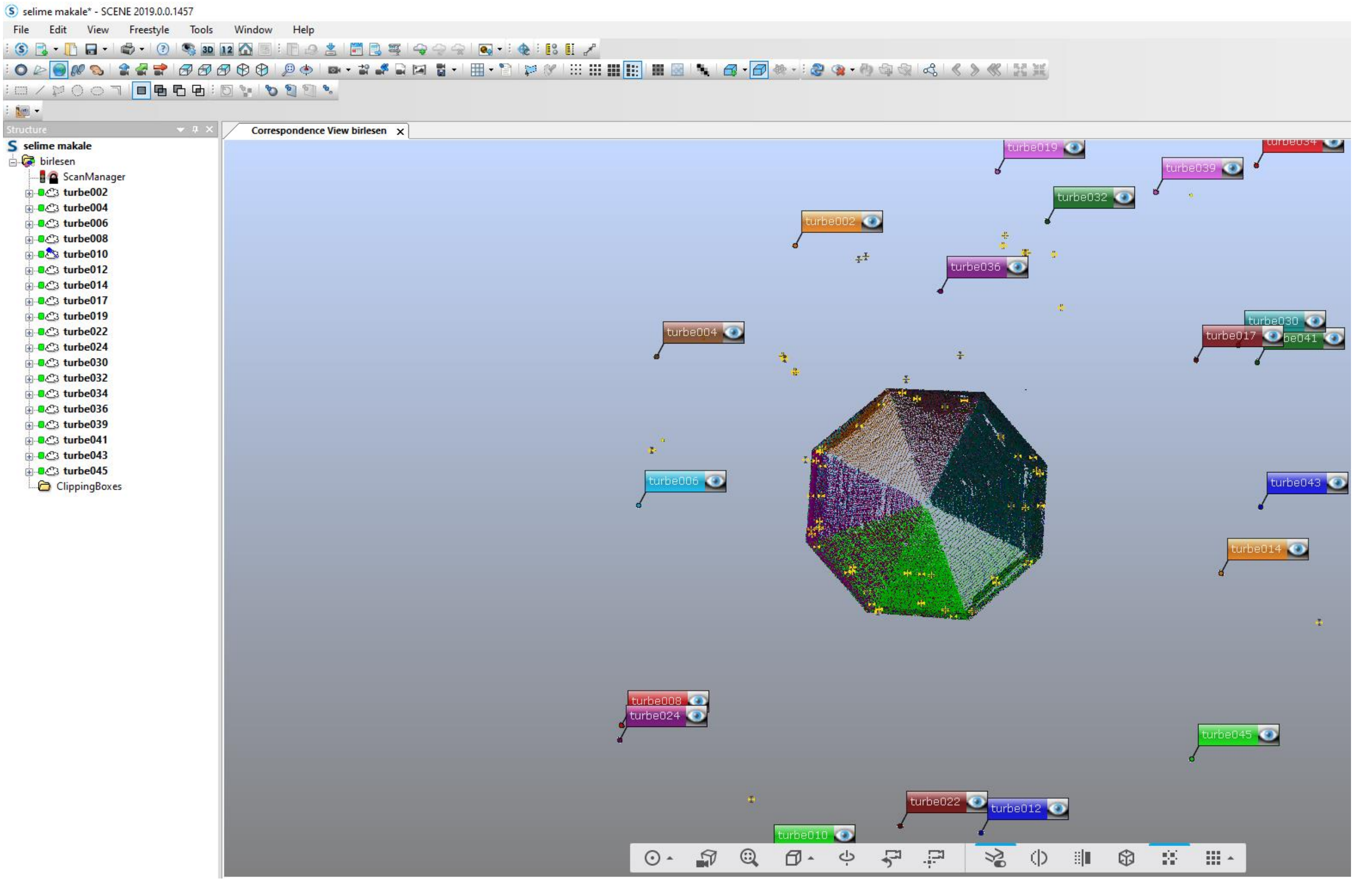

Figure 6. After postprocessing of Tomb's data in Faro Scene.

4.2. 3D Cad Modeling of Tomb

The point cloud was exported in E57 format. The extracted point cloud was imported into SketchUp using the Undet plugin. Undet Plugin was used while importing the point cloud into the Sketch Up. Undet plugin provide to point cloud to be managed and organize point cloud. Thanks to this plug in it is possible to measure distances and vertical and horizontal sections could be prepare for CAD modeling of building. Undet plugin also provide snapping of point cloud. This is very helpful for creating 3D cad model in Sketch Up. Preliminary comparison of the prepared 3d mesh model and the point cloud is made in Sketch Up and User was able to observe the differences between the model and the point cloud (Figure 7-8).

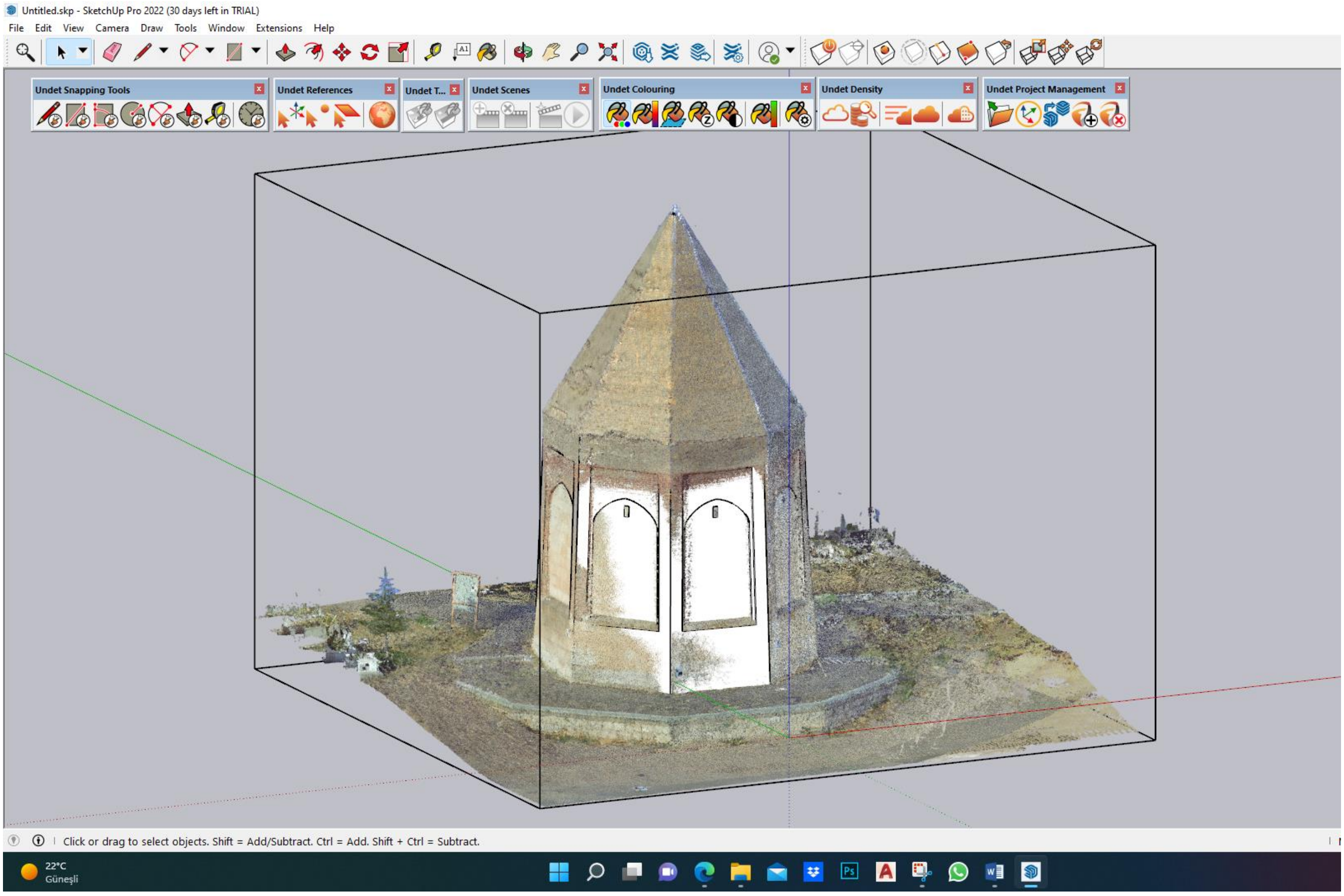

Figure 7. Point Cloud and 3D Mesh Model in Sketch Up.

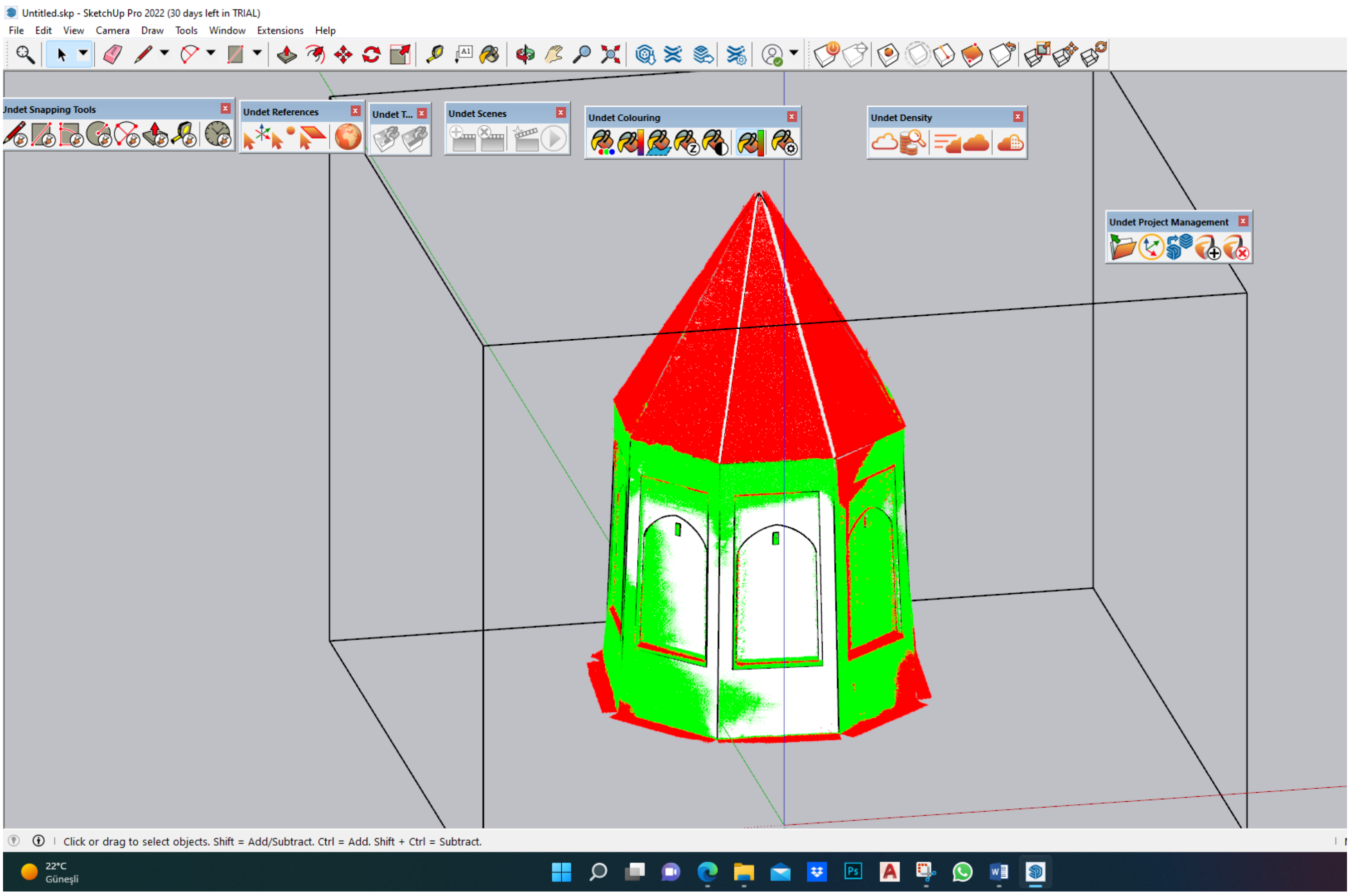

Figure 8. Pre-comparison of point cloud and 3d model in Sketchup with Undet Plugin.

4.4. Comparison of Point Cloud and 3D Mesh Model

CloudCompare is an opensource software for any purpose commercial and education. This software provides significant advantages regarding point cloud postprocessing. The most important of these advantages is the comparison of two point cloud data and mapping according to the distance differences between them. In addition, a reference mesh model and reference plane can be compared with the point cloud. The mesh model and point cloud prepared within the scope of the study were imported into CloudCompare and comparisons were made. It should be considered at this stage is to the overlap of the cloud data and the boundaries of the 3D model. In this context, if deformed points and parts that need to be filtered are observed in the point cloud, these areas must be segmented (after segmentation unnecessery point cloud could be delate) or filter could be applied. At this step, the pointcloud data density could be reduced by sampling so that the point cloud density could be homogeneous. Within the scope of the study, noise filter was applied to the point cloud data and then a homogeneous point cloud was obtained by sampling at 0.005m intervals. After this application, the point cloud, which was around 55 million, decreased to around 22 million (Figure 9-10).

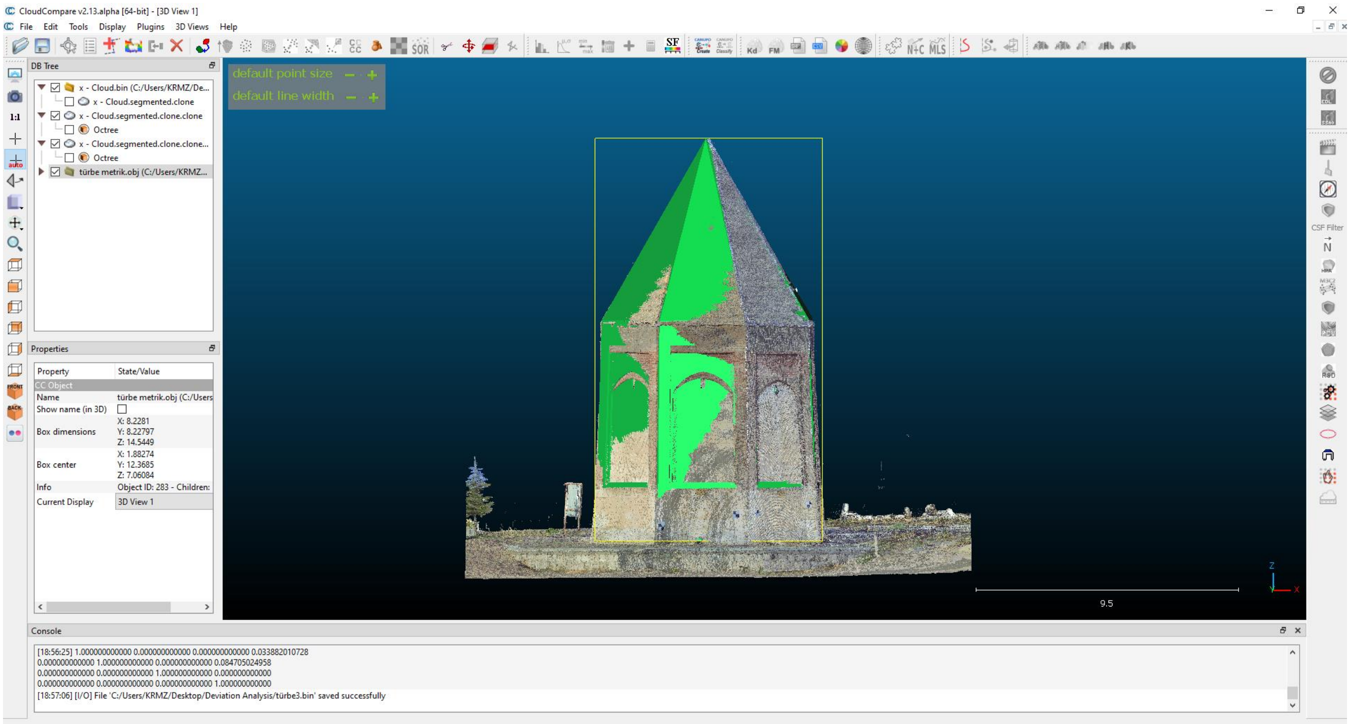

Figure 9. Point Cloud and 3D Mesh model in CloudCompare

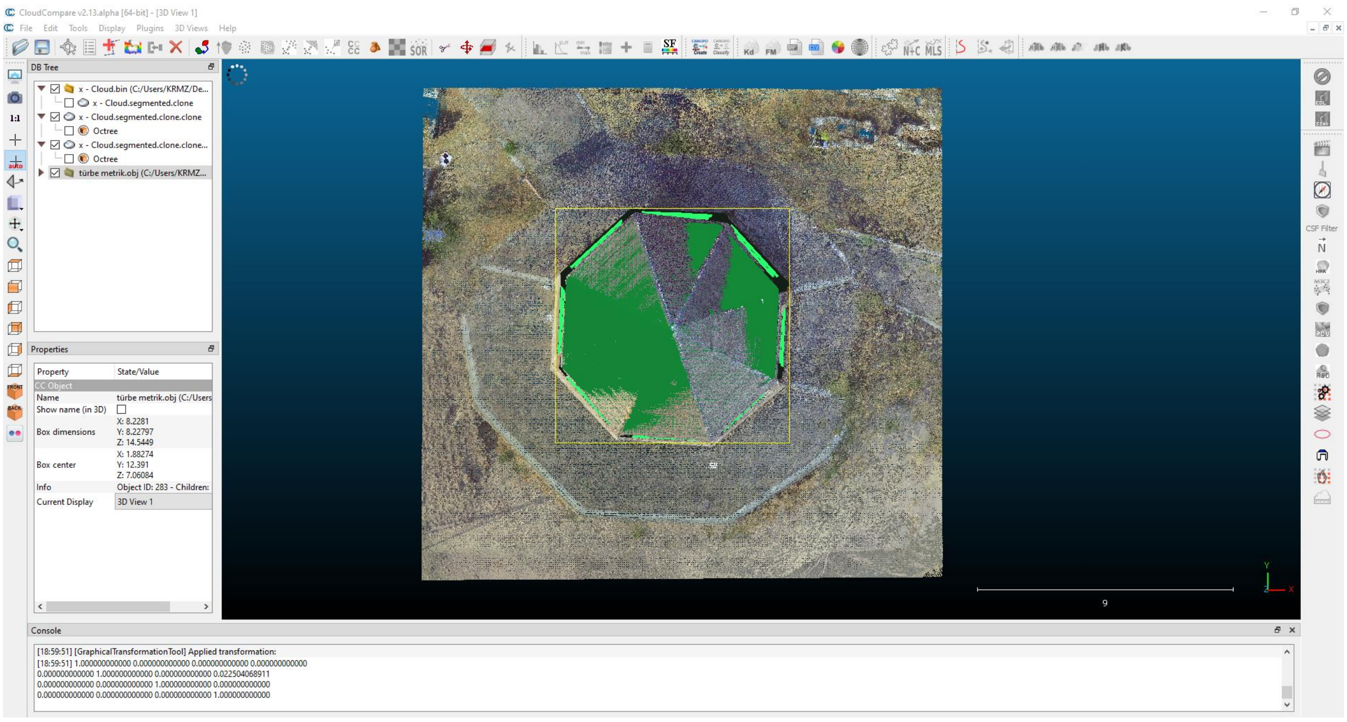

Figure 10. Point Cloud and 3D Mesh model in CloudCompare

After these preparations, the point cloud and the mesh model were compared. In the preliminary comparison, the software makes a pre-evaluation. In this evaluation, 3D mesh model is automatically used as the reference object. For cloud to mesh comparison, these parameters were chosen: Octree level: this is the level of subdivision of the octrees at which the distance computation will be performed. In this article octree level was used as default setting. Signed distance, flip normal and multi-threaded adjustments are used as default setting as well (Figure 11). After the analysis was completed, the results obtained were expressed graphically. In this study, the Cloud to Mesh "*Signed distance*" was determined between +0.3m and -0.3m. The color range of the deformation range is expressed in the display parameter range chart. The most intense color difference in this diagram is used in the deformation map (Figure 12).

As a result of the comparison, it has been observed that the geometry of the tomb differs from the targeted geometry (3d Mesh model) in the first time period and there are slope differences between the surfaces. The surface slopes of the cone and the tomb is different from each other. This difference shows that the tomb was deformed in form within the restorations made in 1996. It shows that the deformation of the sections closes to shades of green on the thematic maps is less than 0.15m. It has been observed that there are more distance differences of more than 0.15m in the red sections. While the biggest differences in the facades were in the entrance facade, it was observed that the differences in the right side and left side facades were less than 0.15m (Figure 13-16).

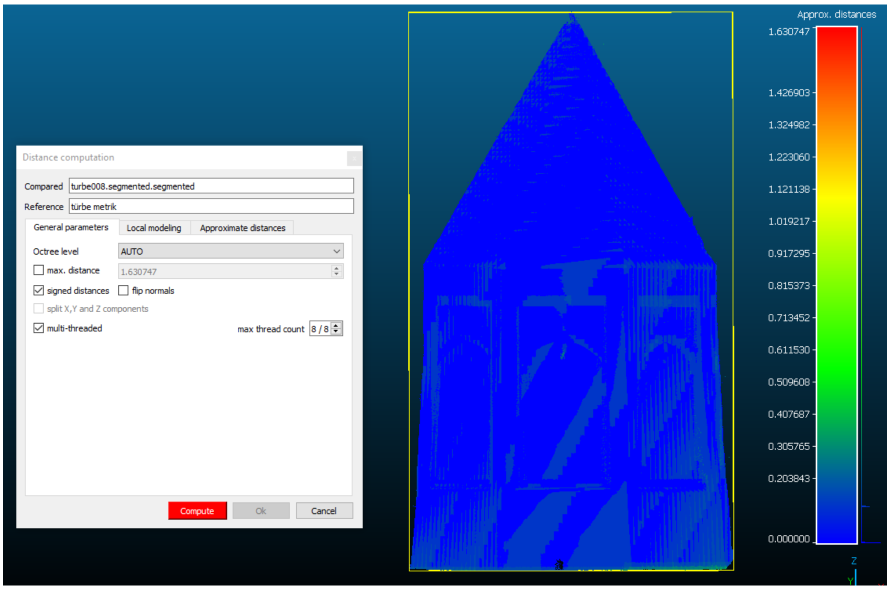

Figure 11. Pre-comparison of Point Cloud and Mesh Model

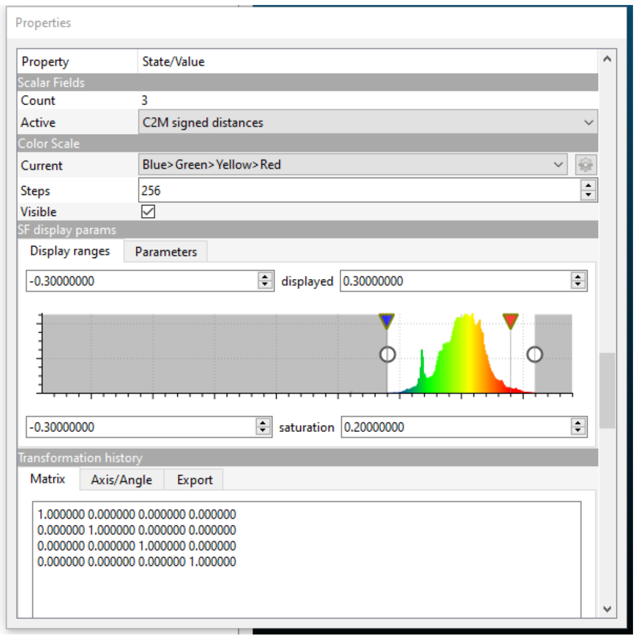

Figure 12. Visual properties of comparison.

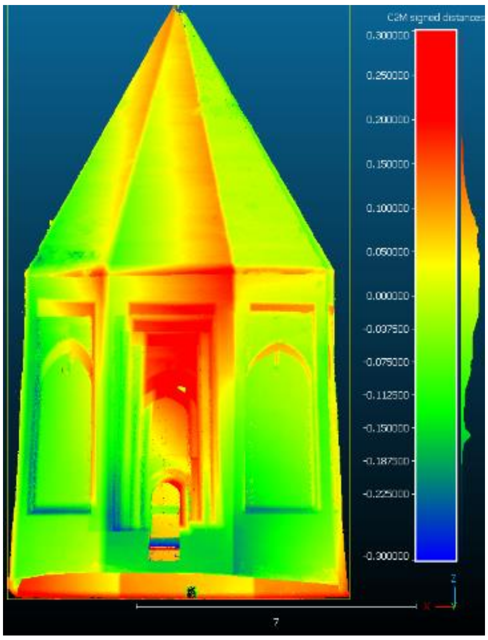

Figure 13. Front view and Back view of thematic map.

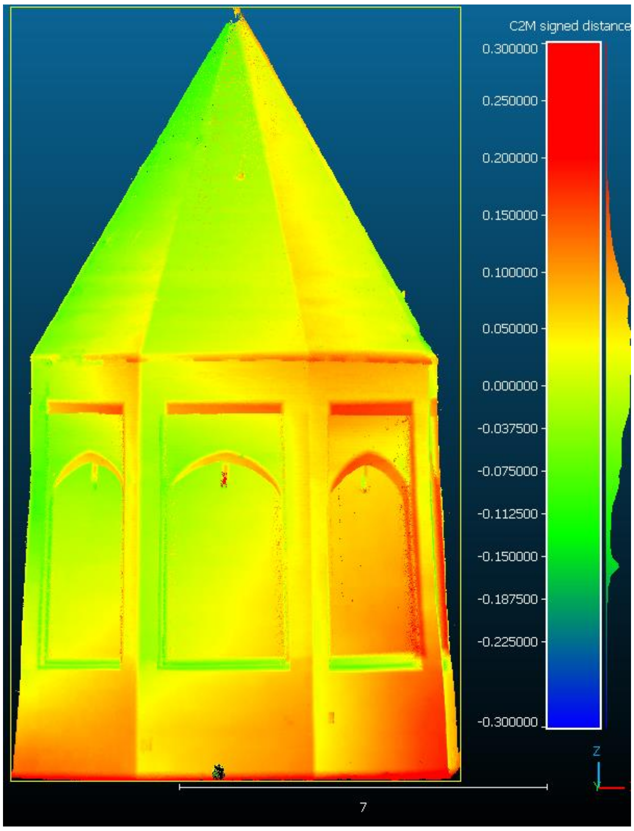

Figure 14. Front view and Back view of thematic map.

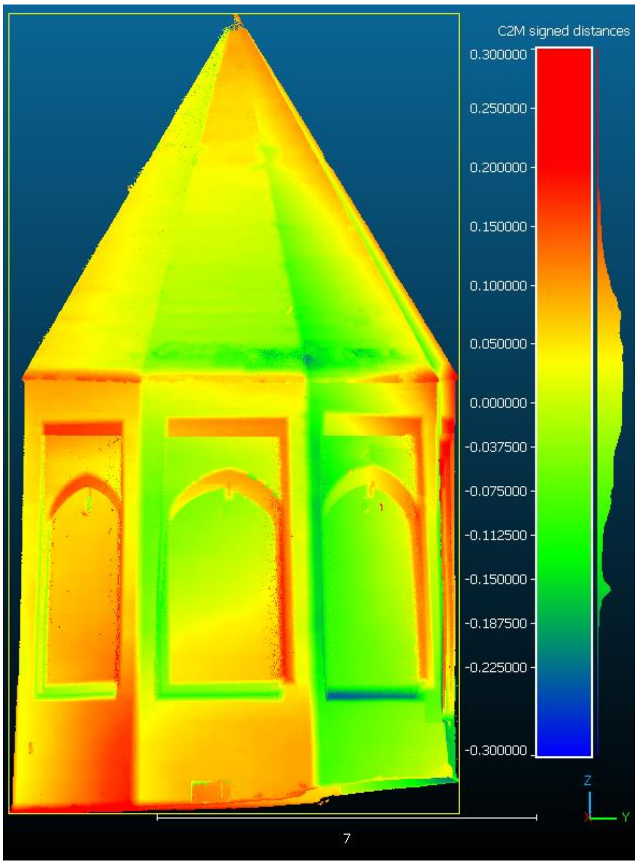

Figure 15. Right view and left view of thematic map.

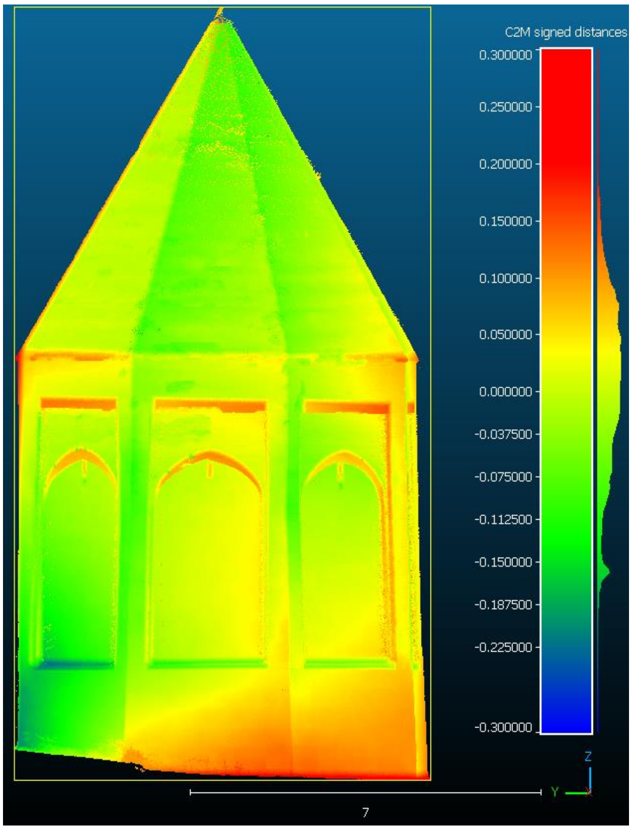

Figure 16. Right view and left view of thematic map.

5. RESULTS

In this article, the results are shared that obtained by comparing point cloud data and 3D mesh model. Deviation analysis method gives an idea of how much difference occurs from ideal reference geometry by comparing point cloud data. These differences could be arisen from the time period when the building was first built, as well as natural disasters, ground and material problems over time.

In the case of Aksaray Selime Sultan Tomb, the historical building was abandoned for a long time, and the building was almost rebuilt with an insensible restoration work in 1996. During the restoration, it was observed that there were formal deformations on the structure, its geometry was disturbed, and there were different slopes on the vertical and lateral surfaces. It is understood that the cone shape deviates from the central point.

This case study is important in terms of identifying restoration errors as a result of comparing the point cloud, which develops an innovative analysis method in cultural heritage studies, with a reference plane and object. An intervention decision for the deformations with the thematic maps obtained from the study could be suggested by the restorer architects or structural engineers.

Author contributions

The authors contributed equally.

Conflicts of interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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