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Constructing a Mesh Model of the Construction for Finite Element Method (FEM) Simulation from the Point Cloud Data Collected by Terrestrial Laser Scanning (TLS)

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Abstract. In recent years, there has been a significant increase in inspecting and evaluating transport infrastructure. Traditionally, these structural data were collected manually by measuring and redrawing the construction against design documents. In recent decades, laser scanning technology can help collect 3D data rapidly and accurately. The 3D point clouds can provide detailed texture and shape information of complex construction such as bridges. This study aims to develop a 3D mesh model for a finite element simulation from a 3D point cloud of a bridge's Pier collected by Terrestrial Laser Scanning (TLS). The point cloud is structured, and the object boundary points are generated using the marching cube algorithm. The boundary and inside points, which imply the vertex of the solid element in the 3D mesh model, are grouped as a new point cloud. The generated point cloud is input into 3D CAD, and the 3D solid model is manually created. As a result, the 3D mesh model is developed and successfully imported to ANSYS software for the structural behavior simulation. The accuracy of generated mesh model is good, with the relative error of geometric parameters being less than 4%. The distance from the point cloud to the mesh model is approximately 5 mm.

Keywords: Point cloud · 3D mesh model generation · Pier · FEM · ANSYS

1 Introduction

Most of the bridges have been in use for many years. It leads to the geometric features deteriorating due to the weather effects. Additionally, the strength of materials gradually decreases over time, and the service life of these structures is impacted by the increasing frequency of high-load and density vehicles moving across the Bridge. Therefore, the

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bridge structure's health should be monitored to ensure safety. Three main factors will evaluate the Bridge's working ability: surface integrity, material quality, and the structure's capacity. The evaluation process is essential to predict the safety of these existing works and make decisions about repairing and replacing the part or the whole structure. The FHWA's Manual for Bridge Evaluation outlines a systematic approach covering every aspect of bridge evaluation, including the structure's surface integrity, material quality, and workability. This comprehensive guidebook provides detailed instructions for assessing the condition of a highway bridge in America. According to this manual, the inspectors will make informed decisions about its maintenance, rebuild, or replacement [1]. In the past, surface integrity and material quality assessment were visual inspections and examined by an inspector. The visual inspection can identify problems such as cracks, rust, or corrosion, indicating potential issues with the structure's stability and safety [2]. However, the result highly depends on the inspector's experiments and personal decisions. The material remains unaltered mainly during use but the effect of weathering and corrosion. Therefore, it is necessary to carry out a study to scrutinize the surface integrity and meticulously assess its structural workability.

Load Testing Response (LTR) is one of the evaluating methods for the capacity of a bridge structure. It is a method used to determine the usability of a bridge structure by subjecting it to loads and observing its response. According to the American Association of State Highway and Transportation Officials (AASHTO) manuals, load testing response is a critical component of the structural health assessment process for bridges [3]. To verify and compare the results of the LTR method, the Finite Element Method (FEM) is applied to simulate the structural behaviors. To solve a problem, the FEM subdivides a large object or system into smaller, simpler parts called finite elements. It is explained as a particular space discretization in the space dimensions. The construction of a mesh of the object achieves it. Wang et al. [4] evaluated several existing bridge structures and proposed guidelines based on a combined load test program and finite element model. Currently, the FEM can provide a detailed analysis of the behavior of a bridge structure under various load conditions. This method can also be used to investigate the effect of different repair and maintenance plans on the remaining lifespan of the structure [5]. In particular, FEM is utilized on various bridge components, including piers, beams, and decks, to simulate destructive testing of the bridge structure at different levels. As a result, data collection and reconstruction of structural components become imperative for inspecting and evaluating structural quality. The numerical model in FEM is highly dependent on the geometry precision of the components, which is crucial for assessing the work capacity of the bridge structure [6]. The geometry model is usually manually reconstructed from the existing drawing. It may contain mistakes caused by the carelessness of the technicians. This process leads to many errors that hinder the quality of the overall assessment of the workability of the existing structure [7]. In addition, in old constructions, the design blueprints are lost, or the works are deformed, subsided, or peeled off some of the structure's cover concrete leading to many efforts for collecting direct measurement data. The advancements in science and technology have introduced several new methods that offer significant advantages, replacing direct measurement methods. In detail, the camera captures the construction images to visualize the construction surface. It is a non-destroyed method for visually inspecting the construction quality. The quality-checking process can be done by an inspector or by applying an image processing algorithm for big data processing. However, using 2D images is not good in some investigations, which need to know the accuracy of geometry dimension or the component is hidden by others, whereas generated 3D point cloud image is inaccuracy. Another method for collecting accurate 3D point clouds of the construction's surface is laser scanning technology. The Laser Scanner, nowadays, facilitates fast 3D point cloud collection with high point density in a short period. This technology has become increasingly prominent and has played a significant role, particularly in the transport infrastructure industry [8]. The 3D point cloud helps assess structural integrity and identify potential defects [9]. For this, the point cloud becomes the input data to create the mesh model for FEM analysis. Several researchers have investigated methods for this conversion, including using machine learning and manual editing. In addition, a new semi-automatic procedure for transforming complex point clouds into finite element models designed explicitly for irregular geometry structures like historic buildings has been presented [10]. The input model processed in FEM software is successful when all characteristics, such as vertices, edges, and faces of adjacent elements, are matched. In other words, the mentioned objects are shared to make the continuation of the model. Solid models of historic buildings in previous studies were built from the point cloud using a full voxel as a cubic element because the surface is almost flat according to the specific shape, whereas the boundary of the complex components, such as the dome, is created by subdividing the octree into suitable size to display the shape of the object [11]. Therefore, challenges remain in converting from a point cloud to a solid model, including data acquisition and processing accuracy [8].

This study focuses on generating a mesh model of construction components from 3D point cloud collecting by laser scanner for FEM simulation. In detail, the point cloud of a concrete pier of the Bridge, which contains flat surfaces and curved surfaces, is converted into a solid model. The proposed method displays a process of identifying the vertex of solid elements from the 3D point cloud of a bridge pier. The generated point must represent the integrity of the structural surface. Then, generated points are used to create the solid model, including tetrahedral and cubic elements. From this, the solid model is created an imported to the ANSYS software to evaluate the workability of the structure.

2 Data Acquisition

The Bridge under investigation for this study is located on the CO16 road in Seßlach, Germany. It is a two-span bridge with a span length of approximately 10,5 m. The Bridge's cross-section includes two traffic lanes of 7,0 m in width and two sidewalks. The Leica Scan Station P20 laser scanner was used for data acquisition. This device offers a maximum scanning range of 120 m and angular accuracy of 8 s in both the vertical and horizontal directions. Five scan stations were set up to obtain the whole Bridge. The point clouds from these scans were registered by Leica Cyclone software. The Bridge's irrelevant points corresponding to the ground surface, vegetation, and moving objects were manually removed. Finally, the point cloud contains x-, y-, and z-coordinates and intensity. The bridge point cloud included 28.505 million points, with an average density of 57,130 points/m2 (Fig. 1). For further analysis in this study, Pier's point cloud is extracted from the original data.

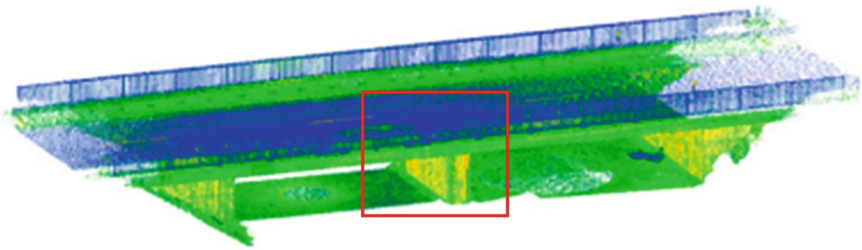

Fig. 1. Bridge on the CO16 road, Seßlach, Germany. The pier locating inside the redtangle is used for this study [12].

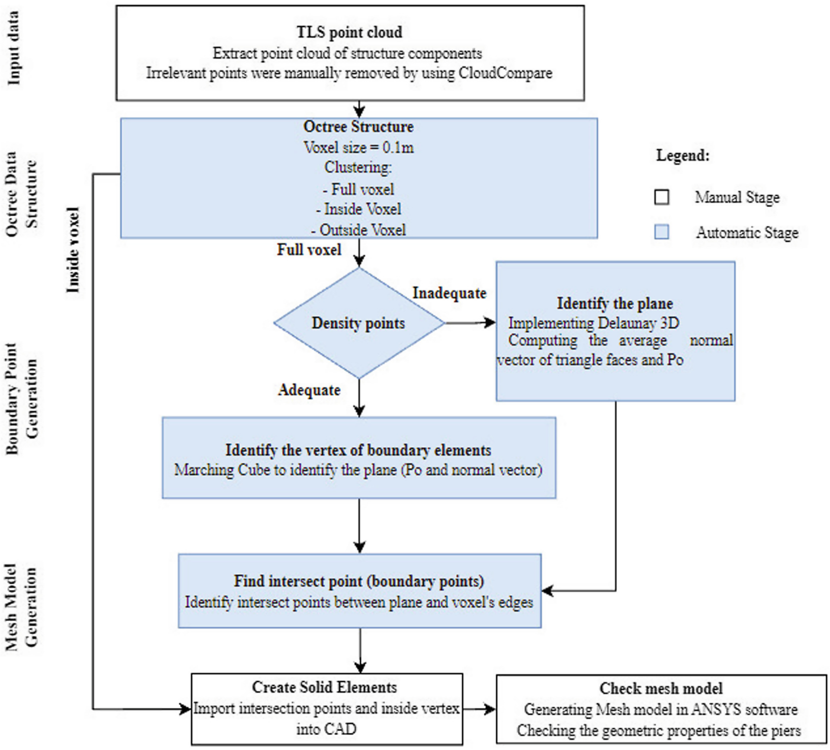

Fig. 2. Workflow of the developed semi-manually approach

3 Proposed Method

3.1 Octree Structure

The data processing includes many steps, as displayed in Fig. 2. For the beginning, the 3D point cloud is organized based on an octree structure. An octree is a tree data structure in which each node has precisely eight children, commonly utilized in the shape reconstruction of 3D objects (Fig. 3). There are two common approaches to stopping octree generation. This study applies a threshold based on voxel size rather than the number of points in a voxel. The voxel size is fixed and must be small enough to ensure the accuracy of the structural surface. However, too small of a voxel leads to dense points and spending more time processing data while the accuracy isn't significantly improved. For this study, the voxel size is set to 0.1 m to ensure detected characteristics of the shape bridge's Pier and to avoid missing unwanted deformities on the surface of the pier surface. Each voxel is named by voxel id. This way, the points belonging to each voxel can easily be accessed. Moreover, the processing time can be reduced by not calling all data at the same step of data processing.

In the next substep, the clustering algorithm is used to identify full and empty voxels. The full voxels contain 3D points, and the voxel with no points inside is empty. The full voxels are boundary voxels because of no points inside the Pier. Then, the empty voxels are classified into inside and outside voxels. The vertex inside voxels denotes the solid element's vertex inside the Pier of the mesh model.

3.2 *Boundary Points Generation*

In this step, the boundary elements of the mesh model are created. In detail, for each boundary voxel, the corners are tested for whether they are inside the Pier. The pier' surface must pass through each voxel with some corners inside and outside the Pier. A normal vector and average point (Po) identify the pier' surface's plane. They are computed from points inside the voxel using principal component analysis (PCA). Then, the new vertexes of outside corners as defined as the intersecting points between the surface and voxel edges. In cases of outliers or areas obscured by obstacles, such as vegetation or other objects close to the Pier, the density of points of full voxels is sparse. It can result in rotated or missing planes for generating pier' surfaces. It recommends a specific process to compute the plane's normal vector from Delaunay triangle faces to address these cases. A result is a group of voxels whose shape is changed to fix Pier's surface instead of cubes as initially.

3.3 *Mesh Model Generation*

In this step, the vertices of the new boundary and inside voxels are input into 3D CAD software. A 3D solid CAD model was created manually. In detail, the 3D CAD model is created by generating the tetrahedral elements of the outer boundary and the cube elements inside the Pier. The critical consideration of this step is ensuring the faces' junction. Finally, the 3D solid model will be exported as a *.igs file for importing into ANSYS software. The checking step by software will be carried out to confirm that the mesh model is successfully analyzed without any errors reported. Moreover, the geometry accuracy of the mesh model will also be checked by comparing the point cloud and generated mesh.

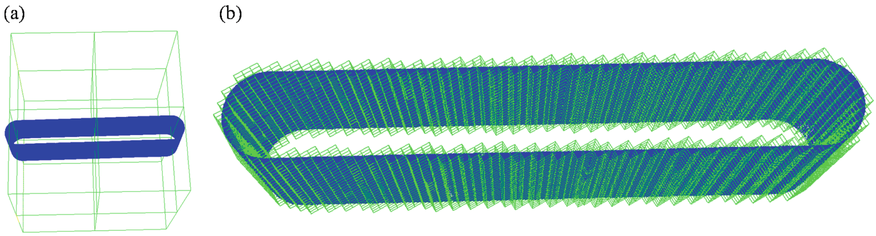

Fig. 3. An illustration of octree generation. **a** octree at the first level with 8 voxels and **b** octree at the final level with cell size of 0.1 mm. The empty voxels are removed.

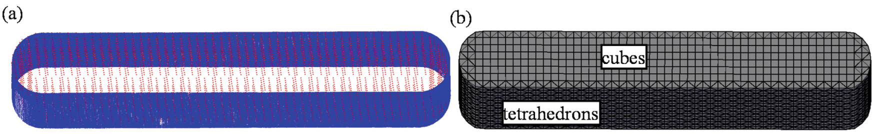

Fig. 4. Solid model generation. **a** The set element's vertexes are displayed in red, whereas the original point cloud is displayed in blue and **b** The mesh solids pier generated from manual processing on AutoCAD.

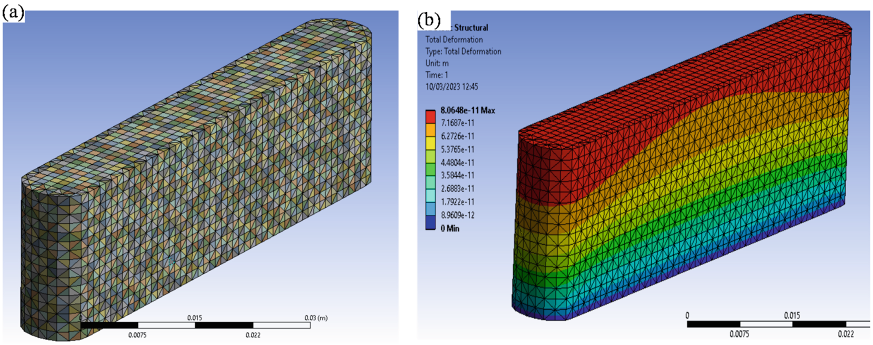

Fig. 5. The results of mesh model generation. **a** Mesh full pier model solved successfully within ANSYS Workbench, and **b** Triumphal internal computation within ANSYS Workbench

4 Results and Discussion

The point cloud is structured using an octree structure algorithm in this study. The voxel size affects the data processing speed. With a small voxel size, the number of voxels is more significant, and it takes more time for data to process in the next step. However,

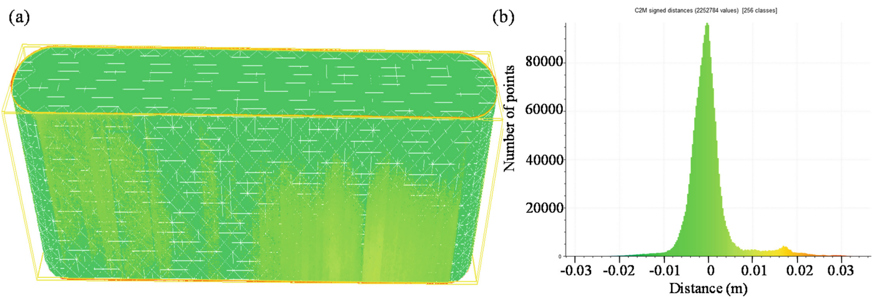

Fig. 6. The absolute accuracy of mesh generation. Most of distance is less than 0.05 mm. The significant distance of 0.02 m is located at the top and bottom of the pier, which may contain the error of choosing boundary points.

Table 1 The geometry characteristics of the pier

	Length (m)	Width (m)	Height (m)	Perimeter (m)	Cross section Area (m2)	Volume (m3)
Point cloud	7,004	1,006	2,136	15,166	6,8323	14,5976
Mesh model	6,981	0,995	2,109	15,202	6,9050	14,0677
Absolute error	−0,023	−0,011	−0,027	0,036	0,0730	−0,5301
Relative errors (%)	0,33%	1,07%	1,26%	0,24%	1,07%	3,63%

the larger voxel size leads to incorrect results of the pier' surface generation (Fig. 3a). Therefore, the voxel size is set to 0.1 m to ensure that the pier' generated surface is a good fit for the existing surface. The boundary, inside and outside voxels are classified for the subsequent analysis (Fig. 3b).

The new 3D point cloud, which implies the vertex mesh's element, is successfully generated (Fig. 4a). As a result, the original point clouds as considered to be resampled with the resolution of voxel size. The new 3D points cloud still keeps the characteristics of pier geometry with less density than the original data. They are manually imported to 3D CAD software to generate a 3D solid model. The mesh is successfully developed by combining tetrahedral and cube objects (Fig. 4b). The tetrahedron is generated for the boundary element, and the cubes are inside elements. In this way, the total number of factors in the mesh model is reduced in the comparison of using tetrahedron elements only. The manually generated mesh is then saved to *.igs file for importing to FEM software.

In the next step, the mesh model will be checked to see whether it works. If the input mesh is not work, the mesh can not be generated on the ANSYS software. As a result, the 3D mesh model has been successfully generated in ANSYS software without error (Fig. 5a). If the mesh can not be generated from ANSYS, the process of a generated solid object in CAD got a problem. The 3D mesh of the pier bridge can be used for the simulation. For example, the primary force analysis is successfully carried out for the mesh model using assumed material and boundary conditions (Fig. 5b).

Moreover, the shape of the bridge pier is maintained. In detail, the geometry of generated mesh is compared to the original point cloud. The difference between the mesh model and the point cloud is slight. The relative error is less than 1,5% in three dimensions, perimeter and volume. The relative volume error is less than 4% (Table 1). Additionally, the distance from points to the mesh surface is checked by using Cloud-compare. According to the results, most of the point has a distance to the corresponding pier' surface of less than 5mm (Fig. 6b). The absolute accuracy of mesh generation is suitable for generating a mesh model from the point cloud (Fig. 6). The significant distance of 2 cm is located at the top and bottom of the Pier, which may contain the error in choosing boundary points.

In general, if the point cloud accuracy depends on the user's devices and the data collecting method is acceptable, the accuracy of generated method model is accepted. This proposed method is suitable for stimulating the existing constructions with no design drawing.

5 Conclusion

This study focused on developing a 3D mesh model from a 3D point cloud of a bridge's Pier for FEM. The point cloud is structured using the octree algorithm. The vertexes of solid elements are generated using a marching cube algorithm and from empty voxels. The solid Pier's model is manually generated on 3D CAD software and the importing to ANSYS. Generally, the mesh model is generated from TLS 3D point cloud for FEM simulation by a semi-automatic method. The FEM model was successfully imported into compatible ANSYS software. The behavior of the structure can be simulated, and the shape of the bridge pier is maintained. The accuracy of generated mesh model is good, with the relative error of geometric parameters being less than 4%. The distance from the point cloud to the mesh model is approximately 5 mm. This result shows that the mesh model best fits the point cloud. Although this method has succeeded initially, it still requires some manual steps. Therefore, the following study develops a more approach for evaluating the pier bridge model without manual steps or applying it to complex construction components.

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References

1. Federal Highway Administration (2018) Manual for bridge evaluation, 3rd edn. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.
2. Phares BM, Rolander DD, Graybeal BA, Washer GA (2021) Reliability of visual bridge inspection. Public Roads, U.S Deparment of Transportation - Federal Highway Administration Research and Technology
3. AASHTO (2011) Manual for bridge evaluation, 2nd edn. AASHTO: Washington, DC, USA
4. Wang N, Ellingwood R, Zureick H (2011) Bridge rating using system reliability assessment. II: Improvements to bridge rating practices. J Bridge Eng 16:863–871
5. Guo Y, Gao X, Zhou J (2020) Remaining life prediction of bridges based on FEM and statistical analysis. J Bridg Eng 25(1):04019114, 33
6. Truong-Hong L et al (2017) A decade of modern bridge monitoring using terrestrial laser scanning: review and future directions. J Bridg Eng 22(7). https://doi.org/10.1061/(ASCE)BE.1943-5592.0001006
7. Gould PL et al (2006) Visual data collection and measurement for construction quality assurance. Autom Constr 15(6):757–768
8. Truong-Hong L, Lindenbergh R (2022) Automatically extracting surfaces of reinforced concrete bridges from terrestrial laser scanning point clouds. ISPRS J Photogramm Remote Sens 87(2014):46–57
9. Truong-Hong L, Laefer F (2019) Laser scanning for bridge inspection. https://doi.org/10.1201/9781351018869-12
10. Castellazzi G et al (2015) From laser scanning to finite element analysis of complex buildings by using a semi-automatic procedure. Sensors 15(8):18360–18380
11. Laefer F, Debra et al (2011) Processing of terrestrial laser scanning point cloud data for computational modelling of building facades. Recent Pat Comput Sci 4(1):16–29, (14)
12. Truong-Hong L Point cloud data of bridge on the CO16 road. Seßlach, Germany collected by Truong-Hong