Tunneling Appropriate Computational Models from Laser Scanning Data

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Abstract

Tunneling projects often require computational models of existing structures. To this end, this paper demonstrates the viability of automatically, robustly reconstructing an individual building model from laser scanning data for further computational modeling without any manual intervention. The resulting model is appropriate for immediate importation into a commercial finite element method (FEM) program. The method combines a voxel-based technique with an angle criterion. Initially, the voxelization model is used to represent the façade model, while an angle criterion is implemented to determine boundaries of the façade and its openings (doors and windows). The algorithm overcomes common problems of occlusions or artefacts that arise during data acquisition. The resulting relative errors of overall dimensions and opening areas of geometric models were less 2% and 6%, respectively, which are generally within industry standards for this type of building modeling.

Keywords: Laser scanning, voxelization model, angle criterion, building reconstruction, finite element analysis, building damage, tunneling-induced settlement

1 Introduction

Computational models are especially important in structural engineering, when assessing the status or determining any risk to existing buildings. Commonly, the models are created from manual survey methods or from existing design drawings. However, this approach can be highly problematic when a large volume of building or complex buildings are involved as arises in infrastructure projects such as tunneling, where hundreds (if not thousands) of potentially vulnerable buildings may exist along a single kilometer of the tunnel route. In that circumstance, implementation of traditional, manual surveying for each structure is cost-prohibitive.

In contrast, laser scanning, also known as Light Detection and Ranging (LiDAR), rapidly and accurately acquires three-dimensional (3D) topographic data of visible surfaces of an object. As such, LiDAR has emerged as an alternative tool for collecting 3D information of buildings for creating 3D models. In practice, the laser sensor(s) can operate from the ground (terrestrial laser scanner, TLS), from a vehicle or train (mobile laser scanner, MLS), or from the sky (aerial laser scanner, ALS). TLS and MLS are mostly suitable for relatively small areas (e.g. a building and small road routes) and give dense data points with high accuracy (within 5mm). In contrast, ALS can cover a large area but gives a comparatively low point density with centimeter level accuracy. Thus, TLS or MLS data are appropriate for generating realistic building models for computational modeling. As such, this paper aims to demonstrate this by introducing an efficient and reliable approach for reconstructing accurate 3D building façade models from LiDAR data of a load-bearing masonry building in a form that is compatible with finite element method (FEM) analysis for an adjacent excavation analysis.

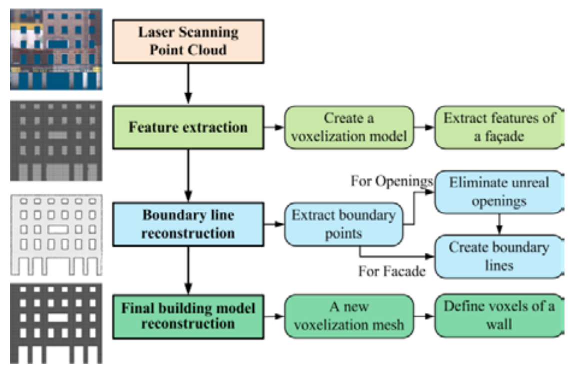
2 Related works

To date, multiple approaches have been developed to semi-automatically and automatically reconstruct building geometry from various LiDAR sources [1, 2]. Since a fairly systematic overview of building reconstruction from ALS data is available elsewhere (e.g. [3] and since such data often lacks sufficient density to identify façade features, this section is restricted to reviewing techniques that reconstruct building models from either MLS and TLS data.

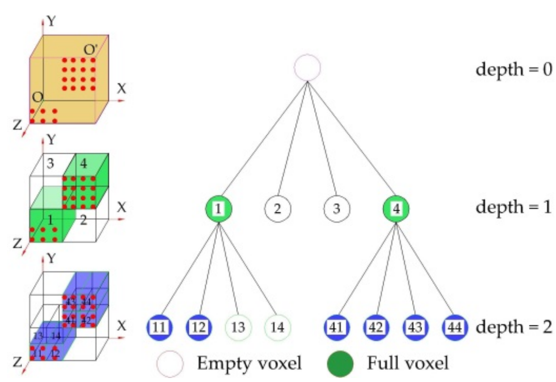
Outlines of buildings and their features (e.g. doors and windows) are commonly generated from points lying on a dataset's boundaries. For example, from triangulation meshing, Pu and Vosselman [4] identified points on boundaries of building features as end points of triangle edges having lengths exceeding a specified threshold. The boundary points of each feature (e.g. façade, doors and windows) were categorized into upper, lower, left and right groups, and a minimum-bounding rectangle was subsequently fitted to the features. Similarly, Boulaassal et al. [5] extracted contour boundary points of openings from a two-dimensional (2D) Delaunay triangulation. Those boundary points were transformed into parametric objects. While these efforts successfully extracted sufficient boundary points to generate outline polygons of major features, the method was highly sensitive to user-defined length thresholds, which generated varying levels of geometric accuracy.

Alternatively, octree representations have been used in building reconstruction. For example, Wang et al. [6] used an octree representation to describe 3D data points, where the voxel was classified as either full or empty based on the number of data points within the voxel. Data points within the selected voxel were classified as boundary points, if they had at least one adjoining empty voxel. This method can detect all openings but gives relatively low geometric accuracy because the boundary points may contain few data points. To improve the geometric accuracy of the resulting models, Truong-Hong et al. [7, 8] proposed two different methods based on octree representations to improve the accuracy building façade and feature identification. One was based on Delaunay triangulation and the other on an angle criterion. Although the methods were successful in reconstructing relatively simple structures, they have not been adapted to more complex structures.

3 Proposed method



a) Proposed method to reconstruct a mesh of a building façade



b) Octree representation implemented in this method

Figure. 1 Overall Conversion Concept

This section presents a method that incorporates an angle criterion into a voxelization model to detect boundaries of a building façade and its features (doors and windows) (Figure 1). The proposed method has three main steps: (1) creation of a voxelization model using a hierarchical data structure by employing an octree representation to represent the façade point cloud; (2) generation of boundaries of the façade and its openings, where an angle criterion is introduced to extract boundary points from data points within the voxels on boundaries and then generation of boundary lines; and (3) reconstruction of a final building model. The building model was stored in a format compatible to FEM packages, where both topology and geometry were described by Boundary-Representations (B-Reps) [9].

After a TLS scanner acquires 3D topographic data of a building façade, a point cloud of the façade is a set of points, $P = \{p_1, p_2, \ldots, p_n\} | p_i = (x_i, y_i, z_i) \in R^3$. The point cloud includes both data points on the building façade and irrelevant data points (e.g. points of the terrain and vehicles), which can be manually removed using proprietary scanner software. Thus, the input data of the proposed method is only a point cloud of the façade projected onto a vertical fitting plane of the façade and excluded data points of architectural details, and the frames of windows/doors.

3.1 Feature extraction

An octree representation [8, 10] was employed to identify the initial bound façade data points. As TLS cannot collect a facade thickness, a preselected voxel dimension along the depth direction of the façade is assigned. Since the proposed method aim to create a 2D building façade, the subsequent subdivision mechanism of the octree representation is analogous to that of a quadtree [11], where a voxel is subdivided into four smaller voxels along the length and height directions of the façade (Figure 1b). Each voxel is described by its geometry and population properties. Geometry is defined by coordinates of each voxel's two opposite corners; for example the corners O and O' at the octree depth of 0 (Figure 1b). The voxel is considered as "full", if it contains at least one point, and is otherwise considered as "empty".

Openings (window and doors) are determined from a group of empty voxels, where no data points are available on a window/door area of limited reflectivity [12]. Similar to the work of Truong-Hong and Laefer [1], the minimum voxel size is considered as the termination condition, where the shortest side (either horizontal or vertical) of the voxel is less than half of the expected minimum opening size (MOS) as proposed as 0.4m [13]. Thus, based on this termination condition, the required octree depth along the x- and y-directions can be expressed as Equations (1) and (2).

$$depth\_x = \left\lceil \log_2 \frac{x_{max} - x_{min}}{MinVoxelSize} \right\rceil \quad (1)$$

$$depth\_y = \left\lceil \log_2 \frac{y_{max} - y_{min}}{MinVoxelSize} \right\rceil \quad (2)$$

where x_{max}, x_{min}, y_{max}, y_{min} are the minimum and maximum coordinates of the input point cloud. The term *MinVoxelSize* is set equal to half of the MOS expected to be detected. In these equations, (x_{max}-x_{min}) and (y_{max}-y_{min}) are, respectively, the length and height of the bounding box. The maximum octree depth is defined as being equal to the smaller value of *depth_x* or *depth_y*. A result of the voxelization model generated from input TLS data points (Figure 3a) is shown in Figure 3b.

3.2 Boundary line reconstruction

In order to reconstruct the building model, boundaries of features doors, windows and the overall façade must be detected. A door or window may appear as a hole representing a group of empty voxels. As such, a flood-filling technique [14] was employed to cluster the empty voxels. Then, the full voxels along the entire perimeter of a hole were extracted to represent the door or window. Moreover, the voxels representing a façade boundary are the full voxels attached to the bounding box of the data set and connected to empty cell groups outside the façade. A result of extracting the full cells describing the building features is shown in Figure 3c.

Next, points on boundaries of the façade and its openings, called boundary points, need to be extracted using the angle criterion from a set of candidate points located within the full voxels along the features' boundaries. A candidate point was stated as a boundary point, if the maximum angle between two consecutive neighbor points exceeded an angle threshold. The neighbor points (**q**) of the given point (p_i) were extracted from the neighbor voxels connected to the voxel containing p_i. The neighboring points, **q**, are subsequently projected onto its target-fitting plane and converted to a cylindrical coordinate system, where the local origin is set at a given point p_i. The angle between two consecutive neighboring points, $\alpha_{i,i+1} = \angle q_i q_{i+1}$, is computed as the difference between their azimuths. The given point p_i is a boundary point, if the angle ($\alpha_{i,i+1}$) exceeds the angle threshold by 90 degrees. A resulting boundary point extraction is shown in Figure 3d.

In reality, due to occlusions or imperfections, unrealistic openings may appear in the façade. To determine if a hole is a door/window, its characteristics are compared to ones of common building doors and windows [4, 8]. The hole is a window or door, if its equivalent height (H_0) and width (B_0) satisfy the condition expressed in Eq. 3. Details for determination of H_0 and B_0 are available in Truong-Hong et al. [1].

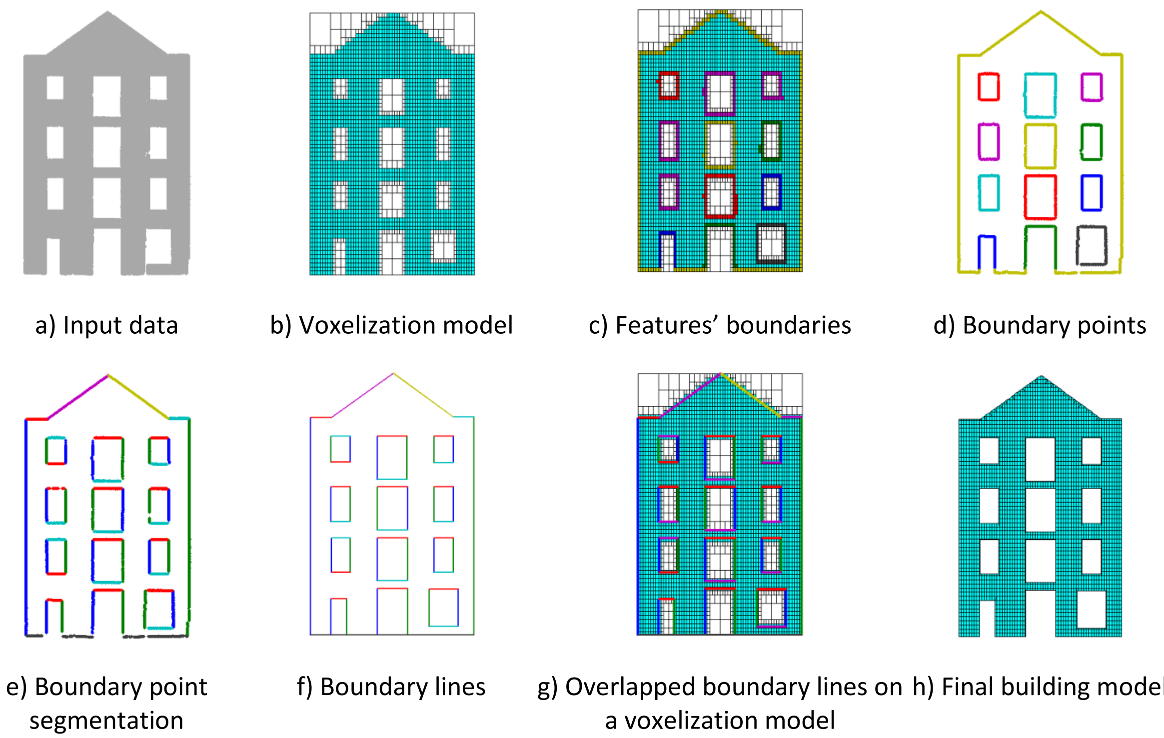


Figure 1. Illustration of the proposed method for building façade reconstruction

$$f(H_o, L_o, H_o/L_o) = \begin{cases} \textit{if } H_o \geq 0.4; L_o \geq 0.4; 0.25 \leq H_o/L_o \leq 5.0: \text{Opening} \\ \text{Otherwise}: \text{non-opening} \end{cases} \quad (3)$$

In actual buildings, many features have straight boundary lines, which are assumed herein. Boundary lines of building's features (i.e. façade, doors and windows), were reconstructed from the boundary points of each feature. The gird clustering technique was employed to extract the boundary points possessed by these voxels on the same grid. A result of the segmentation of the boundary points of each feature is shown in Figure 3e; for details of the clustering process see Truong-Hong and Laefer [1]. Finally, the boundary lines are determined from the boundary points within the full voxels of these voxel sub-clusters by using a least-squares method. After generating the boundary lines of each feature, gaps between the boundary lines are visible, which may not reflect a realistic boundary. To ensure continuity of the boundary, an extending and/or trimming of the boundary line was applied. Finally, complete boundary lines of the façade and its openings are generated (Figure 3f).

3.3 Final building model reconstruction

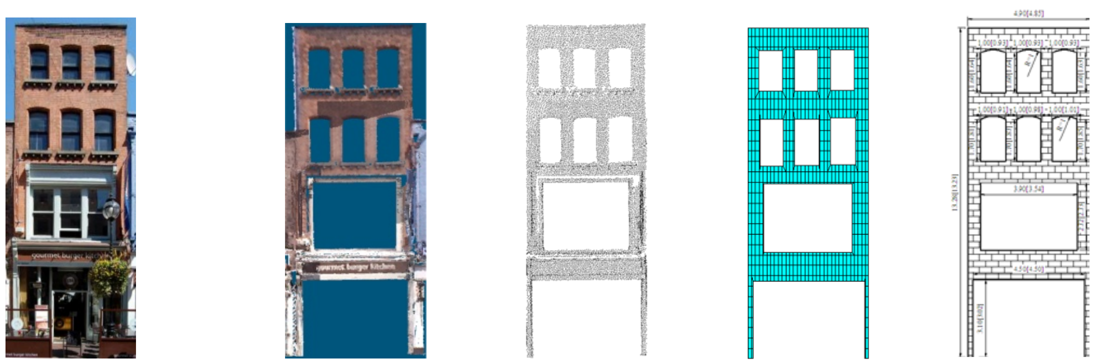
A new voxelization model is generated by dividing the initial voxelization model (Figure 3b) by the boundary lines (Figure 3f). As only full voxels belonging to the solid wall are converted into the solid model for direct importation into FEM packages, voxel properties in the initial octree representation must be re-assessed. Subsequently, each voxel in the re-voxelization model is characterized by using the Flying Voxel method proposed by Truong-Hong et al.[7], in which voxels inside of openings or outside of the façade are labeled as either full or empty. The final building model is shown in Figure 3h. The full voxels in the octree nodes are stored in a neutral file, whereas the topology and geometry are described as a B-Rep scheme [7].

4 Case study

One building façade at 5 Anne St. South in Dublin, Ireland was scan with a Trimble GS200 scanner with a sampling step of 10 mm at a 100 m range. The data collection processing was controlled by the affiliated propriety software RealWorks Survey Advanced (RWS) V6.3 [15]. Reference points for co-registering the multiple scan stations files were scanned with a sampling step of 2 mm at 100m. The acquired data included x-, y-, z-coordinates, intensity, and RGB values; for more details of the data acquisition see Truong-Hong [16].

Pre-processing point clouds by the RWS V6.3 involved registering the scans from the multiple scanner stations, and removing all irrelevant data points. A trial and error registration process was undertaken by selecting a pair of points from the source and target stations until the average error between the pair of data sets could be expressed in terms of a distance error of less than 5 mm. Moreover, data from internal walls/objects or occluding elements (e.g. trees and buses) were in different planes from the facade, which were manually removed using the RWS V6.3 in-built tools.

To evaluate efficiency and robustness of the proposed algorithm and to validate reliability of reconstructed building models, four sampling densities data were tested for the building facade, in which three data sets, NS20 (51,884 points), NS50 (11,119 points), and NS75(5,366 points) were randomly down-sampled using an in-built RWS V6.3 software function. Automatic generation of the building model is shown in Figure 4.



a) Photo Building (4.90m l x 13.28m h) | b) Scanning data points | c) Input point cloud | d) FE mesh of the building | e) CAD drawing(*)

(*) values in [] are derived from the proposed algorithms, while others are the independently measured survey values.

Figure 2. FE mesh for Building 5 Anne St. South based on a dataset of 400 points/m²

The proposed algorithm was successful in reconstructing the building façades and all openings, as well as automatically filling occlusion-based openings (Figures 4). To evaluate accuracy, the geometries of the derived building model were compared to measured drawings from independently produced on-site surveys (Figure 4e); façade dimensions and opening areas are shown in Table 1.

Table 1. Derived overall dimensions and opening areas of 5 Anne St. South

Aspect	Geometric information			
	CAD	**S20**	**S50**	**S75**
Length (m)	4.90	4.87	4.85	4.81
Height (m)	13.28	13.24	13.23	13.09
Opening area (m2)	34.46	32.79	33.17	32.53

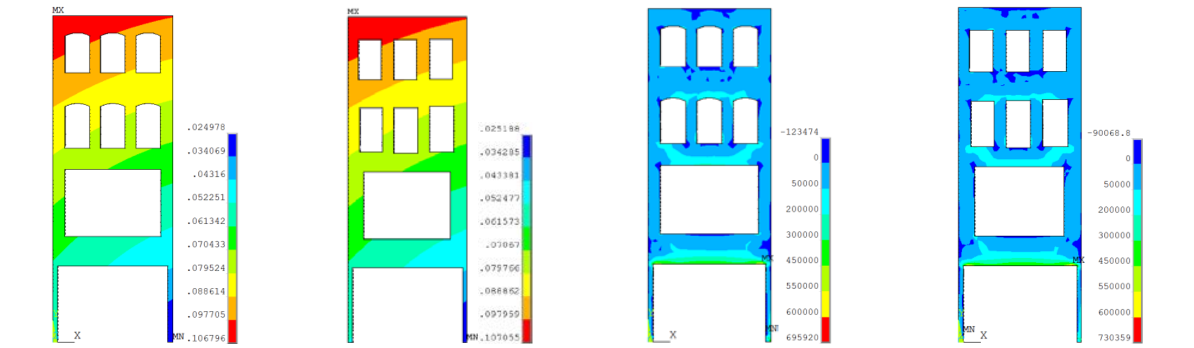
The algorithm slightly underestimated lengths and heights – generally less than 1.92% (<94 mm-S75) and 1.45% (<193 mm-S75), respectively. Additionally, the opening areas in the generated FEM mesh underestimated those apertures by 5.59% (<1.93 m2-S75) in terms of relative errors. The following section aims to evaluate the detailed impact of such geometric discrepancies in the FEM results.

The main goal of the proposed algorithm is to generate a building façade for computational modeling. As such, discrepancy of building geometry in the FEM results must be investigated. To evaluate the usability of these building models for a relevant case, the building was assumed to be subjected to settlement caused by adjacent deep excavation and self-weight. In this section, FEM results based on a building model derived from the proposed algorithm were compared to ones based on CAD drawings. The sampling data set S50 mesh was selected for further investigation.

Non-linear analysis was adopted for analyzing these brick buildings by using ANSYS Mechanical APDL product [17], where a macro-modeling strategy was employed to model the building facade by using the SOLID65 element [18]. Additionally, a William Warnke (WW) failure criterion and Drucker-Prager (DP) yield criterion built into the ANSYS program were respectively to model masonry behavior in tension and compression. Material properties were selected from existing experimental reports and the peer-reviewed literature to represent medium-strength masonry properties [19]. These were as follows: for elastic behavior a Young's modulus of 3,480 MPa and Poisson's ratio of 0.16, and for plastic behaviour 26.15/1.15 MPa for the compressive/tensile strength, 6.81 MPa internal cohesion, 35° internal friction angle, and 10° dilatancy angle. The ANSYS meshing engine was employed to generate the FEM meshes for the building models-based CAD drawings with a predefined element size of 0.15 m. The buildings were assumed to be 2 m behind the excavation face (Table 2). Imposed displacements due to excavation-induced settlements were directly applied to nodes on the bottom of the model (Figure 4d).

Table 2. Trough settlement profile adopted as input for numerical modeling

Distance (m)	Displacement	
	Vertical	Horizontal
0.00	64.12	39.36
0.64	57.40	
1.52	48.01	28.75
2.79	38.61	
4.57	28.19	25.63
6.60	18.29	
7.62		15.42
9.14	11.43	
12.19	6.10	14.02



a) Displacements in CAD b) Displacements in S50 c) Principal stress 1 in CAD d) Principal stress 1 in S50

Figure 3. FEM results of 5 Anne St. South

Graphically, FEM results show a consistency of nodal results (displacement and principal stress 1) between the FEM models based on two sources, although their values differ slightly (Figure 5). The maximum nodal displacement differs by no more 0.3% (CAD: 96.203 mm vs. S50: 96.473 mm) for a vertical displacement, with an absolute difference of only 0.27 mm. Moreover, differences in horizontal displacements are generally greater than ones in the vertical, where the relative error of the vertical displacement is 0.01% with the absolute error of 0.04 mm.

Similarly, principal stress and strain 1 in the FEM models generated from the proposed method also show only small differences from those in the models based CAD drawing. In terms of the absolute error, the principal stress 1 differs 0.044 MPa (CAD: 0.659 MPa vs. S50: 0.703 MPa), while this error is 0.200x10-3 for the principal strain found in a pair of FEM models. From an engineering perspective, this difference in FEM results is well below accepted uncertainty levels within structural analysis of a building. Indeed, the algorithm proposed herein can be used for auto-generating FEM meshes from TLS data.

5 Concluding remarks

This paper presents a method to automatically reconstruct the building model from laser scanning data without any manual intervention. The method mainly involves a combination of a voxel-based technique and an angle criterion. Initially, the voxelization model was used to represent the façade model, while the angle criterion is implemented to determine boundaries of the façade and its openings (doors and windows). The algorithm overcomes the common problem of occlusions or artefacts that arise during data acquisition.

The proposed method was successfully deployed in automatically generating meshes of building façade models compatible with commercial FEM software. The resulting geometric models were validated by checking the mean discrepancy of their geometries with relative errors of overall dimension and opening area less 2% and 6%, respectively. Furthermore, the subsequent FEM results were compared ones derived manually from the reference data using the application case of excavation, where a building was subjected to self-weight and settlement caused by deep excavation. Differences in the FEM results were generally less than 1.6% for the maximum nodal displacements, while the maximum principal stress and strain 1 are respectively 0.478 MPa and 4.74×10^{-3}.

6 Acknowledgments

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