Automated generation of geometric digital twin of roof for building retrofitting

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ABSTRACT

Digital representations of buildings play a crucial role in building retrofitting and energy modelling. Acquiring sufficient and accurate building data poses challenges, particularly in obtaining geometric information about a building's roof. Previous studies have been conducted on roof detection using aerial laser scanning point cloud data on an urban city scale. However, extracting roof geometry information from individual buildings using terrestrial laser scanning remains a challenging task due to the natural incompleteness of data for building roofs. This research aims to propose a digital twin-based framework for automatically generating the geometric information of existing building roofs required for retrofitting from terrestrial laser scanning point cloud data. The 3D laser scanning technique is adopted for data capturing. The framework includes: (1) collecting and pre-processing the point cloud data, (2) automated detection of the roof points from the building's point cloud, and (3) extracting roof geometry parameters required for building energy modelling. The final output of the proposed method is an information-rich digital twin of the building's roof. The proposed framework is validated through a case study, presenting an automated pipeline to enrich a geometric digital twin of the roof with details. This research contributes to providing geometric information for energy simulation, building energy modelling, and building retrofitting. The findings can be further validated across various building types and applied to urban building energy modelling.

INTRODUCTION

The energy-efficient retrofitting of existing buildings is a crucial task in many countries (Previtali et al. 2014; Sun et al. 2019). For example, in Europe, numerous old buildings face challenges such as energy loss and higher operational costs, and there is an increasing need for them to become more energy-efficient (Massafra et al. 2022). Building envelope retrofit plans should be assessed before execution. However, current building energy simulation for retrofit is mainly based on parameters as they are documented instead of in their present conditions (Hou and Volk 2022). As mentioned by Gao et al. (2019), in previous methods of building energy simulation modelling, only regular shapes of a building have been tested, and a more complex geometry such as roof geometry is required to be included as well. In real practice, there are different types of roof structures that could have complex roof shapes. The roof is always simplified as a horizontal planar, rather than pitched (Yan et al. 2019). In addition, the inclination angles of the building roof are also a critical factor for energy simulation (Mazzeo and Kontoleon 2020). Providing detailed roof information could enhance the accuracy and reliability of the building energy simulation results. However, limited studies have been conducted for this purpose.

Therefore, an approach to obtain the geometry information of roof accurately and efficiently is required to be developed. This research aims to propose a digital twin-based framework for automatically generating the geometric information of existing building roofs required for retrofitting. The proposed framework includes automated detection of the geometry information and the roof inclination angles. This research combines the concept of the energy simulation modelling and digital twin, which could provide sufficient information for building retrofitting. Compared to previous studies, this research contributes to providing geometric information for energy simulation, building and urban building energy modelling, and building retrofitting.

LITERATURE REVIEW

Remote sensing techniques, such as photogrammetry and Light Detection and Ranging (LiDAR), are effective in collecting 3D information of building structures effectively and accurately. Previous studies have been intensively conducted on the reconstruction of building roofs from airborne Light Detection and Ranging (LiDAR) point clouds (Li et al. 2022). Currently, there are mainly three categories of the methods to reconstruct building roofs from aerial laser scanning (ALS) point cloud data: model-based methods, data-driven methods, and deep learning-based methods (Li et al. 2022). Model-based methods typically assume that the structure of buildings can be approximated by the combination of several predefined simple parametric shapes (Haala and Brenner 1999). Data-driven methods reconstruct 3D building models from extracted primitives. The main roof primitives are extracted from input LiDAR point clouds using point segmentation algorithms, with the roof faces assumed to be planar. Subsequently, 3D building models are reconstructed by analysing the primitive topology (Chen et al. 2014). Deep learning methods have been proposed for building roof reconstruction with the advancements in artificial intelligence techniques. The shape type of each point can be predicted by applying deep learning methods, such as PointNet (Xu et al. 2020). The deep networks can detect and refine the locations of model vertices for each building, as well as predict the valid edges between vertices for each building (Li et al. 2022). Following this, the roof primitives for each shape can be extracted, and the 3D building models can be reconstructed using the roof topology, similar to data-driven methods.

However, although these methods could segment the roof from the point clouds, the crucial step for the building energy simulation modelling is still missing that needs to consider more detailed geometry information of the roof for the building retrofitting. Moreover, previous studies conducted on roof detection mainly utilised the point cloud collected by ALS, however, in real practice, the ALS point cloud data is not always available for the individual building. The traditional terrestrial laser scanning (TLS) is usually not able to collect the surfaces of roofs. The lack of scanning of roof surface remains a common problem and there is a research gap of how to extract roof geometry information from the TLS point cloud data.

METHODOLOGY AND EXPERIMENT RESULTS

The proposed framework includes automated detection of geometry information and the roof inclination angle from TLS point cloud data. The pipeline is illustrated in Figure 1. This research focuses on the hip roof with inclination angles, as depicted in Figure 2a. To automatically detect the roof from the point cloud and extract the required geometry information, this research adopts façade detection first. Based on the extraction of the façade, a polygon is fitted on each façade. With prior knowledge of the building, it is assumed that the highest three vertices of the fitted polygon belong to the edge of the roof. Thus, the main geometry information of the roof, as shown in Figure 2a, can be extracted.

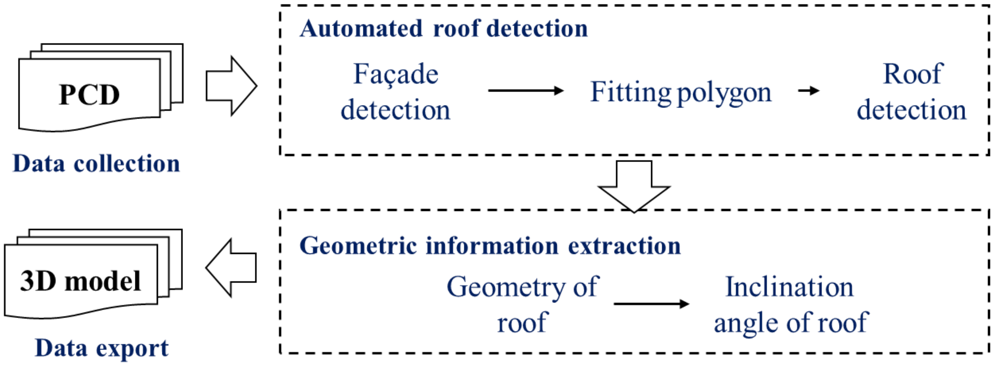
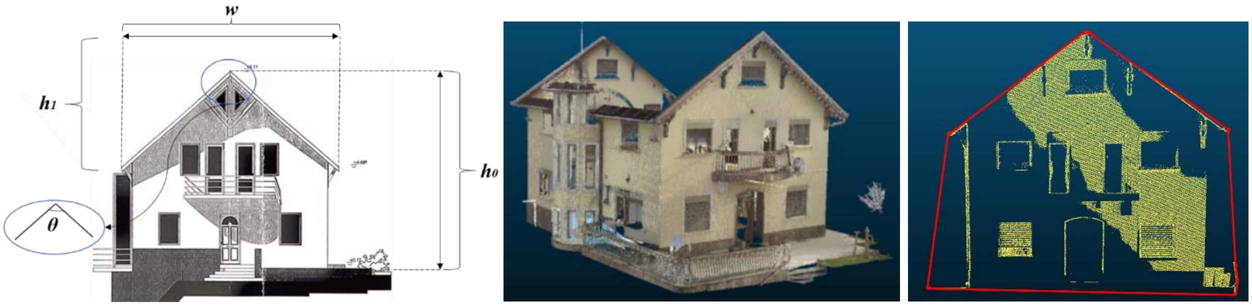


Figure 1. Pipeline of the proposed framework.

The input to the proposed framework is the point cloud of the building façade. Given that façades are generally vertical planes in common building structures, this research focuses on detecting vertical or near-vertical planes from the input point cloud. To correctly estimate the height h_0, the algorithm also requires horizontal or near-horizontal floors. The highest, leftmost, and rightmost vertices of the higher part of the polygon derived from the detected planes are identified as the vertices of the roof. According to the calculation of the distances, the width of the roof w and h_1 can be also computed. The roof inclination angle θ is determined equal to the angle of the polygon.

To validate the effectiveness of the proposed approach, a real case of a house with a hip roof is used for experimentation. The point cloud data of the case is presented in Figure 2b, containing the façade of the house. It is obvious that the roof part is not completed scanned in the data. To reconstruct the roof, the geometry of the roof in Figure 2a were extracted. Following the processing of the point cloud data, the vertical plane of the façade is successfully detected, as depicted in Figure 2c. Assuming that the hip roof should resemble the shape of a triangle, the side view of the façade is automatically selected for subsequent processing.

After the detection of the façade, a polygon is fitted to envelop the point cloud boundaries, as shown in Figure 2c. Identifying the vertices of the point cloud forms the basis of the polygon. Subsequently, geometry information is successfully extracted based on the fitted polygon from Figure 2c. The computed results indicate h_1 as 4.6 m, h_1 as 9.9 m, θ as 45 °, and w as 10.7 m. This information can be directly employed as roof parameters in building retrofitting and building simulation modelling.



(a) (b) (c)

Figure 2. Experiment results (a) Geometry parameters of the hip roof, (b) Point cloud data of the façade, (c) Fitted polygon of façade

DISCUSSION AND CONCLUSION

In conclusion, this research addresses a critical challenge in building retrofitting and energy modelling by proposing a digital twin-based framework for automatically generating geometric information of existing building roofs from terrestrial laser scanning point cloud data. The study acknowledges the difficulties in acquiring accurate roof geometry, particularly from the incomplete data collected by TLS at the individual building level. The proposed framework encompasses the collection and pre-processing of point cloud data, automated roof point detection, and extraction of essential roof geometry parameters. The outcome of the method is a comprehensive digital twin of the building's roof, rich in information.

The validation of the framework through a case study demonstrates its effectiveness in automating the process and enriching the geometric digital twin with intricate details. This innovative approach contributes significantly to providing essential geometric information crucial for building roof. This research has various practical applications, which contribute to building energy efficiency and building retrofitting studies.

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