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BENCHMARK FOR TOPOLOGICAL AND SPATIAL ASSESSMENT OF INDOOR RESIDENTIAL BUILDINGS

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Abstract

Our paper introduces a new benchmark for evaluating indoor residential buildings, addressing the lack of standardization in building assessment methods. Utilizing laser-scanned point clouds, we capture diverse architectural styles, enhancing accuracy in maintenance, navigation, and safety planning. Our approach, underpinned by precise reference models and metrics, allows for comprehensive method comparisons. The accompanying datasets ensure reproducibility and wide applicability. This benchmark, available publicly, fosters collaborative research and advances building assessment techniques, ultimately improving the resilience and sustainability of residential structures.

Introduction

In the domain of building assessment, understanding, and analyzing indoor residential environments is crucial. These environments, central to daily human experiences, are characterized by a myriad of spatial and topological complexities (Zhang *et al.*, 2022).

Accurate spatial analysis is vital for effective space management, enhancing living comfort and functionality, while topological assessment is crucial for efficient navigation, particularly in emergencies, to ensure safety and accessibility. The point cloud technology marks a significant leap in accurately representing these environments. With its ability to provide precise 3D representations, point cloud offers an unprecedented level of detail and accuracy(Cheng *et al.*, 2018). This advancement has facilitated more realistic modeling of indoor environments, impacting fields ranging from architectural design to emergency planning (Gankhuyag and Han, 2020; Guo *et al.*, 2021).

Despite its importance, the field of building assessment faces significant challenges, primarily due to a lack of comprehensive and precise benchmarks specifically tailored for residential buildings. Existing methods and datasets often fall short in capturing the unique complexities and diversity inherent in residential environments (Chen *et al.*, 2023). This gap in accurate and scalable representation and assessment tools hinders advancements in architectural design, maintenance, and safety planning, ultimately impacting the efficacy of residential space utilization.

Our research addresses this critical gap by introducing a novel benchmark for the topological and spatial assessment of indoor residential buildings. Utilizing advanced laser-scanned point cloud datasets, this benchmark is meticulously crafted to capture diverse architectural styles and layouts of residential environments. The primary objective is to provide a robust and versatile tool that enhances the accuracy and comprehensiveness of building assessments, thereby facilitating effective maintenance, navigation, and safety planning in residential spaces.

In developing this benchmark, we employed a multifaceted approach that integrates various scanning technologies and environmental conditions. This approach ensures a broad and realistic representation of residential spaces, reflecting the complexities encountered in real-world scenarios. The benchmark's methodology emphasizes the precision, accuracy, and chromatic fidelity of the point cloud data, making it a highly reliable resource for evaluating building assessment methodologies.

Our primary goal is to bridge the existing research gap by offering a new database and robust evaluation metrics. This benchmark, featuring diverse point cloud data, is designed to advance algorithms tailored for residential settings, contributing to more efficient and accurate building maintenance, safety planning, and architectural design, ultimately enriching residential living spaces. This paper is structured as follows: Section 2 provides a detailed review of related work addressing the study foundation. Section 3 discusses the benchmark setup, from data acquisition to evaluation. Finally, Section 4 concludes the paper, summarizing our contributions and suggesting directions for future research.

Point of Departure

In this section, we discuss existing datasets and benchmarks in the field of residential indoor building assessment, specially from laser scanning. This frames our study within the broader landscape of architectural technology and highlights the value of our research focus. In the exploration of indoor datasets, various collections have emerged, each with unique attributes and limitations. ISPRS dataset (Khoshelham *et al.*, 2017) emerges as a notable collection, focusing on indoor modeling through point clouds, while rich in indoor point cloud data from varied environments like universities and a fire brigade office, presents certain limitations for our research focused on residential environments. The dataset's emphasis on institutional settings differs markedly from the complexities inherent in residential spaces, making it less applicable for studies centered on residential layouts. Similarly, the ScanNet dataset (Dai *et al.*, 2017) and the SceneNN dataset (Cheng, Meng and Sun, 2020) have made strides in capturing a range of indoor scenes. However, most of their scans are constrained to one or two rooms. This limitation significantly hinders their applicability in the domain of scalability, where a broader understanding of entire residential units is essential.

The ETH3D dataset [13], for instance, includes a modest collection of 16 indoor scans. While valuable for multi-view stereo applications, its limited scope and primary focus on stereo rather than 3D point-cloud processing render it less suitable for our scope. Contrasting with real-world data, the SUNCG dataset (Song *et al.*, 2017) offers a synthetic alternative, presenting a wide array of indoor scenes with CAD-quality geometry and annotations. However, the synthetic nature of SUNCG means it cannot fully capture the complexity and unpredictability of real-world residential settings, a crucial element for authentic floorplan generation.

Diverging from these, Floor-SP (Chen *et al.*, 2019) and Matterport3D (Yadav *et al.*, 2022) bring RGBD image sets. Matterport3D dataset brings forth high-quality panorama RGBD image sets encompassing 90 luxurious houses. While offering rich visual data, its format and focus do not align with the specific needs of laser scanning. In a similar vein, the Stanford 2D-3D-S dataset (Armeni *et al.*, 2016) provides large-scale scans of office spaces using the same Matterport camera technology. Despite its scale, the dataset's emphasis on 2D and 3D semantic annotations does not address the nuanced requirements of residential environments.

Among these, the Floor-NET dataset (Liu, Wu and Furukawa, 2018) stands out with its provision of full floorplan annotations and corresponding RGBD videos from smartphones for 155 residential units. Despite its closer alignment with residential applications, its format and the mode of data collection may pose challenges in scalability and accuracy when applied to broader residential scenarios. In addition to these datasets, numerous ad-hoc datasets have been developed (Fang *et al.*, 2021; Tang *et al.*, 2022; Kim and Lee, 2023), each tailored to specific tasks or applications. While these datasets contribute valuable insights to their respective areas, their specialized nature often limits their utility in a broader context, particularly in studies focused on scalability and general applicability in residential environments.

This examination of various indoor datasets underscores a prevalent issue: while numerous datasets provide valuable insights into indoor environments, they notably lack in addressing the comprehensive needs of residential building representation. A key challenge is the absence of datasets offering extensive scans of real-world residential spaces, including furnishings, a gap often attributed to privacy concerns. Moreover, the tendency for many datasets to be ad-hoc or overly specialized limits their utility in research focused on scalability and broad applicability in diverse residential settings. Considering these limitations, our research introduces a novel benchmark utilizing laser scanning (point cloud) technology. This benchmark is specifically designed to capture the intricate details and complexities of residential buildings, addressing the critical need for a more accurate and scalable approach in the topological and spatial assessment of indoor residential environments. This advancement not only fills a significant void in the current research landscape but also sets a new standard for precision and comprehensiveness in the field of building assessment.

Benchmark Setup

Benchmark dataset

In constructing this benchmark, we implemented a wide selection process for point cloud data, adhering to meticulously defined criteria to ensure a comprehensive and accurate depiction of a variety of residential buildings. This evaluation focused on key factors such as precision, accuracy, chromatic fidelity, and the granularity of details within individual data points.

We also prioritized diversity in data acquisition methodologies, incorporating a range of scanning technologies and environmental conditions to authentically mirror complex, real-world data collection scenarios. Moreover, the curation of point cloud content was strategically executed to encompass a wide array of residential spaces, each with their unique architectural styles and spatial layouts. Table 1 delineates these point cloud specifications and criteria. First, we classify the criteria into three main categories: point criteria (PCr.), scan condition (SCd.), and scan content (SCt.). then, accuracy, colors, number of points in millions (No.), and sensor type were added to the point criteria. Acquisition complexity (AC) and moving objects (MO) were added to scan condition category. Finally, building type (BT) and furniture (F) were added to the scan content. This systematic approach in dataset compilation not only addresses the shortfall in publicly available datasets but also establishes our benchmark as a model of versatility and practical applicability in residential building assessment.

Table 1:Point cloud data criteria

		D1	D2	D3	D4	D5
PCr.	Acc.	6-8 mm				1 cm
	Color	✓	✓	x	✓	✓
	No.	316	321	319	6.6	252
	Sensor	TLS / MLS		TLS	MLS	TLS
SCd.	AC	✓	✓	x	✓	✓
	MO	x	x	x	x	✓
SCt.	BT	H	H	H	D	A
	F	✓	✓	x	✓	✓

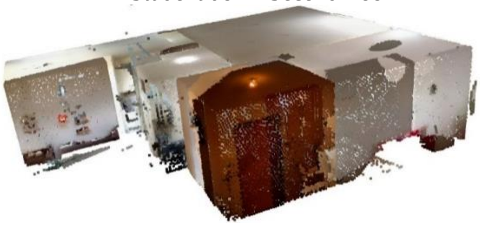
Our dataset includes a curated selection of five residential environments, each representing different living settings and contexts. It features datasets from a multi-floor house (D1, D2), offering an urban residential perspective with challenges like clutter, occlusions, and elaborate interior designs.

D1-House-First Floor

D2-House-Second Floor

D3-House-Under construction

D4-Student dorm-Second floor



D5-Apartment-11th Floor

Figure 1:Point cloud data screenshots.

An additional dataset from a fully furnished apartment (D5), situated on the 11th floor, showcases the intricacies of high-rise living environments. We also included a ground floor dataset from a house under construction (D3), highlighting the complexities of unfinished architecture. Complementing these, a dataset from the second floor of a fully furnished student dormitory (D4) adds to the architectural and contextual diversity. Figure 1 provides a visual representation of these diverse point cloud data.

For data acquisition, we employed both Terrestrial Laser Scanning (TLS) and Mobile Laser Scanning (MLS) methodologies, tailored to the specific characteristics of each residential setting in our dataset. The Trimble X9 TLS system, renowned for its extensive range and high precision, was used, achieving an exceptional accuracy of 8 mm, particularly in interior scans. In contrast, for the dormitory dataset (D4), we utilized the MLS capabilities of the iPhone’s LiDAR sensor, which offers suitable navigation and accuracy (±1 cm) within apartment spaces (Luetzenburg, Kroon, and Bjørk, 2021). Notably, datasets D1 and D2 were captured using a combination of TLS and MLS technologies, leveraging the comprehensive range of the Trimble X9 and the agility of the iPhone's LiDAR sensor. This dual-technology approach for D1 and D2 ensures a richly detailed representation of the intricacies inherent in residential spaces.

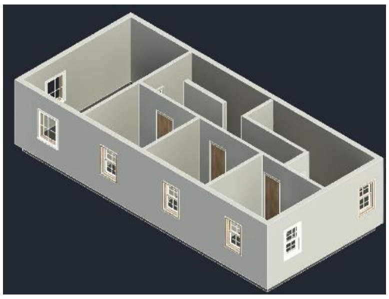
Table 2 provides detailed technical characteristics of these two scanning devices. By integrating both TLS and MLS methods, our benchmark accurately reflects the varied challenges and scenarios present in residential buildings, demonstrating the efficacy and adaptability of diverse laser scanning technologies in different residential contexts. Contrasting with many existing benchmarks that typically engage in preprocessing to remove noise and reflections, our benchmark adopts a novel approach. We emphasize the importance of preserving and incorporating indoor noise elements within each residential space. This decision stems from our understanding that noise, particularly in indoor environments, is an inherent characteristic of real-world data. It offers valuable insights into the everyday use and dynamics of residential spaces.

Table 2: Laser scanners technical characteristics

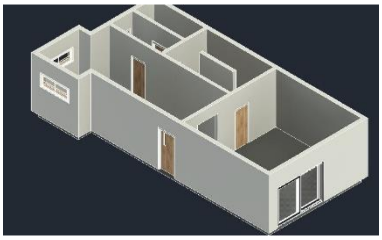
Specs.	TLS	MLS
Range	120 m	3 m
Accuracy	6 – 8 mm	± 1 cm
Acquisition time (one floor)	60 min	3 min

Reference models

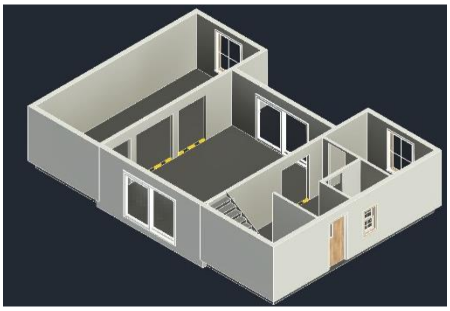
In the development of our benchmark, a fundamental component was the construction of models using Autodesk Revit™. This step involved the detailed creation of 3D models that are essential in residential buildings. While our primary focus was on the 3D models themselves, these models inherently facilitate the generation of crucial elements like adjacency graphs, navigation plans, and evacuation paths. As depicted in Figure 2, these models provide a comprehensive foundation for understanding and analyzing the spatial and topological aspects of residential environments. By focusing on 3D modeling, we ensure that the essential characteristics of residential buildings are accurately captured, laying the groundwork for subsequent analytical processes that are vital in assessing and understanding the dynamics of these spaces.



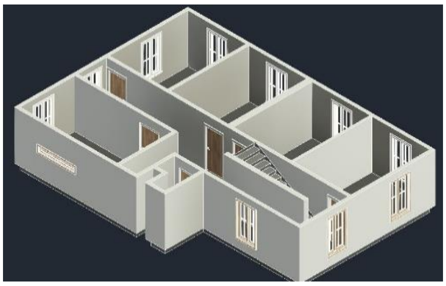
D1



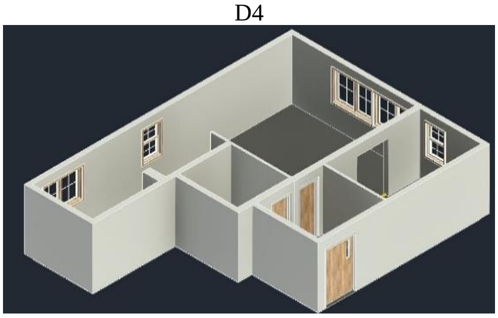
D2



D3



D4



D5

Figure 2: 3D reference models.

In the geometric reconstruction phase, we undertook a series of systematic procedures. These included adjusting levels, constructing walls, and other architectural elements, and integrating doors, windows, and circulation components. Notably, this reconstruction process did not rely on manual on-site measurements but solely on the precision inherent in the point cloud data. This strategy highlights the effectiveness of modern scanning technologies in accurately capturing indoor residential environments. By depending exclusively on point cloud data, our reference models not only demonstrate the capabilities of advanced scanning technologies in building assessment but also challenge the traditional dependency on labor-intensive manual measurement methods.

Additionally, it is crucial to address the concept of 'ground truth' within the context of point cloud processing. Typically, 'ground truth' refers to a model manually constructed in software, representing an 'as-built' or 'as-is' scenario. While these models are highly accurate, they are not without limitations. In our benchmark, these models are utilized more as a comparative standard rather than an absolute ground truth. They provide a robust and reliable foundation for evaluation but are acknowledged as not being infallible. This nuanced understanding of 'ground truth' is fundamental in our approach, ensuring that our benchmark provides a realistic and practical standard for evaluating the performance of various methodologies in the realm of residential building assessment.

Evaluation metrics

In our benchmark, specifically designed for topological and spatial assessments in residential environments, we incorporate a range of tasks including area measurement, floorplan generation, adjacency graph construction, navigation, and evacuation planning. Recognizing the integral role of geometric evaluation in understanding topological and spatial data (Pintore *et al.*, 2020), our metrics also encompass the assessment of geometric accuracy in reconstructed models. This approach ensures a thorough evaluation of algorithm performance beyond just computational efficiency and automation level, with a focus on the quality of algorithms in relation to indoor residential environments.

For geometric accuracy assessment, we utilize the Root Mean Square Error (RMSE), a well-established statistical measure in spatial data analysis (Li *et al.*, 2017). RMSE quantifies the variance between predicted and observed spatial dimensions, thereby evaluating the precision of area measurements in a reliable and quantifiable manner.

In evaluating floorplan generation, our benchmark employs accuracy metrics: Recall, Precision, and F1-score. These metrics, prevalent in pattern recognition and information retrieval, offer a multidimensional perspective on the accuracy and completeness of generated floorplans (Kim and Lee, 2023).

To address the evaluation of topological relations and spatial assessments, such as adjacency graph construction, navigation, and evacuation planning, we adopt a dual approach. **Qualitatively**, usually experts conduct a visualization evaluation, subjectively assessing the clarity, accuracy, and usability of the representations (Knauff, Rauh and Renz, 1997). **Quantitatively**, we implement graph similarity measures, like graph edit distance, to evaluate topological relations. This measure calculates the minimum number of edits needed to transform one graph into another, thus gauging the fidelity of the algorithm-generated graphs compared to our reference models. Additionally, spatial accuracy metrics should be employed to assess deviations in spatial configurations, and consistency checks are conducted to ensure the logical coherence of spatial arrangements. This combination of subjective and objective evaluations forms a comprehensive assessment framework, capturing both the perceptual quality and the measurable accuracy of spatial models in residential environments.

Accessibility and Participation

In line with our commitment to collaborative scientific progress, our benchmark will be made publicly accessible. We invite scholars, practitioners, and members of the scientific community to engage with this dataset, which will be available for download from the Deposit once Repository. This open-access initiative is designed to stimulate comprehensive utilization and analysis of the dataset, thereby contributing significantly to advancements in the field.

We strongly encourage scholarly engagement from researchers interested in applying and investigating various methodologies and algorithms with our database. This invitation extends to a diverse spectrum of researchers from both academic and industrial spheres. We advocate for the exploration of a wide range of application scenarios, including emergency response planning and architectural design. The insights gained from these explorations are expected to be invaluable in enhancing our understanding of current algorithmic capabilities and limitations and could lead to innovative developments in the field.

We are introducing a set of guidelines for its effective use and implementation. These are designed to bridge the gap between theoretical research and practical application, providing clear, actionable steps for accessing and utilizing the benchmark. Users can navigate the point cloud raw data and reference Revit files via the repository, enabling straightforward integration into their projects. For each specific application, practitioners are encouraged to refer back to this paper for the relevant proposed evaluation metrics to ensure accurate and effective application. This commitment to support aims to foster a collaborative environment, encouraging the widespread adoption and application of the benchmark across various professional domains.

Conclusion

This research has established a new benchmark for the topological and spatial assessment of indoor residential buildings, an area that has been inadequately represented in existing datasets. By incorporating a variety of point cloud data acquired through laser scanning, this benchmark serves as a crucial tool for the precise evaluation of algorithms related to this domain. Our benchmark, anchored in constructed reference models, provides a solid criterion for both geometric and topo-spatial assessments. This addresses significant gaps in existing methodologies and sets a new standard in the field. Looking forward, this benchmark opens the door to a multitude of research avenues and practical applications, marking a significant advancement in the field of spatial data analysis. Its potential extends across various domains, from enhancing emergency response strategies to innovating architectural design and urban planning. A key direction for our future work will involve conducting real-world case studies to present and validate the practical applicability and effectiveness of our benchmark across a diverse range of architectural styles and environments. we will illustrate how the application of our benchmark can lead to tangible improvements in building performance, such as increased energy efficiency, improved occupant well-being, and reduced environmental impact, thereby fulfilling our vision of fostering more sustainable and resilient living environments. The benchmark is poised to be a cornerstone in the development of more accurate and efficient algorithms, fostering interdisciplinary collaborations that blend expertise from architecture, urban planning, data science, and beyond. Additionally, it offers a platform for integrating emerging technologies like augmented reality for immersive visualizations and AI to develop advanced evaluation metrics, we aim to set new standards in spatial analysis, ensuring our benchmark remains at the forefront of architectural assessment and urban planning. While our dataset encompasses a variety of architectural styles, we aim to expand its diversity by incorporating more settings, featuring unique design elements and circulation patterns, to enhance its applicability. Also, by integrating socio-cultural aspects, recognizing the impact of social norms and cultural values on residential architecture. This inclusion will allow our benchmark to evaluate and guide the design of spaces that are not only physically sound but also resonate with the cultural and social fabric of their communities more accurately. In addressing the limitations of our benchmark, we acknowledge challenges in the acquisition of point cloud data for complex residential indoor environments, like furniture, which may not fully capture the intricacies of such spaces. However, this journey also invites us to confront and navigate the challenges and limitations inherent in such pioneering work, ensuring continuous improvement and relevance in an ever-evolving landscape.

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