The Evolution of 3D Point Cloud Applications in Construction: A Review from 2014 to 2023

Hongzhe Yue

School of Civil Engineering, Southeast University, Nanjing 211189, China
Corresponding author's E-mail: yuehongzhe@seu.edu.cn

Abstract

The construction industry is shifting from traditional methods to digital approaches. Point cloud technology, which offers precise geometric information, is increasingly used for 3D model reconstruction, quality inspection, and more. Existing reviews often fail to capture recent trends or focus narrowly. This paper reviews the latest advancements in point cloud applications in construction, covering literature from 2014 to 2023 and summarizing six major applications: 3D model reconstruction, geometry quality inspection, construction progress tracking, safety management, heritage management, and construction robot applications. This review underscores the significance of point cloud technology in driving the digital transformation of the construction industry.

Keywords: point cloud, construction industry, applications.

1. INTRODUCTION

In the Construction 4.0 era, the industry is moving from manual methods to a digital and intelligent paradigm. Traditionally, construction relied on laborious tasks and manual BIM creation, prone to errors and time-consuming. Point clouds, obtained through high-precision 3D scanning, offer faster and more accurate measurements compared to manual techniques. This technology supports the industry's transition to Industry 4.0 by providing precise data capture and efficient processing, facilitating digital transformation.

Point clouds have become essential in model reconstruction, geometric quality checks, and progress tracking. They enable accurate BIM workflows and structural integrity assessments. Integration with technologies like BIM and Digital Twins allows for real-time analysis of construction projects. This review addresses the gap in literature by providing a comprehensive overview of 3D point cloud applications in construction from 2014 to 2023.

2. APPLICATION OF POINT CLOUD IN CONSTRUCTION INDUSTRY

Based on the literature reviewed, the applications of 3D point cloud data in the construction industry are primarily centered around 3D model reconstruction and geometry quality inspection, as depicted in Fig.1. In addition to these fundamental applications, point cloud technology is also employed in progress monitoring and tracking, construction safety management, heritage, and historical management, building energy monitoring, and applications in construction robotics.

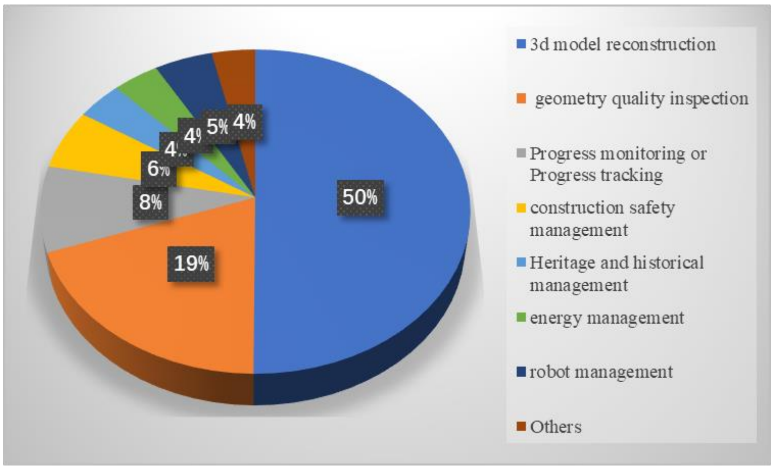

Fig. 1. Number of papers for each point cloud application in the construction industry.

2.1. 3D model reconstruction

In 3D model reconstruction, point cloud data is crucial, enabling the creation of three-dimensional models for construction-related objects, including construction sites, buildings, and civil infrastructures. Construction sites feature elements such as scaffolds, construction equipment, while buildings encompass various structures, predominantly office buildings, focusing on architectural elements like rooms, floors, ceilings, beams, walls, stairs, windows, and doors. Industrial buildings primarily assess MEP components and pipes, and other structures like heritage buildings, schools, apartments, and parking lots are also included, as shown in Table 1.

Table 1. Representative literature on 3D model reconstruction across various categories.

Category	Literature
Construction site	Scaffolds [19,25,59], construction equipment [52], earthwork model [15]
Buildings	Office buildings [2,24,28,31,35,38,47,57,58,62,64], industrial buildings [39,46,50,51], heritage buildings [32,37,40], school and apartment [22], residential and industrial buildings [53], parking lots [11], 3D bas-relief [5]， steel structures [27]， ribbed masonry vaults[1]
Civil infrastructures	Bridges [16,21,28,30], sewer manholes [3], roads [4,17,18,67], tunnel [12]

3D model reconstruction using point cloud data is divided into geometric and semantic model reconstruction. Geometric model reconstruction translates original sensory data into point clouds, representing target objects' physical dimensions and shapes, utilizing techniques like feature-based registration for laser scans and photogrammetry or videogrammetry for 2D data [7,8,63,66]. Semantic model reconstruction adds object-based semantic information into geometric data, encompassing geometric modeling and object recognition, labeling point cloud parts into categories like walls, floors, or windows, employing methods such as the Hough Transform, region growing and RANSAC for surface detection [14,42,48], and various learning methods for object recognition. This combination provides a detailed and functional 3D model.

Regarding object recognition, there are two main approaches: based on prior knowledge and machine learning or deep-learning. The prior knowledge-based approach focuses on using object attributes and geometrical relationships to generate as-built Building Information Models (BIMs). Some studies utilize object attributes, for instance, identifying floors and ceilings as horizontal [43], walls based on verticality and large surfaces [2], and pipes, valves, and pumps by their contours [46], or distinctive curvature patterns of pipe spools [10]. Others use geometrical relationships, like columns identified by parallel gaps between floors and ceilings [43], walls being vertical and positioned between floors and ceilings [28]. Many studies combine object attributes and geometrical relationships, for example, walls as vertical surfaces with windows and doors as openings in the walls, the positioning of windows above doors, and roofs as vertical elements above walls [53].

2.2. Geometry quality inspection

Point cloud data, capturing the precise existing conditions of various structures, are increasingly utilized in the geometric quality assessment of architectural and civil engineering projects. These assessments, tailored to the specific types of geometric quality concerns, can be broadly classified into three distinct categories: (1) dimensional quality inspection, (2) surface quality inspection, and (3) displacement inspection.

An essential application of point cloud technology is manifested in its pivotal role in dimensional quality inspection. This process, integral for verifying the accuracy of various construction elements, ensures their compliance with preplanned models and established standards. Its extensive application spans across the inspection of building structures, and precast concrete components, pipes, including the assessment of these components' size, shape, position, and orientation. One common method involves comparing point cloud data with BIM models [61]. This 'BIM-vs.-scan' approach is particularly effective for inspecting a range of construction elements, including precast concrete, and building façades. Given that BIM models are not always available, alternative methods are employed. For instance, in situations where buildings are already constructed, point cloud technology is utilized for quality maintenance and inspection [26]. This involves converting laser scanning data into 2D geometric shapes for comparison with the actual structure to detect quality defects. In post-disaster assessments, the direct analysis of laser spectral data is used for damage detection [23]. Another approach involves comparing elements with established rules or standards, such as the spacing of steel reinforcements [65].

Surface quality inspection represents another critical facet, primarily targeting the identification of concrete-related issues such as cracks, spalling, and honeycombing. This inspection doesn't necessarily require BIM models, as most surfaces are flat and can be directly compared with point cloud data for assessment. This technology is also adept at inspecting deformation and distortion, scrutinizing the deflection and slope of beams, as well as the tilt and straightness of columns [33,44]. A notable area of research is the control of surface flatness, a critical determinant of a structure's aesthetic and functional integrity.

The third category, displacement inspection, shifts the focus to alterations in the relative positioning of structures, as opposed to changes in their geometric shape. This aspect is especially pertinent to structures such as bridges and retaining walls [9,36], where monitoring structural displacement is paramount. Some studies, like that of [60], simultaneously explore multiple inspection types, encompassing both surface defects and the dimensional quality of precast concrete components.

The trajectory of quality inspection in construction and infrastructure sectors is progressively evolving from manual feature extraction towards a more holistic, automated detection approach. End-to-end systems, characterized by their ability to automate the entire inspection process from data input to final output, with minimal human intervention, are becoming increasingly prevalent. Deep learning plays a crucial role in these processes, enabling semantic segmentation and automatic feature extraction from raw data. For concrete surface quality inspection, deep learning is typically used to perform semantic segmentation or classification of concrete surface defect types, thereby identifying the nature of defects. For instance, the Surface Normal Enhanced PointNet++ (SNEPointNet++) model [6] fuses depth information with normal vectors for enhanced semantic segmentation, categorizing concrete bridge surfaces into cracks, flaking defects, and non-defect areas.

In dimensional quality inspection, deep learning models do not directly detect dimensional quality defects. Instead, they segment components into different types, followed by specific methods to assess the dimensions of these components. For example, Mirzaei, et al. [34] employs a bounding box method to slice components and calculate the dimensions of each slice's bounding box, thus achieving automated detection and measurement of the dimensions of structural components.

2.3. Construction progress tracking and monitoring

Traditional methods of progress monitoring, heavily reliant on manual measurements and visual inspections, are increasingly proving inadequate. The advent of point cloud data signifies a pivotal shift, offering a more accurate, efficient, and automated approach to monitoring construction progress. Progress monitoring based on point clouds is divided into outdoor monitoring and indoor monitoring. For outdoor progress monitoring, the scope usually involves larger areas, necessitating long-range scanning capabilities. Unmanned Aerial Vehicles (UAVs) can rapidly acquire image data of construction sites, significantly enhancing monitoring efficiency compared to traditional manual methods and are widely applied in monitoring road and outdoor construction engineering. Given the limited indoor space, lightweight monitoring methods such as RGB cameras [29] and 360° panoramic cameras [13] are preferred for their cost-effectiveness and mobility. Additionally, portable mobile devices and wearable technologies like helmet-mounted scanners [41] and indoor mobile mapping systems [49] have become popular for their versatility in monitoring.

2.4. Construction safety management, heritage management, and applications in construction robotics, construction safety management

Point cloud technology plays a crucial role in enhancing construction safety by providing accurate geometric information about construction sites. It is used to identify and mitigate risks associated with physical elements and dynamic environments. For instance, Wang, et al. [54] used point cloud data to detect fall hazards at excavation sites, while Wang [55] developed an automated inspection method to ensure safety compliance for scaffolding and other components. Additionally, robot dogs equipped with laser scanners have been used for effective safety monitoring of scaffold structures. Despite its potential, there is a notable gap in research focused on tracking the gait of construction workers, suggesting an area for future development.

Heritage Management: Point cloud technology is vital in cultural heritage for analysis, assessment, monitoring, and preservation. It provides high-resolution 3D models for capturing structural changes and aiding in structural health evaluation, as demonstrated by Werbrouck, et al. [56] in their assessment of medieval churches. For preservation, point clouds enable high-precision documentation of heritage sites, which is essential for reliable conservation efforts. The integration of point clouds with images and other data enhances understanding and aids in preventative conservation strategies, as shown by Sánchez-Aparicio, et al. [45].

Applications in Construction Robotics: The integration of point cloud data with robotic technology is increasingly prevalent in construction. Point clouds provide critical environmental information for robots, supporting navigation, positioning, object detection, and 3D reconstruction. Wheeled and quadruped robots use point clouds for path planning and obstacle avoidance in complex environments. For instance, Hu, et al. [20] used robots and point clouds to automate GPR data collection and 3D reconstruction of underground facilities. Industrial robots use point cloud data for precise measurement and positioning, ensuring accuracy and safety in operations. Point clouds also enable virtual robots to simulate real-world tasks, enhancing automation and precision on construction sites.

3 CONCLUSION

This review highlights the latest advancements in point cloud applications in the construction industry from 2014 to 2023, covering key areas such as 3D model reconstruction, geometry quality inspection, construction progress tracking, safety management, heritage management, and construction robot applications. The findings underscore the growing importance of point cloud technology in facilitating the industry's digital transformation.

REFERENCE:

[1] G. Angjeliu, G. Cardani, D. Coronelli, A parametric model for ribbed masonry vaults, Automation in Construction 105 (2019).

[2] M. Bassier, M. Vergauwen, Unsupervised reconstruction of Building Information Modeling wall objects from point cloud data, Automation in Construction 120 (2020) 103338.

[3] C. Bellés, F. Pla, A Kinect-Based System for 3D Reconstruction of Sewer Manholes, Computer-Aided Civil and Infrastructure Engineering 30 (11) (2015) 906-917.
[4] S. Biçici, M. Zeybek, An approach for the automated extraction of road surface distress from a UAV-derived point cloud, Automation in Construction 122 (2021).
[5] W. Blaszczak-Bak, C. Suchocki, M. Mrowezynska, Optimization of point clouds for 3D bas-relief modeling, Automation in Construction 140 (2022).
[6] N. Bolourian, M. Nasrollahi, F. Bahreini, A. Hammad, Point Cloud–Based Concrete Surface Defect Semantic Segmentation, Journal of Computing in Civil Engineering 37 (2) (2023) 04022056.
[7] M. Bueno, F. Bosché, H. González-Jorge, J. Martínez-Sánchez, P. Arias, 4-Plane congruent sets for automatic registration of as-is 3D point clouds with 3D BIM models, Automation in Construction 89 (2018) 120-134.
[8] M. Bueno, H. González-Jorge, J. Martínez-Sánchez, H. Lorenzo, Automatic point cloud coarse registration using geometric keypoint descriptors for indoor scenes, Automation in Construction 81 (2017) 134-148.
[9] G. Cha, S. Park, T. Oh, A terrestrial LiDAR-based detection of shape deformation for maintenance of bridge structures, Journal of Construction Engineering and Management 145 (12) (2019) 04019075.
[10] T. Czerniawski, M. Nahangi, C. Haas, S. Walbridge, Pipe spool recognition in cluttered point clouds using a curvature-based shape descriptor, Automation in Construction 71 (2016) 346-358.
[11] L. Díaz-Vilariño, B. Conde, S. Lagüela, H. Lorenzo, Automatic detection and segmentation of columns in as-built buildings from point clouds, Remote Sensing 7 (11) (2015) 15651-15667.
[12] D.Y. Duan, W.G. Qiu, Y.J. Cheng, Y.C. Zheng, F. Lu, Reconstruction of shield tunnel lining using point cloud, Automation in Construction 130 (2021).
[13] X. Fang, H. Li, H.T. Wu, L. Fan, T. Kong, Y. Wu, A fast end-to-end method for automatic interior progress evaluation using panoramic images, Engineering Applications of Artificial Intelligence 126 (2023).
[14] J.J. Guo, Q. Wang, J.H. Park, Geometric quality inspection of prefabricated MEP modules with 3D laser scanning, Automation in Construction 111 (2020).
[15] S.S. Han, Y.H. Jiang, Y. Bai, Fast-PGMED: Fast and Dense Elevation Determination for Earthwork Using Drone and Deep Learning, Journal of Construction Engineering and Management 148 (4) (2022).
[16] Y. Han, D. Feng, W. Wu, X. Yu, G. Wu, J. Liu, Geometric shape measurement and its application in bridge construction based on UAV and terrestrial laser scanner, Automation in Construction 151 (2023) 104880.
[17] A. Holgado-Barco, D. González-Aguilera, P. Arias-Sanchez, J. Martinez-Sanchez, Semiautomatic Extraction of Road Horizontal Alignment from a Mobile LiDAR System, Computer-Aided Civil and Infrastructure Engineering 30 (3) (2015) 217-228.
[18] A. Holgado-Barco, B. Riveiro, D. González-Aguilera, P. Arias, Automatic Inventory of Road Cross-Sections from Mobile Laser Scanning System, Computer-Aided Civil and Infrastructure Engineering 32 (1) (2017) 3-17.
[19] D. Hu, V.J. Gan, C. Yin, Robot-assisted mobile scanning for automated 3D reconstruction and point cloud semantic segmentation of building interiors, Automation in Construction 152 (2023) 104949.
[20] D. Hu, V.J.L. Gan, C. Yin, Robot-assisted mobile scanning for automated 3D reconstruction and point cloud semantic segmentation of building interiors, Automation in Construction 152 (2023).
[21] F.Q. Hu, J. Zhao, Y. Huang, H. Li, Structure-aware 3D reconstruction for cable-stayed bridges: A learning-based method, Computer-Aided Civil and Infrastructure Engineering 36 (1) (2021) 89-108.
[22] J. Jung, C. Stachniss, S. Ju, J. Heo, Automated 3D volumetric reconstruction of multiple-room building interiors for as-built BIM, Advanced Engineering Informatics 38 (2018) 811-825.
[23] A.G. Kashani, A.J. Graettinger, Cluster-based roof covering damage detection in ground-based lidar data, Remote Sensing 58 (2015) 19-27.
[24] H. Kim, C. Kim, 3D as-built modeling from incomplete point clouds using connectivity relations, Automation in Construction 130 (2021) 103855.
[25] J. Kim, D. Chung, Y. Kim, H. Kim, Deep learning-based 3D reconstruction of scaffolds using a robot dog, Automation in Construction 134 (2022) 104092.

[26] M. Kim, D. Lee, Automated two-dimensional geometric model reconstruction from point cloud data for construction quality inspection and maintenance, Automation in Construction 154 (2023) 105024.
[27] D.F. Laefer, L. Truong-Hong, Toward automatic generation of 3D steel structures for building information modelling, Automation in Construction 74 (2017) 66-77.
[28] J.S. Lee, J. Park, Y.-M. Ryu, Semantic segmentation of bridge components based on hierarchical point cloud model, Automation in Construction 130 (2021) 103847.
[29] L. Lei, Y. Zhou, H.B. Luo, P.E.D. Love, A CNN-based 3D patch registration approach for integrating sequential models in support of progress monitoring, Advanced Engineering Informatics 41 (2019).
[30] R. Lu, I. Brilakis, C.R. Middleton, Detection of structural components in point clouds of existing RC bridges, Computer‐ Aided Civil Infrastructure Engineering 34 (3) (2019) 191-212.
[31] J.W. Ma, T. Czerniawski, F. Leite, Semantic segmentation of point clouds of building interiors with deep learning: Augmenting training datasets with synthetic BIM-based point clouds, Automation in Construction 113 (2020) 103144.
[32] H. Macher, L. Roy, T. Landes, Automation of windows detection from geometric and radiometric information of point clouds in a scan-to-BIM process, XXIV ISPRS Congress (2021 edition), 5-9 juillet 2021, Nice (en ligne), Vol. 43, 2021.
[33] K. Mirzaei, M. Arashpour, E. Asadi, H. Feng, S.R. Mohandes, M. Bazli, Automatic compliance inspection and monitoring of building structural members using multi-temporal point clouds, Journal of Building Engineering 72 (2023) 106570.
[34] K. Mirzaei, M. Arashpour, E. Asadi, H. Masoumi, A. Mahdiyar, V. Gonzalez, End-to-end point cloud-based segmentation of building members for automating dimensional quality control, Advanced Engineering Informatics 55 (2023).
[35] S. Ochmann, R. Vock, R. Klein, Automatic reconstruction of fully volumetric 3D building models from oriented point clouds, ISPRS journal of photogrammetry remote sensing 151 (2019) 251-262.
[36] P. Oskouie, B. Becerik-Gerber, L. Soibelman, Automated measurement of highway retaining wall displacements using terrestrial laser scanners, Automation in Construction 65 (2016) 86-101.
[37] P.V. Paiva, C.K. Cogima, E. Dezen-Kempter, M.A. Carvalho, Historical building point cloud segmentation combining hierarchical watershed transform and curvature analysis, Pattern Recognition Letters 135 (2020) 114-121.
[38] J. Park, J. Kim, D. Lee, K. Jeong, J. Lee, H. Kim, T. Hong, Deep learning–based automation of scan-to-BIM with modeling objects from occluded point clouds, Journal Of Management In Engineering 38 (4) (2022) 04022025.
[39] Y. Perez-Perez, M. Golparvar-Fard, K.J. El-Rayes, Scan2BIM-NET: Deep learning method for segmentation of point clouds for scan-to-BIM, Journal of Construction Engineering Management 147 (9) (2021) 04021107.
[40] R. Pierdicca, M. Paolanti, F. Matrone, M. Martini, C. Morbidoni, E.S. Malinverni, E. Frontoni, A.M. Lingua, Point cloud semantic segmentation using a deep learning framework for cultural heritage, Remote Sensing 12 (6) (2020) 1005.
[41] Z. Pučko, N. Šuman, D. Rebolj, Automated continuous construction progress monitoring using multiple workplace real time 3D scans, Advanced Engineering Informatics 38 (2018) 27-40.
[42] Q. Qiu, M.J. Wang, J.J. Guo, Z.W. Liu, Q. Wang, An adaptive down-sampling method of laser scan data for scan-to-BIM, Automation in Construction 135 (2022).
[43] R. Romero-Jarén, J. Arranz, Automatic segmentation and classification of BIM elements from point clouds, Automation in Construction 124 (2021) 103576.
[44] L.J. Sánchez-Aparicio, S. Del Pozo, L.F. Ramos, A. Arce, F.M. Fernandes, Heritage site preservation with combined radiometric and geometric analysis of TLS data, Automation in Construction 85 (2018) 24-39.
[45] L.J. Sánchez-Aparicio, M.-G. Masciotta, J. García-Alvarez, L.F. Ramos, D.V. Oliveira, J.A. Martín-Jiménez, D. González-Aguilera, P. Monteiro, Web-GIS approach to preventive conservation of heritage buildings, Automation in Construction 118 (2020) 103304.

[46] H. Son, C. Kim, C. Kim, 3D reconstruction of as-built industrial instrumentation models from laser-scan data and a 3D CAD database based on prior knowledge, Automation in Construction 49 (2015) 193-200.
[47] S. Tang, X. Li, X. Zheng, B. Wu, W. Wang, Y. Zhang, BIM generation from 3D point clouds by combining 3D deep learning and improved morphological approach, Automation in Construction 141 (2022) 104422.
[48] Y.F. Tian, W. Song, L. Chen, Y. Sung, J. Kwak, S. Sun, Fast Planar Detection System Using a GPU-Based 3D Hough Transform for LiDAR Point Clouds, Applied Sciences-Basel 10 (5) (2020).
[49] G.P. Vassena, L. Perfetti, S. Comai, S. Mastrolembo Ventura, A.L. Ciribini, Construction Progress Monitoring through the Integration of 4D BIM and SLAM-Based Mapping Devices, Buildings 13 (10) (2023) 2488.
[50] B. Wang, Q. Wang, J.C. Cheng, C. Song, C. Yin, Vision-assisted BIM reconstruction from 3D LiDAR point clouds for MEP scenes, Automation in Construction 133 (2022) 103997.
[51] B. Wang, Q. Wang, J.C. Cheng, C. Yin, Object verification based on deep learning point feature comparison for scan-to-BIM, Automation in Construction 142 (2022) 104515.
[52] C. Wang, Y.K. Cho, Smart scanning and near real-time 3D surface modeling of dynamic construction equipment from a point cloud, Automation in Construction 49 (2015) 239-249.
[53] C. Wang, Y.K. Cho, C. Kim, Automatic BIM component extraction from point clouds of existing buildings for sustainability applications, Automation in Construction 56 (2015) 1-13.
[54] J. Wang, S. Zhang, J. Teizer, Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling, Automation in Construction 49 (2015) 250-261.
[55] Q. Wang, Automatic checks from 3D point cloud data for safety regulation compliance for scaffold work platforms, Automation in Construction 104 (2019) 38-51.
[56] J. Werbrouck, P. Pauwels, M. Bonduel, J. Beetz, W. Bekers, Scan-to-graph: Semantic enrichment of existing building geometry, Automation in Construction 119 (2020) 103286.
[57] Z. Xiong, T. Wang, Research on BIM reconstruction method using semantic segmentation point cloud data based on PointNet, IOP Conference Series: Earth and Environmental Science, Vol. 719, IOP Publishing, 2021, p. 022042.
[58] Y. Xu, X. Tong, U. Stilla, Voxel-based representation of 3D point clouds: Methods, applications, and its potential use in the construction industry, Automation in Construction 126 (2021) 103675.
[59] Y. Xu, S. Tuttas, L. Hoegner, U. Stilla, Reconstruction of scaffolds from a photogrammetric point cloud of construction sites using a novel 3D local feature descriptor, Automation in Construction 85 (2018) 76-95.
[60] Z. Xu, R. Kang, R. Lu, 3D reconstruction and measurement of surface defects in prefabricated elements using point clouds, Journal of Computing in Civil Engineering 34 (5) (2020) 04020033.
[61] Z. Xu, Y. Liang, Y. Xu, Z. Fang, U. Stilla, Geometric Modeling and Surface-Quality Inspection of Prefabricated Concrete Components Using Sliced Point Clouds, Journal of Construction Engineering and Management 148 (9) (2022) 04022087.
[62] F. Xue, W. Lu, K. Chen, C.J. Webster, BIM reconstruction from 3D point clouds: A semantic registration approach based on multimodal optimization and architectural design knowledge, Advanced Engineering Informatics 42 (2019) 100965.
[63] F. Yang, Y.T. Pan, F.S. Zhang, F.Y. Feng, Z.J. Liu, J.Y. Zhang, Y. Liu, L. Li, Geometry and Topology Reconstruction of BIM Wall Objects from Photogrammetric Meshes and Laser Point Clouds, Remote Sensing 15 (11) (2023).
[64] C. Yin, B. Wang, V.J. Gan, M. Wang, J.C. Cheng, Automated semantic segmentation of industrial point clouds using ResPointNet++, Automation in Construction 130 (2021) 103874.
[65] X. Yuan, A. Smith, F. Moreu, R. Sarlo, C.D. Lippitt, M. Hojati, S. Alampalli, S. Zhang, Automatic evaluation of rebar spacing and quality using LiDAR data: Field application for bridge structural assessment, Automation in Construction 146 (2023) 104708.
[66] D. Yun, S. Kim, H. Heo, K.H. Ko, Automated registration of multi-view point clouds using sphere targets, Advanced Engineering Informatics 29 (4) (2015) 930-939.
[67] Z. Zou, H. Lang, Y.X. Lou, J. Lu, Plane-based global registration for pavement 3D reconstruction using hybrid solid-state LiDAR point cloud, Automation in Construction 152 (2023).