A Comprehensive Review of 3D Laser Scanning Point Cloud Data Processing Techniques: Assessing the Dominant Focus and Exploring 3D Modeling and Data Optimization

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Abstracts: Three-dimensional laser scanning technology primarily relies on dense scanning points to collect vectorized information of the target object and perform point cloud data processing without physical contact. There are numerous case studies in various fields regarding the use of three-dimensional laser scanning technology for point cloud data acquisition of different objects. By utilizing a three-dimensional laser scanner, precise three-dimensional data of the object's surface can be obtained, effectively meeting the high-precision measurement requirements of three-dimensional points on the object. The main objective of this study is to determine the most suitable point cloud processing method for preprocessing the solid obtained through laser-based 3D scanning. To achieve this goal, we systematically reviewed and reported the technical papers discussing/proposing point cloud data acquisition and processing techniques based on 3D laser scanning technology. As a result of our search, we collected 31 papers on this topic. In this report, we present the process of data collection, result analysis, and classification of related studies. The classification is based on the applicability of methods in processing point cloud data using 3D laser scanning technology. The proposed research clearly demonstrates the latest approaches in data processing in this field and highlights areas that remain unexplored, providing potential avenues for further research.

Keywords: 3D Laser Scanning, Point Cloud Denoising, Point Cloud Data Processing.

1. INTRODUCTION

3D laser scanning technology is a new technique that has emerged in the field of surveying in recent years. It overcomes the limitations of traditional measurement techniques that rely on single-point measurements (B. Pradhan & Sameen, 2020). Based on the basic principle of laser ranging, this technology rapidly captures high-precision spatial point position information and surface texture information of the measured object through non-contact, active measurements. The resulting point cloud data and image information have been widely applied in various fields such as 3D modeling of buildings, cultural heritage preservation, geological hazard monitoring, and civil engineering. With the advancement and improvement of hardware and software of 3D laser scanners, researchers have become increasingly interested in the collection and registration of point cloud data for different types of structures. This emphasizes the need for in-depth analysis and review of existing technologies.

In the past decade, the collection and registration of architectural point cloud data using 3D laser scanning technology has garnered significant attention in the research community. The availability of high-resolution and dense point clouds has provided unprecedented opportunities for the analysis and reconstruction of complex 3D structures. However, the sheer volume and complexity of point cloud data pose significant challenges in terms of effective processing, denoising, feature extraction, and data interpretation.

The motivation behind this research is to address the limitations and gaps in current point cloud data processing methods. By understanding and evaluating state-of-the-art techniques, we aim to foster the development of advanced algorithms and tools to enhance the accuracy, robustness, and automation of point cloud data processing (Pradhan & Sameen, 2021). Furthermore, the potential applications of these techniques in fields such as architecture, civil engineering, cultural heritage preservation, and virtual reality underscore the importance of this research.

During the process of collecting point cloud data on building surfaces, the scanning of the entire surface cannot be completed in a single scan due to the limitations of the scanner's field of view. It is necessary to perform scans from different viewpoints to obtain point cloud data of the entire building surface (Li & Cheng, 2021). Depending on the operation mode, 3D laser scanners can be divided into three modes: (1) target-based point cloud data acquisition mode, (2) shape matching-based point cloud data acquisition mode, and (3) point cloud data acquisition mode based on station back sight or resection. The point cloud data obtained from the first two modes are in the coordinate system of the scanner, while the third mode, based on the polar coordinate method of total stations, provides point cloud data in a unified spatial coordinate system.

3D laser scanners are also classified into four categories based on the scanning range: close-range, medium-close-range, medium-long-range, and long-range. Close-range scanners are typically handheld scanners with an effective scanning range of 2 meters. Medium-close-range scanners have a scanning range of 1 to 25 meters. (Wang, 2021) Medium-long-range scanners refer to scanners with a scanning distance between 40 and 1,000 meters (C. Wen et al., 2022). Long-range scanners are used for scanning ranges above 1 kilometer. In ground-based 3D laser scanning operations, medium-long-range scanners arecommonly used. The instruments used for unified 3D laser point cloud data acquisition in this report are the Maptek I-Site 8200SR ground-based 3D laser scanner, and the point cloud data processing software used is Maptek I-Site Studio 6.0, which ensures the reference ability of the sample data.

Therefore, this review article aims to critically analyze the strengths and weaknesses of existing methods and delve into the complexity of point cloud data processing techniques in 3D laser scanning. By identifying challenges and research gaps, our goal is to inspire further investigation and propose new solutions to streamline the processing workflow and unleash the full potential of 3D laser scanning in capturing and analyzing real-world objects and environments.

2. SELECTION OF DATA PREPROCESSING METHODS

In this study, we primarily utilized the China National Knowledge Infrastructure (CNKI), commonly known as CNKI, and open-access databases such as arXiv to collect research paper data. In the first phase, a search was conducted in databases related to the field of information technology, and a total of 320 papers published between 2019 and 2022, including various journals and master's and doctoral dissertations, were selected. In the second phase, papers that did not meet the research criteria were excluded from the initial set of 320 papers based on their titles and abstracts. The criteria for inclusion in this study were as follows: a) papers describing 3D laser scanning technology, b) papers on point cloud data processing methods, and c) papers on the application of 3D laser scanning technology in various fields. After this stage, a final set of 31 papers that met the criteria was obtained. In the final phase, specific papers were reviewed, and methods related to point cloud data acquisition and point cloud denoising were extracted to categorize the papers accordingly.

3. RESULTS AND ANALYSIS

Among the various methods used for point cloud data preprocessing, denoising algorithms are commonly employed. Additionally, there are several other methods that are utilized, including:

- Slope Theory: This method involves analyzing the slope characteristics of the point cloud data to identify and filter out noise.

- Minimum Region Theory: The minimum region theory focuses on identifying the smallest possible regions within the point cloud data and removing outliers or noise points.

- Surface Theory: This method involves analyzing the surface characteristics of the point cloud data and utilizing surface properties to filter out noise or irrelevant points.

- Feature Point Method: This method focuses on extracting feature points from the point cloud data based on specific criteria or algorithms, which can help in denoising and capturing essential geometric features.

- Common Region Method: This method involves identifying common regions or areas within multiple point cloud datasets and utilizing the overlapping information to enhance the quality and accuracy of the data.

- These methods, including denoising algorithms and other approaches like slope theory, minimum region theory, surface theory, feature point method, and common region method, are commonly applied for point cloud data preprocessing.

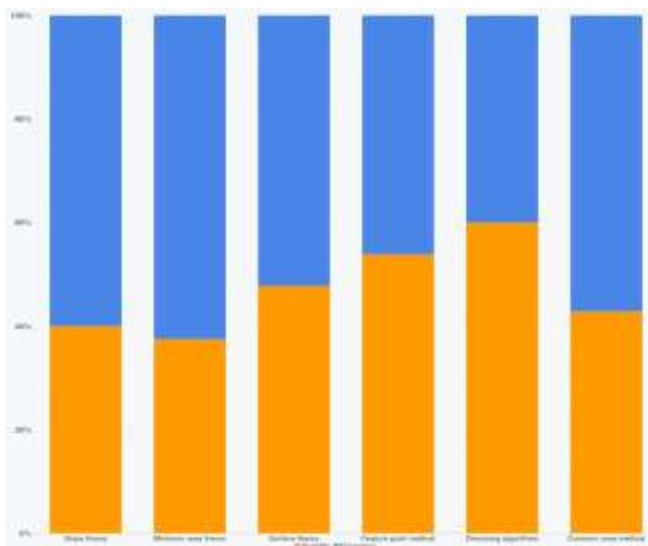

Fig 1: Comparison of data pre-processing methods used In the following text, we will provide a detailed explanation of the presented terms.

3.1. Denoising algorithm

Image denoising is typically treated as a regression model using CNN:

$$\arg\min \sum_{i}^{l} L(f(x_i), y_i)$$

Where f： represents the CNN model, x denotes the noisy sample, y represents the noise-free sample, and L represents the loss function.

Then, the corresponding clean sample is inferred from the noisy signal x. (H. Rastiveis, Shams, Sarasua, & Li, 2021).

3.2. Slope Theory

When the terrain of the surface is complex and contains rich information, the slope or height difference between point cloud data can be calculated. If the calculated result exceeds a given threshold, the data points with higher elevation are considered as objects and should be removed. (Rastiveis et al., 2022)

3.3. Minimum Area Theory

First, an initial horizontal plane is identified in the point cloud data. Then, a vertical plane is determined perpendicular to this horizontal plane. A three-dimensional buffer zone is set on this vertical plane. Points within this buffer zone are considered as ground points, while the rest can be regarded as noise points and removed. (S. Pu, Rutzinger, Vosselman, & Oude Elberink, 2020)

3.4. Surface Fitting Theory

Based on the actual point cloud data, a spatial surface is fitted. An appropriate three-dimensional buffer zone is set above the surface. Points within this zone are considered as ground points. This method is similar to the minimum area theory. (P. Wang, Hunter, Bayen, Schechtner, & González, 2019)

3.5. Feature-based Method

This method utilizes the common areas between adjacent point cloud data from multiple stations. Specifically, it searches for corresponding point pairs in the common areas and calculates constraints for point cloud registration based on the relative relationships between these pairs. [13]-[14]

Table 1: List of selected papers. Based on how the papers select preprocessing methods for point cloud data, they can be classified into five different categories. This table describes the methods used in this paper for processing three-dimensional laser scanning point cloud data.

No.	Describe the method of 3D laser scanning point cloud data processing technology in this paperCategory 1: denoising algorithm.
1	In this paper, we follow the principle of minimizing point cloud errors by implementing a fine stitching process for data acquisition. [13]
2	Relying on the 3D laser scanner, by collecting the data of the target 3D point cloud as the basis, the point cloud data model proposed in this paper improves the resolution for both image and accuracy, and enrichesthe diversity of product service types. [11]
3	Unreasonable noise points are removed from the collected real data. In this paper, we use the median filtering method to remove some noise that is more scattered in distribution and has a burr-like shape. [10]
4	Considering that the choice of point neighborhood size in noisy point cloud data has a relatively important influence on the estimation of noise point normals and curvature, this paper proposes a robust normal estimation algorithm based on multi-scale neighborhood size iteration. [8]
5	In this paper, we reduce the amount of point cloud data in the horizontal direction of the original point cloud and improve the accuracy of the filtered point cloud by reverse engineering technology and conclude that the filtering quality is better than the traditional method. [15]
6	In this paper, according to the current status of point cloud data processing research, relying on the working principle of

LiDAR, the classification and domain of point cloud data are discussed and analyzed, and several common point cloud domains finding methods are reviewed. [3]

7 In order to eliminate the influence of system errors of 3D laser instruments and uncontrollable factors such as data acquisition, this paper improves the efficiency of traditional laser mapping by analyzing the causes of noisy point clouds in point data. [16]

8 Data acquisition by 3D laser scanner is carried out in three modes respectively, and this paper uses three types of point cloud data acquisition based on target, based on shape matching, and based on station hind view to reduce the impact of chance errors on data processing. [18]

Category 2: Slope Theory

9 The paper focuses on the application of GeoSLAM 3D laser scanner scanning measurement in underground mine production and concludes that the application of GeoSLAM 3D laser scanning mapping in underground has high technical value through cost estimation and multi-scenario application. [27]

10For denoising, this paper proposes the use of a point cloud filtering algorithm, which determines the specific shape by calculating the average distance from any point in the point cloud to its specified number of neighbors, using the mean and standard deviation, and the final conclusion shows that the algorithm is moreeffective for outliers. [7]

11Through 3D scanning technology, the road is mapped on multiple multidimensional levels based on conventional objects such as buildings and road surfaces using different testing tools and software, and thearticle finally concludes that this technique is best applied in this kind of scenario [4]

12This paper studies the accuracy testing of the steps presented among the point cloud data techniques usingthe curvature interpolation method. Although the area scanned in this paper is not large, it is concluded that the method has a high degree of performance, simple processing and high efficiency in the supervision of the quality of road works and also the mapping of the terrain [14]

13With the maturity of 3D laser technology, scanning efficiency is also improving, point cloud pre-processed data including noise point data is too large, resulting in the subsequent data trimming and model reconstruction caused trouble, so Gaussian filtering this algorithm can deal with a large range of irregular noise points [2]

14The paper is based on 3D laser scanner technology for the proof of the point cloud bilateral filtering algorithm, and it is concluded that the method has good feature retention and can be denoised in a wide range of processing, but at the same time there is also local feature loss [5]

15After ground detection filtering of 3D point cloud data, there is noise in non-ground point clouds, while clustering of point clouds is an unsupervised machine learning, and this clustering algorithm is not aggregable as well as insensitive to data order. In this paper, we distinguish object instances into different clusters to represent the basic features in different algorithms [20]

Category 3: minimal area theory

16The article discusses in detail a non-ground point cloud data clustering method. The objects near and far arescreened by vectors between adjacent point cloud regions and sensors, the point cloud data are simplified in the clustering process, and the nodes are traversed using an optimization algorithm [1]

17In the process of 3D laser scanning of different spatial regions, some deviation value data are collected in anode or time range, and for these non-normal point cloud data, the distinctive features of such noisy points are proposed, and the curvature perimeter ratio is proposed as a basis for effective identification and filtering [22]

18Three-dimensional laser scanning technology can achieve a comprehensive measurement of the spatial territory, and the paper carries out a triple fusion of visual tracking technology and intelligent switching technology to arrive at a technical method with faster scanning speed and wider measurement area [31]

19In this paper, we studied the data acquisition of the point cloud data acquisition platform, pre-processed the collected initial point cloud data using denoising method, formed a set of acquisition process and demonstrated it [6]

20	The 3D laser scanner for spatial point cloud data acquisition has the problem of object complexity leading to low recognition rate of point cloud data. The method of KD-Tree is proposed for blind area recognition to be modified, and finally the precise boundary is extracted. [28]
21	After importing the scanned point cloud data and the target objects taken by UAV, the images are compared with the point cloud data for identification, and the location spatial match is derived, while the I am not a combined superimposed image is enhanced for visualization and clustered for differentiation [12]
Category 4: face theory	
22	This paper concludes that the collected point cloud data must be denoised before 3D modeling, mentioning three methods, which are least squares-based point cloud denoising method, PCL function denoising, and least squares based multi-step denoising method [30]
23	In this thesis, the nuscenes dataset is used to correlate the LiDAR point cloud data for vehicle detection. It mainly uses the data collection of different parts of the sensor on the vehicle, collecting data maps and applying the dataset module [21]
24	LIDAR has many application scenarios and is more widely used in the field of autonomous driving. With LIDAR the relative distance between the target and its own object can be calculated and the laser beam measures the object contour will point cloud data collected and modeled. [26]
25	The article studies the relevant functions of ArcGIS platform, describes a method of processing 3D point cloud data based on ArcGIS, determines data attributes, data dictionary, and establishes topological relationships based on the data model in the geodatabase to complete the study. [23]
Category 5: feature point method	
26	The article is concerned with the processing problem in acquiring massive, self-annotated point cloud data. By training the dataset with deep learning methods, the article proposes a method to automatically acquire the annotated laser point cloud data [24]
27	The paper proposes a coupling method based on multi-line laser point cloud data, which can process the point cloud data in multi-line laser point cloud beams to make the initial sparse regional point cloud planes dense and increase the range of point cloud data [9]
28	Exploring 3D laser scanning point cloud structured modeling under machine learning, artificial intelligence and other technical methods to study the localization and classification of object targets in multidimensionalcomplex regional scenes [17]
29	3D laser scanning technology reflects surface feature points by processing and storing point cloud data and using point cloud data denoising methods to smooth the noise after data correction for deviations from theoretical values. [25]
30	In this paper, we study convolutional neural network image features, such as extraction of shared eigenvalues for weights and finally reduction of convolutional layer parameters. [19]
31	The article studies 3D laser scanning point cloud processing techniques, with detailed arguments for reducing measurement discrimination, extracting inhomogeneous sampling values, unequal distances, and finally describing the applications under different domains. [29]

4. DISCUSSION

During the process of acquiring three-dimensional laser scanning point cloud data, a significant amount ofnoise is inevitably generated. Depending on the different models of the scanning equipment, the influence of external environmental factors during the acquisition process, and the varying sparsity of point cloud region filtering, we have focused on answering the question of "how to select and effectively improve point cloud data processing techniques." To do so, we start by examining existing works and comparing the differences in relevant methods.

As the final selection, there are 31 research papers that have investigated techniques for processing three-dimensional laser scanning point cloud data. These papers have classified point cloud noise processing into five different methods: denoising algorithms, slope theory, minimum area theory, surface theory, and feature point methods.

Figure 2 displays the distribution of papers published in conferences and journals from 2019 to 2022 that meet the criteria of the topic. The increasing publication rate indicates that there is growing research interest and practical application of three-dimensional laser scanning point cloud data processing methods.

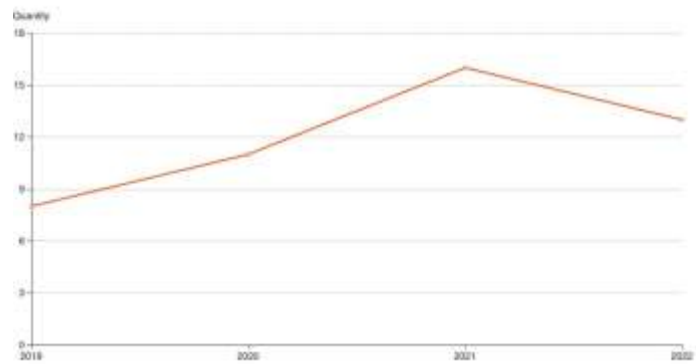

Fig 2. Number of papers published per year on the topic of 3D laser scanning point cloud data

Literature research aims to familiarize ourselves with the field by reviewing and listing the contributions made by existing studies. Its main purpose is to identify gaps and develop work in a coherent manner. Through the investigation of selected papers and the analysis of collected data, several findings have been obtained:

- Point cloud data processing techniques are essential and complex parts of three-dimensional laser scanning systems. The purpose is to process point cloud data effectively in order to generate three-dimensional digital models of target objects and extract their features.

- In the majority of the selected sample papers, the main objective is to use three-dimensional laser scanners to acquire relevant data and employ point cloud data processing methods to obtain accuratethree-dimensional data. This is done to fulfill the high-precision measurement requirements of specific objectives.

- Most papers discuss methods for denoising point cloud data, while only a small number of papers address topics such as three-dimensional modeling and data simplification.

5. DISCUSSION

In this study, we have examined the significance of denoising algorithms in the context of 3D laser scanning point cloud data processing techniques. Specifically, our focus has been on investigating three point cloud denoising algorithms. Through the collection, analysis, and categorization of existing research studies in this field, we have arrived at several key conclusions.

Firstly, we have determined that the primary objective of point cloud data processing methods is to obtain accurate data. This goal underscores the critical importance of denoising algorithms in enhancing the quality and reliability of point cloud data.

Furthermore, our analysis has revealed that 3D laser scanners are extensively employed as crucial tools for collecting point cloud data. Importantly, we have established that the acquired point cloud data can be subject to biases depending on the specific characteristics and capabilities of the scanning tool utilized.

A noteworthy observation from our findings is that studies focusing on detailed 3D model construction following the acquisition of accurate data are relatively rare. Instead, a majority of research in this domain predominantly revolves around filtering and removing the noise and outliers present in the acquired point cloud data.

However, it is crucial to address the concern raised by the reviewer regarding the simplicity and limited persuasiveness of our conclusions. While our study provides valuable insights into the prevalence of point cloud denoising through counting methods versus the relatively limited emphasis on 3D modeling and data optimization, we acknowledge the necessity to delve deeper into the underlying reasons for this phenomenon.

To strengthen our conclusions and better understand the reasons driving this trend, further investigations could be conducted. This may encompass a more extensive review of literature, surveying researchers involved in this field, and conducting interviews with subject matter experts. Consequently, a more comprehensive understanding of the factors contributing to the observed research distribution can be achieved, enabling us to provide a more convincing and robust analysis.

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