International Journal of Applied Methods in Electronics and Computers 12(2): 048-053, 2024

INTERNATIONAL JOURNAL OF APPLIED METHODS IN ELECTRONICS AND COMPUTERS

www.ijamec.org

International Open Access

Volume 12
Issue 02

June, 2024

Research Article

Development of a bulk material volume estimation system using automatic moving rail LiDAR technology

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ARTICLE INFO

Article history:
Received 15 May 2024
Accepted 25 June 2024

Keywords:
Bulk material,
Volume estimation,
LiDAR technology,
Point cloud data

ABSTRACT

This paper focuses on developing a bulk material volume estimation system employing automatic moving rail optical distance measuring technology. The research objective is to devise a system capable of estimating warehouse bulk material volumes utilizing point cloud data. Additionally, the research proposes guidelines for enhancing efficiency in bulk material volume estimation processes. A prototype system was developed and tested using dry rice husk with a humidity level of 15% as the sample material. The testing environment comprised a laboratory with dimensions of 36 square meters and a height of 3 meters, wherein the sample material was arranged in a cone shape with a volume of 1 cubic meter. The system was designed to test with movement speed range from 2 to 30 centimeters per second, and the scanning angles of 0, 45, and 90 degrees. Statistical principles were applied to analyze the collected data, determining averages, and comparing results with actual data to assess accuracy and precision in volumetric measurements. Furthermore, the research evaluated the advantages and disadvantages of alternative tools for bulk material volume estimation in comparison to the developed system, considering factors such as data collection duration, operational costs, and safety measures. Experimental results revealed that at a scanning angle of 90 degrees and a moving speed of 20 centimeters per second achieve a volumetric data accuracy of 97%.

1. Introduction

Large rice mills commonly utilize bulk warehouses for storing paddy, favouring this method over packing bags due to risks associated with bag overlap and breakage. In the context of inventory management within warehouses, basic estimation methods involve tracking weight or volume, often facilitated by tools such as truck scales [1]. However, these methods may be susceptible to errors stemming from internal factors like pest infestation or spoilage. Modern technology has increasingly become pivotal in enhancing the accuracy of material quantity assessments in warehouses. Tools like integrated cameras and unmanned aerial vehicles (UAVs) have emerged as popular choices due to their ability to measure with millimeter-level precision [2]. However, integrated camera surveys are time-consuming and impractical for complex bulk cargo shapes, while UAVs are more suitable for outdoor environments requiring GNSS systems for signal reception from satellites [3]. Ground-based laser scanners offer higher-quality data and versatility for both indoor and outdoor applications, yet they are often criticized for being time-consuming and unsafe [3]. This paper seeks to address the limitations of existing data collection methods by employing automatic moving rail LiDAR technology, aimed at swiftly and safely capturing bulk cargo data. Through a comprehensive literature review, this study identifies gaps in bulk product quantity assessment systems and proposes the utilization of automatic moving rail LiDAR technology as a solution.

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DOI: 10.58190/ijamec.2024.97

The research methodology encompasses the design and testing of key components, utilizing sample materials of known volume to evaluate the efficiency and efficacy of the developed system. By enhancing the potential for managing bulk warehouses, particularly in rice mills, this research endeavors to empower operators with improved inventory management capabilities and operational efficiency.

2. Related Work

Estimating the volume of bulk materials within warehouse environments presents distinct challenges compared to outdoor storage assessments, such as poorly lit areas, unreliable satellite signals, or hazardous substances, which have resulted in comparatively less research in this domain. A literature review of this area encompasses an examination of technologies employed for volume estimation of bulk materials within warehouses, categorized into three main types: drones operating indoors, rail systems, and stand-mounted systems [4].

2.1. Using Drones Inside Buildings

Multi-rotor drones have been developed to facilitate volume estimation of bulk materials within warehouses, alleviating the workload of personnel and capable of autonomous operation. Kumar et al. [5] devised an algorithm employing stereo depth cameras and deep learning to estimate bulk material volumes within aerial warehouses, independent of GPS signals. However, this method is constrained to smaller bulk material piles due to the necessity of comprehensive material pile detection for volume estimation, with estimation errors escalating from 1% to 9.8% for volumes six times the original. In a separate endeavor, Gago et al. [6] introduced a quantitative estimation technique utilizing a DJI quadcopter drone, model Matrice 100, equipped with a Velodyne 3D LiDAR, model VLP 16 Puck Lite, for navigation and mapping within warehouses. By leveraging warehouse walls or ceilings as reference points for autonomous flight, they employed an offline mapping approach to construct a 3D model of the warehouse, achieving volumetric accuracies of 98.5% and 97.8% in simulation and real-world tests, respectively.

Alsayed et al. [7,8] proposed an efficient scan-matching approach for drone mapping based on an iterative closest point (ICP) algorithm suitable for low-density LiDAR scanning, facilitating real-time 3D map creation and route planning within warehouses. Despite being tested solely through simulations, their method demonstrated 97% accuracy in estimating material volumes within mapped warehouses. Innovatively, Alsayed and Nabawy [9] advocated a warehouse scanning method employing a single-point LiDAR sensor operated by a micro servo motor, outperforming traditional 2D and 3D LiDAR systems in terms of scanning speed, weight, and cost efficiency. In a related study, Alsayed et al. [10] investigated the control of an autonomous multi-drone model employing 1D LiDAR sensors for warehouse mapping, comparing the cost-effectiveness of multiple low-cost sensors versus a single advanced laser scanner (2D/3D LiDAR) through simulations. Results indicated that increasing the number of drones up to five enhanced volume estimation accuracy, rivalling sophisticated LiDAR scanners at significantly reduced costs. However, practical implementation necessitates a data interpretation system for accurate drone localization and orientation during mapping operations. Conclusions

The review process will be conducted on the internet, with the two blind reviewers. At least one of the researchers must have completed the registration of the congress in order for the declarations to be taken into consideration. The outcome of the evaluation will be sent to all the declaration holders as a result letter.

2.2. Stand-Mounted System

For estimating bulk material quantities within warehouses, LiDAR sensors can be mounted on tripods or beams. Mahlberg et al. [11] developed the SMART (Stockpile Management and Reporting Technology) system, incorporating two 3D LiDAR sensors and a GoPro camera mounted on a tripod. The system enables manual rotation for scanning and data collection, with the option of ceiling mounting to expand the scanning field of view, achieving a volume estimation accuracy exceeding 99.9% compared to data obtained with TLS scanners. This system has been deployed in over 30 factories. Additionally, Liu et al. [12] enhanced the SMART system's data collection process and conducted tests within domes, utilizing scan matching techniques to improve bulk material volume estimation accuracy.

Another study by Lima and Costa [13] devised a volume estimation system featuring a 2D LiDAR mounted on a tripod to scan data vertically for estimating the volume of conical bulk materials. The accuracy of volume estimation increases with pile size, although this method applies solely to single conical bulk materials and may not suit complex cone-shaped piles. Tripod-mounted LiDAR scanners have demonstrated efficient volume estimation in warehouses; however, to enhance data collection coverage, relocating the tripod to multiple positions within confined spaces is often necessary, posing potential risks to operators in many scenarios.

2.3. Rail System

Rail systems represent a viable approach for estimating the quantity of bulk materials within warehouses, typically comprising a sliding rail system installed above the warehouse space. Zhao et al. [14] investigated the utilization of a 2D LiDAR scanner (Sick LMS200) mounted on a rail above the warehouse. The LiDAR measures the X and Y directions, while a laser distance meter gauges the distance travelled in the Z direction. Experimental findings revealed volume estimation accuracy ranging between 96.2% and 99.4%. Similarly, Xu et al. [15] developed a comparable system employing two LiDAR scanners and compared volume values with the GeoSLAM scanner, achieving a volume estimation accuracy of up to 99%. Moreover, the developed system boasted a remarkable speed, being 35 times faster than the GeoSLAM scanner.

Daofang Chang et al. [16] proposed a methodology utilizing 3D LiDAR to estimate bulk material volumes within warehouses. Mounted on the arm of a stacker reclaimer and moving along a rail, the 3D LiDAR scans the surface of warehouse stacks. Although tested in real environments, the accuracy of volumetric data estimation remains unverified. Similarly, Zhang et al. [17] explored a vision-laser system for estimating bulk material volumes within warehouses. This system utilizes a camera to capture laser lines on the vertical material surfaces of warehouse sections, mounted on rails. Although the accuracy of all volume estimates was not verified, the vertical scanning accuracy reached approximately 99%, making it a potentially widely utilized method. However, a primary limitation arises in dark and dusty environments, where removing sensor devices for cleaning and maintenance proves challenging.

The differences in the volume estimation of bulk materials using three methods are summarized in Table 1.

Table 1. Summary of differences methods in bulk materials volume estimation.

Methodologies	Strengths	Weaknesses
Using Drones Inside Buildings	High precision in controlled environments and autonomous operation reduces human error.	Limited by pile size errors increase with larger volumes.
Stand-Mounted System	High accuracy and versatility are effective in both indoor and outdoor environments.	Requires manual repositioning potential safety risks for operators.
Rail System	Efficient for large-scale environments with high-speed data collection.	Limited by rail installation and maintenance challenges potential issues in dark and dusty environments.

3. Automatic Moving Rail System

The Automatic Moving Rail System functions as a data scanning apparatus employing solid-state optical distance sensors to estimate the volume of bulk materials stored in warehouses. It comprises a singular solid-state LiDAR unit and a compact computer dedicated to controlling and storing scanning data from the LiDAR sensors. Enclosed within a single housing, as shown in Figure 1. All components operate on an 18V lithium-ion battery provided with the kit, facilitating motor-driven movement along rails.

This system is designed in a plug-and-play format. The drive unit on the rail and the data scanning box can be disassembled and separated, which reduces the limitations of using drones in buildings and the need for personnel involvement during installation and operation. Additionally, the ability to adjust the scanning speed according to the size of the warehouse area increases flexibility for use in warehouses of different sizes.

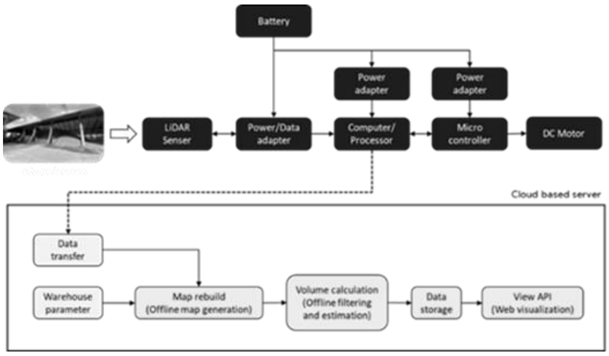

Figure 1. Components and working flow of the system.

3.1. Components

Utilizing LiDAR technology, the system employs Livox brand solid-state LiDAR, featuring a scanning field of view with a non-repetitive pattern of 70.4 degrees horizontally and 77.2 degrees vertically. Capable of capturing 240,000-point clouds per second in single-backward mode, it weighs 0.498 kg and incorporates a built-in processor, as shown in Table 2.

Table 2. Table of the characteristics of the Livox Avia sensor.

Laser Wavelength	905 nm
Laser Safety	Class 1(IEC 60825-1:2014) (safe for eyes)
Detection Range (@100 klx)	190 m @10% reflectivity
	230 m @20% reflectivity
	320 m @80% reflectivity
Detection Range (@0 klx)	190 m @10% reflectivity
	260 m @20% reflectivity
	450 m @80% reflectivity
FOV	Non-repetitive scanning pattern: 70.4° (horizontal) ×77.2° (vertical)
	Repetitive scanning pattern: 70.4°(horizontal) ×4.5° (vertical)
Distance Random Error	1σ (@ 20 m) < 2 cm
Angular Random Error	1σ < 0.05°
Beam Divergence	0.03° (Horizontal) ×0.28° (Vertical)
Point Rate	240,000 points/s (first or strongest return)
	480,000 points/s (dual return)
	720,000 points/s (triple return)
Data Latency	≤ 2 ms
IMU	Built-in IMU model: BMI088
Weight	Approx. 498 g (without cables)

Operation of the system is commanded by a single computer, wired to a computer module for the storage of point cloud data retrieved from LiDAR sensors. Additionally, remote operation is facilitated through another computer, specifically, the Intel NUC Gen 11 brand, equipped with an Intel® Core™ i7-1165G7 central processing unit and 16 GB DDR4-3200 temporary memory, all powered by 18V lithium-ion batteries. Housed within a 35 x 40-centimeter aluminium box standing 35 centimeters tall, the assembly enables easy mounting onto the rail drive unit.

The Automatic Moving Rail System is engineered to traverse a 1-inch rail, capable of supporting a maximum weight of 30 kilograms while offering adjustable speeds ranging from 0 to 30 centimeters per second. Comprising two sets of rail wheels to bear the vertical force exerted by the LiDAR box and a set of high-torque motors to propel the wheels forward along the rail, the system incorporates various accessories, including warning lights to indicate operational status, a movement direction switch button, and limit switches to cease operations upon cycle completion. Furthermore, a Quick assembly rail system is devised to facilitate the installation and maintenance of equipment within the LiDAR box, as shown in Figure 2.

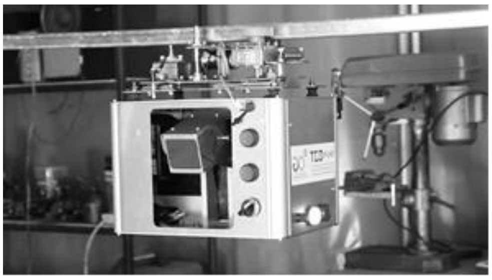

Figure 2. Automatic moving rail system.

3.2. Experimental

The experiments were conducted at the university lab. The developed system underwent testing using dry rice husk as the sample material, with a humidity level of 15%, within a laboratory measuring 36 square meters and standing 3 meters tall. Movement speeds ranged from 2 to 30 centimeters per second while scanning angles of 0, 45, and 90 degrees were employed to assess the cone-shaped bulking behavior of the sample material. The sample volume amounted to 1 cubic meter, verified for accuracy using a FARO focus (TLS), a mapping system equipped with a high-precision distance sensor [18], as shown in Figure 3.

Figure 3. Verified for accuracy using a FARO focus.

3.3. Data Collection Strategy

Data collection techniques at 0 and 45-degree scanning angles enabled the acquisition of complete sample pile data, revealing surface characteristics of the material piles. LiDAR sensors excel in gathering information across various environments, aiding in self-referencing their position. However, data collection at a 90-degree scanning angle poses challenges due to the sensor's narrow viewing angle, resulting in inaccurate position referencing. Consequently, complete sample material data cannot be collected directly. To address this, researchers created a simulated environment to assist the LiDAR sensor algorithm in self-referencing its position during data collection, as shown in Figure 4.

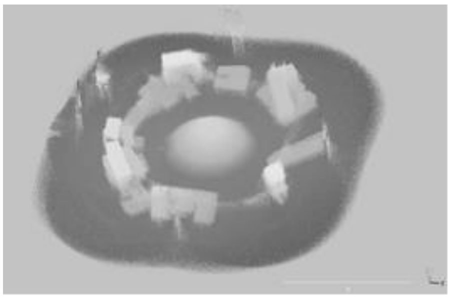

Figure 4. Creating a simulation environment in the data scanning view.

3.4. System Calibration

System accuracy calibration involves collecting data on groups of three-dimensional data points from a material sample of known size. This process allows for the adjustment of instrument accuracy. The sample material used for accuracy calibration is a cube-shaped sample with a volume of 1 cubic meter, as shown in Figure 5, ensuring minimal tool tolerances before its application in research data collection.

Figure 5. Sample material of known size is used to calibrate accuracy.

3.5. Surface Reconstruction

Following the scanning of bulk material 3D point groups within a warehouse using the developed tool, raw data is obtained, which has not undergone filtering to remove unwanted elements. To streamline data processing and align with the efficiency of the research equipment, a 3D point group processing algorithm [19] is utilized to reduce data size and flatten surfaces. The Cloud Compare program is employed for data management, initiating the creation of a triangular mesh of the pile surface with voxels. The irregular data shape is voxelized to produce a bottom grid, which is segmented into numerous triangular prisms for enhanced accuracy. Rectangles are diagonally divided using a diagonal line with minimal height differences between two points, ensuring prism proximity to the real surface, as shown in Figure 6.

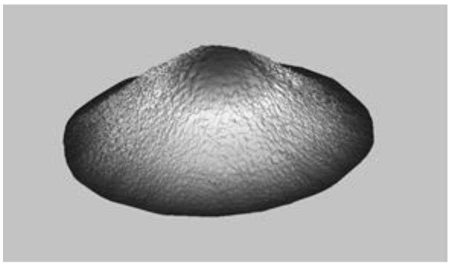

Figure 6. Creating a 3D prism from point cloud data.

3.6. Volume Calculation

Upon generating a 3D image of the data, the three-dimensional figure is partitioned into multiple triangular prisms, with each prism's volume (V_i) calculated individually, as shown in Figure 7. The volumes of all prisms are summed to derive the total bulk material volume. This computation encompasses surface points A, B, and C, and designated pile base areas A', B', and C'. The volume of a triangular prism is calculated using the formula (1):

$$V_i = \frac{1}{3} S_{A'B'C'}(Z_a + Z_b + Z_c) \tag{1}$$

Where $\mathbf{S_{A'B'C'}}$ represents the area of triangles A', B', and C' on the base plane of the material pile [20].

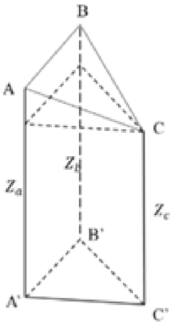

Figure 7. Calculation of the volume of each prism [20].

3.7. Precision of Volume (PoV)

The precision of volume calculations is determined by assessing the relative volume of the developed system to the actual volume using the formula (2):

$$\mathrm{PoV} = \left(1 - \frac{|v - \bar{v}|}{v}\right) \times 100\% \tag{2}$$

This assessment compares the actual volume v to the calculated volume $\bar{v}$ of the developed system. The accuracy of volume estimation is directly proportional to the accuracy of the developed system [20].

4. Result And Discussion

Results of experiments evaluating the volume of bulk materials in warehouses revealed that conical sample materials with a known volume of 1 cubic meter were scanned at viewing angles of 0, 45, and 90 degrees, and tested at travel speeds ranging from 2 to 30 centimeters per second. The Cloud Compare program was employed to manage point cloud data and assess volume. The highest volume estimation accuracy, 97%, was achieved at a scanning angle of 90 degrees and a system movement speed of 20 cm/s. Conversely, at a scanning angle of 0 degrees, the best volume estimation accuracy reached 68% at a speed of 30 cm/s, while at a 45-degree scanning angle, accuracy peaked at 91%, also at a speed of 30 cm/s. Therefore, it can be inferred that volume estimation accuracy tends to increase at scanning angles of 0 and 45 degrees as the system's movement speed rises, as shown in Table 3.

Table 3. Experiment results collection table sample material with a volume equal to 1 cubic meter.

Sensor angle (degree)	**Speed (m/s)**	**Estimated volume** (m^3)				**Accuracy (%)**
		1st	**2nd**	**3rd**	**Average**	
0	0.02	1.39	1.35	1.42	1.387	61
	0.05	1.45	1.52	1.53	1.503	50
	0.10	1.50	1.47	1.51	1.494	51
	0.15	1.52	1.48	1.46	1.489	51
	0.20	1.42	1.47	1.35	1.413	59
	0.25	1.29	1.33	1.33	1.317	68
	0.30	1.29	1.33	1.33	1.315	68
45	0.02	0.48	0.56	0.51	0.516	52
	0.05	0.47	0.61	0.57	0.550	55
	0.10	0.57	0.47	0.48	0.506	51
	0.15	0.66	0.67	0.67	0.670	67
	0.20	0.85	0.81	0.77	0.809	81
	0.25	0.87	0.90	0.90	0.890	89
	0.30	0.98	0.87	0.89	0.914	91
90	0.02	0.83	0.77	0.60	0.736	74
	0.05	0.79	0.76	0.76	0.770	77
	0.10	0.87	0.86	0.98	0.905	90
	0.15	0.87	0.96	1.00	0.941	94
	0.20	0.95	0.97	0.99	0.970	97
	0.25	1.01	1.06	1.06	1.044	96
	0.30	1.06	1.07	1.01	1.045	95

5. Conclusions And Recommendations

The bulk material volume estimation system, employing automatic moving rail optical distance measuring technology, was developed to estimate bulk material volumes in warehouses using point cloud data. The system demonstrated an accuracy of 97%, consistent with the research findings of Zhao et al. [11], which reported volume estimation accuracy ranging from 96.2% to 99.4%. This system can mitigate the limitations associated with traditional bulk product evaluation methods, which are time-consuming and pose risks to operating personnel. Like the findings of Xu et al. [12] The developed system comprises simple equipment, including a small computer for data processing, a solid-state LiDAR sensor, and a battery for power, along with a drive unit on the rails. These components are significantly more cost-effective than existing 3D data acquisition tools, rendering them suitable for many small and medium-sized rice mill operators in Thailand, thereby enhancing bulk warehouse management capabilities.

Although this experiment focuses on the development of a volume estimation system for bulk materials using automatic moving rail optical distance measuring technology, it only covers scanning data for conical bulk materials at a maximum speed of 30 centimeters per second. Therefore, future research should expand the scope to better suit the actual environment of bulk material storage in warehouses with a wider variety of products. The following suggestions are for those interested in further developing this research:

1. Increase the known volume of bulk materials to a wider range of sizes, such as 5, 10, 30, 50, or 100 cubic meters. This will make the developed system more reliable and applicable to various workplaces.
2. Specify a variety of stacking patterns, such as stacks with multiple peaks and slopes, or piles with sinkholes in the middle. The accuracy of the volume estimation of the developed system may vary with different stacking patterns.
3. Change the sample materials used in data collection to include a variety of bulk products, such as bagasse, chopped cassava, animal feed corn, etc. This will allow bulk product operators to understand the current technology and apply it to their businesses.

Acknowledgment

The authors would like to acknowledge the Suranaree University of Technology, particularly the School of Industrial Engineering, Institute of Engineering, for supporting the research.

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