Review of Key Technologies for Non-Contact Ore Volume Measurement Based on Dense Linear Laser Scanning Arrays

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Abstract: Driven by the demand for "efficiency, reliability, and traceability" in volume data for mine inventory and production monitoring, dense linear laser scanning arrays have emerged as a pivotal technical approach for acquiring stockpile volume due to their non-contact measurement capability and high-density sampling. Based on a systematic review of domestic and international research, this paper starts from system configurations and engineering workflows to summarize the key methods and applicable conditions across various stages, including data acquisition, calibration and synchronization, point cloud quality control, stockpile segmentation and bottom surface modeling, surface reconstruction, and volume calculation. Furthermore, the error sources and stability-influencing factors of volume estimation strategies—such as mesh-based, grid-based, and voxel-based methods—are critically evaluated. Integrating typical application scenarios like concentrate inventory, this study further analyzes the main operational factors affecting measurement accuracy and repeatability, proposes optimization strategies for workflow, and suggests evaluation metrics for engineering deployment. Finally, the development trends of array-based scanning toward online operation, automation, and standardization are prospected. This paper aims to provide a comprehensive reference for the design, implementation, and application promotion of non-contact ore volume measurement systems.

Keywords: Non-Contact Volume Measurement; Dense Linear Laser Scanning Array; Point Cloud Processing; Surface Reconstruction; Volume Estimation; Accuracy Assessment

1. Introduction

With the escalating demand for refined management and optimized production organization in mining operations, ore volume data has become a critical foundation for inventory management, logistics settlement, and production scheduling. Consequently, errors in this data can propagate to yield accounting and cost control. Regarding the acquisition of stockpile and bulk material volumes, existing reviews have noted that manual measurement and empirical geometric approximation struggle to balance efficiency and accuracy under conditions involving irregular morphologies, occlusions, and confined spaces; furthermore, the lack of unified evaluation criteria undermines result comparability [1]. Domestic research in mine surveying suggests that while 3D laser scanning offers advantages such as non-contact operation, high-density sampling, and rapid modeling, its widespread adoption is impeded by the computational burden associated with complex operating conditions, equipment costs, and logistical challenges [2]. From a theoretical perspective, point cloud accuracy is subject to the coupled effects of error sources, including ranging errors, positional/orientational inaccuracies, temporal deviations, and scanning geometry. Baltsavias provided a formulaic analysis of 3D positioning accuracy and primary error terms, establishing a framework for engineering error budgeting [3]. Further domestic studies have quantified the influence of various error factors, providing a basis for parameter optimization and accuracy improvement [4]. For ore volume measurement specifically, dense linear laser scanning arrays enhance coverage and sampling density through multi-line/multi-view synchronous scanning. Engineering system research has verified that integrating this technology with point cloud integration enables a controllable level of error

[5]. In the context of online belt conveyor monitoring, volume/flow estimation models that couple material cross-sectional profiles (acquired via laser scanning) with belt speed have been validated [6]. Practical applications in mineral concentrate inventory have also demonstrated that optimizing scanning paths and workflows can concurrently improve inventory accuracy, efficiency, and operational safety [7]. Nevertheless, point cloud-driven automatic stockpile extraction and volume estimation remain susceptible to variations in pile morphology, base conditions, and overlapping stockpiles; boundary identification and volume stability thus remain challenging issues [8]. Therefore, it is necessary to conduct a comprehensive review focusing on the system configuration, calibration and synchronization, point cloud quality control, reconstruction and volume estimation, and accuracy assessment of array-based scanning. This study aims to provide reusable references for the engineering deployment of mine inventory and online measurement systems.

2. Unified Technical Framework for Volume Measurement Using Dense Linear Laser Scanning Arrays

2.1 System Configuration and Measurement Mechanism

To facilitate the comparison of diverse research outcomes within a consistent framework, this paper conceptualizes the research object of utilizing dense linear laser scanning arrays for ore volume measurement as a class of engineering systems defined by the architecture: "multi-channel linear laser triangulation units—synchronous triggering and time reference—common coordinate framework—point cloud processing and volume calculation." Linear laser triangulation represents a critical branch of active 3D acquisition. Its core advantage lies in the ability to acquire high-density geometric information within a short timeframe, making it suitable for rapid contour sampling and 3D reconstruction of irregular surfaces. The developmental trajectory, precision characteristics, and key engineering implementation points of such ranging and imaging-based measurements have been systematically reviewed, serving as the technical foundation for the discussion on array-based system configurations in this paper [9].The key to array-based scanning is not merely the addition of "more laser lines," but rather the enhancement of coverage through spatial arrangements involving multiple perspectives and baselines. Furthermore, it enables complementary observations on stockpile surfaces with significant occlusions, thereby improving point cloud integrity and the stability of volume estimation. Relevant studies have proposed improving the scanning mode and imaging effects of linear laser sensors through synchronized scanning mechanisms. This concept of "synchronization-geometric consistency" offers significant insight into why array-based scanning places such strong emphasis on triggering and time references [10].

2.2 Unified Process Chain: The "Engineering Chain" from Point Clouds to Volume

In engineering implementation, array-based linear laser measurement typically follows a relatively stable processing chain: first, data acquisition is completed and operating conditions (such as station position/path, sampling rate, occlusion, and dust conditions) are recorded; subsequently, multi-channel geometric calibration and time synchronization are performed to ensure that outputs from different channels can be fused under the same coordinate system and at the same time; then, point cloud preprocessing and fusion (denoising, outlier removal, necessary downsampling, and stitching) are carried out, followed by the stages of stockpile extraction and bottom surface modeling; finally, volume results are obtained through surface reconstruction and volume calculation, along with accuracy assessment and quality control. For array systems, calibration and synchronization determine "whether the data is usable," while stockpile extraction and bottom surface modeling determine "whether the volume is stable."At the calibration level, external parameter solution for multi-sensors (cameras/lasers) and automated calibration tools are relatively mature. Relevant studies have shown that rapid calibration between cameras and ranging sensors can also be achieved with minimal manual intervention, providing a practical path for reducing the maintenance costs of multi-channel array systems [11]. In multi-beam or multi-channel laser systems, the systematic errors of the sensors themselves and the consistency between channels significantly affect the quality of point cloud fusion. Existing studies, taking mobile multi-beam lidar as an example, have improved geometric consistency through target-free internal parameter calibration and point cloud refinement, and this conclusion is also applicable to the long-term stable operation of array-based linear laser systems [12].

2.3 Key Algorithm Modules and Unified Evaluation Criteria

In the point cloud fusion and reconstruction stage, registration is one of the core steps to unify point clouds from different channels and perspectives into a common coordinate framework. The classic Iterative Closest Point (ICP) method provides a general framework for rigid body registration of two point sets. Although it is often modified by combining features, constraints, or initial value strategies in practical engineering, its basic idea still constitutes the core logic of multi-source point cloud fusion [13]. Point cloud processing presents a trend of "modularization and componentization" in engineering. The Point Cloud Library (PCL) systematically integrates common operators such as filtering, feature extraction, registration, model fitting, segmentation, and reconstruction, which objectively supports the review writing style of "describing different system implementations with unified algorithm modules" [14].In terms of surface reconstruction, ore stockpiles often have problems such as noise, cavities, and unclear boundaries, which require converting discrete point clouds into integrable continuous surfaces. Poisson reconstruction recovers closed surfaces from oriented points in a global manner. Due to its adaptability to noise and uneven sampling, it is widely adopted and often serves as a representative route of "grid-based reconstruction" in volume calculation [15]. To improve the comparability of different research results, this paper suggests that the evaluation criteria should cover at least three types of information simultaneously: first, accuracy (relative volume error and repeatability); second, efficiency (acquisition duration and processing duration); third, usability/robustness (failure rate or cavity rate under operating conditions such as occlusion and dust).For example, some studies have reported the operation organization and application frequency of LiDAR volume measurement in actual inventory scenarios, indicating that "efficiency-process-sustainable operation" itself is also an important part of engineering evaluation, which provides a reference for the evaluation dimensions of mine inventory systems [16]. By describing system configurations and algorithm chains under the same process chain and the same index criteria, subsequent sections can conduct more targeted comparisons and reviews on issues such as calibration and synchronization, point cloud quality control, bottom surface modeling, and volume estimation, and form reusable suggestions for engineering deployment.

3. Four Typical Engineering Measurement Paths and Their Key Technologies

3.1 Fixed Arrays for Inventory of Open-Pit Stockyards/Sheds

In the inventory scenarios of open-pit stockyards and sheds, the measurement targets are usually large-scale, irregular, and ill-defined stockpile surfaces. Moreover, on-site operations are often intertwined with loading, unloading, transportation, and other processes, requiring the measurement process to be as "fast, non-intrusive, and repeatable" as possible. The engineering idea of fixed dense linear laser scanning arrays is to exchange multi-view coverage for point cloud integrity: by arranging multi-channel or multi-station observations around the stockpile, complementary coverage of occluded areas from different line-of-sight directions is achieved, thereby reducing the systematic impact of "single-view invisibility" on volume estimation.Practical experience has shown that if a unified coordinate datum can be stably established within the same site, and consistent definitions of the bottom surface/datum plane and volume calculation criteria are adopted, the comparability and traceability of inventory results from different batches can be significantly improved. When comparing stockpile volume monitoring processes, relevant studies also generally emphasize that "unification of control points and datums, and cross-validation of results from different acquisition methods" are important means to ensure the reliability of volume results [17].

3.2 Confined Space Scenarios: Silos, Chutes, and Internal Stockpiles

Volume measurement in confined spaces such as silos and chutes often places greater emphasis on safety and accessibility. Narrow spaces result in a limited field of view, while dust and low-reflectivity materials introduce noise and unstable echoes; furthermore, structural occlusions frequently occur in bottom and boundary regions, leading to point cloud voids. In such scenarios, the primary engineering challenge usually lies not in "whether points can be acquired," but rather in "how to define the bottom surface, handle voids, and constrain boundaries," as uncertainty regarding the bottom surface directly translates into volume deviations. To address the common issue of missing bottom point clouds, relevant studies focusing on ground-stacked bulk materials have proposed an automated workflow of "bottom plane fitting—closed reconstruction—volume calculation." The core idea is to estimate the bottom surface using observable bottom edges or surrounding points, thereby satisfying geometric closure conditions and improving the stability of volume calculation. This approach offers direct transferable value for silo-type scenarios [18].

3.3 Conveyor Belts and Chute Points: Online Volume (Volume Flow) Estimation

In online measurement scenarios, the target is the "morphology of bulk materials in motion." Volume estimation requires strong coupling with belt speed or time synchronization; consequently, system design places greater emphasis on scanning frequency, trigger consistency, and real-time processing capabilities. Engineering implementations typically utilize line lasers (or line structured light) to acquire material cross-sectional profiles, then map the "cross-sectional area—time/displacement" relationship to volume (or volume flow rate) by incorporating conveyor belt speed. Furthermore, filtering and vibration compensation are employed to suppress error amplification caused by transient fluctuations. Addressing the dynamic measurement of high-capacity belt conveyors, relevant studies have proposed online non-contact metering systems based on laser triangulation. These systems recover 3D profiles through line laser projection and image/signal processing. Verified on experimental platforms for the stability and usability of dynamic measurements, they provide representative examples for the engineering route of "line laser-based online cross-section—volume flow estimation" [19].

3.4 Mobile/Vehicle/Robotic Array Scanning: Large-Scale Rapid Modeling and Re-Survey

In scenarios characterized by large stockyard areas, dispersed survey regions, or the need for rapid re-survey, mobile scanning (employing vehicle-mounted, backpack, robotic, or UAV platforms) enables the acquisition of continuous point clouds with higher operational efficiency. However, their accuracy and stability are highly dependent on trajectory calculation, loop closure constraints, and multi-source fusion strategies. This dependency is particularly pronounced in GNSS-denied environments such as mine roadways and the interiors of storage sheds.In recent years, the application of SLAM-based mobile scanning devices in mining environments has increased significantly. Relevant studies have compared various SLAM scanning and static scanning devices within mine roadways, establishing error assessment workflows and quantifying typical accuracy levels. These studies further indicate that while next-generation SLAM scanners offer high operational efficiency in confined spaces, their noise control and quality assessment protocols still need to be aligned with engineering acceptance criteria. These conclusions provide direct evidence for the feasibility of mobile array scanning in mine inventory and re-survey tasks [20].

4. Horizontal Comparison and Common Patterns

4.1 Horizontal Comparison of Typical Measurement Paths

Although the aforementioned four engineering paths exhibit significant differences in hardware morphology, operational organization, and data processing chains, their impact on the "acceptability of volume results" typically converges on three aspects: first, the adequacy of point cloud coverage (and whether occlusion-induced voids are controllable); second, the stability of boundary and bottom surface criteria (and whether cross-batch re-surveys are feasible); and third, the uniformity of evaluation metrics (and whether accuracy, efficiency, and usability can be demonstrated concurrently). To facilitate the induction of application scenarios, risk factors, and deployment key points for different paths under a consistent framework, this paper compares and summarizes the typical measurement paths within the three-dimensional evaluation framework of "accuracy—efficiency—usability/robustness," as illustrated in Table 1.

Table 1. Comparison of Four Typical Measurement Paths

Path Type	Typical Scenarios	Data Acquisition Characteristics	Primary Error Sensitivity	Efficiency Focus	Recommended Volume Strategy	Key Engineering Deployment Points
Fixed Array (Open-pit/Shed Inventory)	Stockyards, storage sheds, open-pit piles	Multi-view coverage, high point density, repeatable inventory	Occlusion-induced voids, ill-defined boundaries, bottom surface datum drift	Targeting "inventory cycle time"	Grid (DEM) integration or TIN-based volume calculation	Stabilization of coordinate datum; station layout and occlusion planning; long-term calibration maintenance
Confined Space Array (Silos/Ore Passes)	Silos, ore passes, internal stockpiles	Limited FOV, high dust impact, strong boundary constraints	Invisible bottom surface, void filling, insufficient boundary constraints	Priority on safety and accessibility	Volume integration after "bottom surface modeling + closed reconstruction"	Strong boundary constraints; bottom surface modeling strategy; void detection and supplementary measurement mechanism
Online Section Measurement (Conveyors/ Drop Points)	Conveyor belts, drop points	High sampling rate, strong coupling with speed/time	Synchronization errors, vibration, unstable section segmentation	Real-time or quasi-real-time	Cross-sectional area × displacement/time; local reconstruction if necessary	Trigger synchronization; speed acquisition and compensation; abnormal section filtering and smoothing
Mobile/SLAM Scanning (Rapid Re-survey)	Large-scale stockyards, roadways/workshops	High speed, wide coverage, trajectory calculation is critical	SLAM drift, noise, insufficient loop closure and registration	Extremely high operational efficiency	Reconstruction + volume estimation under trajectory constraints	Quality index system; loop closure/datum control; cross-validation with static benchmarks

4.2 Extraction of Common Patterns

Synthesizing research conclusions from different paths, several common patterns with significant guiding significance for engineering deployment can be deduced. First, the "systematic term" of volume error typically originates from the definition of the bottom surface and boundaries, rather than the complexity of the volume algorithm itself; consequently, regardless of whether grid, raster, or voxel methods are adopted, the repeatability of volume results will degrade significantly if the bottom surface or boundaries are unstable [21]. Second, occlusion is one of the most common and recalcitrant error sources in stockpile measurement. While multi-view coverage can alleviate occlusion, it inevitably leads to an increase in data volume and fusion complexity. Therefore, engineering practices should incorporate "coverage rate/void rate" as a process quality metric into acceptance criteria [22]. Third, the accuracy ceiling of array-based solutions is determined by "multi-channel calibration and synchronization." Calibration drift and temporal deviations directly manifest as point cloud misalignment and boundary jitter, ultimately amplifying into volume fluctuations [23]. For dynamic conveyor belt scenarios, errors tend to manifest as coupling terms involving "cross-section segmentation—speed estimation—temporal alignment." Therefore, synchronization and real-time performance must be treated as system-level indicators rather than mere algorithmic adjuncts [24]. For mobile/SLAM scanning paths, noise and drift are generally higher than in static scanning. Without establishing a quality metric system and cross-validation mechanism tailored to mining scenarios, it is difficult to convert "high efficiency" into "acceptable volume results" [25].

5. Research Gaps and Development Trends

The first common limitation of existing research is that the evaluation criteria are still not unified enough. In particular, there is a lack of consistent standards in aspects such as "true value acquisition methods, repeatability testing, and void rate/coverage rate reporting," making it difficult to directly compare the accuracy and efficiency of similar schemes. The second limitation is that the robustness under complex operating conditions still relies heavily on empirical configuration. For example, issues such as dust, reflectivity differences, boundary aliasing, and stockpile superposition often yield "effective" conclusions in algorithms, but more operable quality control and supplementary measurement strategies are still needed in engineering deployment. The third limitation focuses on the online and automated links.

Dynamic volume measurement must ensure both real-time performance and the stability of segmentation and reconstruction, and there is still a need for lighter point cloud reconstruction strategies and more interpretable anomaly detection mechanisms. Regarding future development trends, first, automatic boundary extraction and bottom surface modeling for stockpiles/bulk materials will place greater emphasis on "less manual intervention, reusability, and transferability," so as to maintain consistent volume criteria for inventory in different sites and different batches. Second, dynamic online measurement will increasingly introduce the combination of learning-based segmentation and geometric reconstruction to improve robustness under conditions of speed changes and uneven loads, and realize quasi-real-time volume estimation on this basis. Third, mobile/SLAM measurement will further move towards the integration of "quality index system + engineering acceptance criteria," limiting drift and noise within an acceptable range through quantifiable quality metrics, thereby supporting more frequent and lower-cost re-surveys and safety inspections.

6. Conclusion

Dense linear laser scanning arrays provide a technical foundation with high density, processability, and high safety for non-contact volume measurement of ores, which can significantly improve operational efficiency and data traceability in tasks such as inventory counting and production metering. Existing research and engineering practices have shown that this technical route has good applicability in open-pit stockyards, storage sheds, and some confined spaces. However, its measurement effect is not only determined by the volume algorithm, but also constrained by the integrity of point cloud coverage, the stability of boundary and bottom surface criteria, and the reliability of multi-channel calibration and time synchronization. From the perspective of engineering acceptability, the main "systematic terms" of volume errors often come from the uncertainty of bottom surface modeling and boundary determination, as well as voids and point cloud misalignment caused by occlusion. In dynamic online metering scenarios, errors will be further reflected as coupled amplification of "cross-section segmentation—belt speed estimation—temporal alignment." Therefore, it is difficult to reflect the long-term stability of the system relying solely on a single error report. To address the above issues, this paper summarizes typical measurement paths by unifying the process chain and evaluation criteria, emphasizing that accuracy, efficiency, and usability (coverage rate/void rate, failure rate, repeatability) should be taken as common acceptance dimensions, and cross-validation and quality grading mechanisms should be established in key scenarios to improve the repeatability and traceability of volume results. In general, the further application of volume measurement using dense linear laser scanning arrays needs to move from "algorithmically effective" to "engineered reliable." Future research should focus more on three aspects: first, automatic boundary extraction and bottom surface modeling methods for complex operating conditions, reducing sensitivity to manual experience and site differences; second, synchronization mechanisms, anomaly detection, and lightweight reconstruction strategies for online metering, maintaining stable accuracy while meeting on-site cycle requirements; third, integration of quality index systems and engineering acceptance criteria for mobile/SLAM measurement, converting high efficiency into acceptable results through quantifiable quality metrics and benchmark constraints.

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