AI-Based Internal Structural Modeling Using Muon Tomography and Few-shot Parameter Calibration

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Abstract -

Reconstructing internal structural elements remains a significant challenge in the construction industry due to limited access to concealed components. Muon tomography provides a non-destructive approach for capturing information about internal structural conditions, yet its application in construction remains limited, especially in 3D model reconstruction. This paper proposes a few-shot parameter calibration–based framework for automated segmentation and reconstruction of internal building elements from muon tomography data, with a focus on reinforcement bars. The proposed method learns geometric and spatial patterns from a limited number of annotated datasets and generalizes to unseen configurations, reducing reliance on large labeled datasets. Experimental results demonstrate improved accuracy in rebar identification compared to existing segmentation approaches. The reconstructed rebar elements can be converted into BIM-ready representations, enabling applications such as defect detection, structural condition assessment, and digital twin development.

Keywords -

Few-shot geometric calibration; Muon tomography; Point cloud segmentation; Internal reconstruction; Scan-to-BIM

1 Introduction

Reconstruction of the internal condition of concrete structures is essential for ensuring structural safety, assessing durability, and supporting maintenance and retrofit decisions throughout the lifecycle of built assets [1, 2]. Internal features such as reinforcement layout, voids, and concealed damage directly influence structural performance, yet they are often undocumented or difficult to access in existing buildings and infrastructure [3]. As-built documentation may be incomplete, outdated, or unavailable, particularly for ageing structures, further increasing uncertainty in structural assessment and decision-making [4].

To address these challenges, internal concrete structure reconstruction has become an important research topic in construction informatics and structural health monitoring, aiming to infer concealed structural components from indirect sensing data [2]. A range of non-destructive testing techniques has been explored, including ultrasonic testing, electrical resistance tomography, and electromagnetic sensing, with demonstrated potential for detecting internal anomalies and reinforcement [3, 5]. However, many existing approaches are limited in penetration depth, sensitivity to material heterogeneity, or scalability to large and densely reinforced structures [4]. In addition, the resulting outputs are often image-based or qualitative, which restricts their direct use in engineering-oriented digital workflows.

With the growing adoption of digital twins and as-built Building Information Modeling (BIM) in the construction industry, there is an increasing demand for internal sensing methods that can provide volumetric information at structural scale and support downstream modeling and analysis tasks [6]. This has motivated interest in alternative imaging techniques capable of overcoming the physical and practical limitations of conventional non-destructive testing methods [2]. Currently, muon tomography has emerged as a promising solution, offering a fundamentally different inspection mechanism based on naturally occurring cosmic-ray muons [7]. Due to the high penetration capability of muons, this technique enables internal inspection of large and dense concrete structures with millimeter-level accuracy that are difficult to assess using traditional approaches [8, 9].

When applied to construction assets, muon tomography produces volumetric datasets that encode internal material distributions at structural scale [9]. However, these datasets are inherently complex, characterized by large spatial dimensions, indirect measurements, and uncertainty introduced during tomographic reconstruction [10]. Although recent studies have demonstrated the feasibility of applying muon tomography to reinforced concrete structures and other civil infrastructure [6], the interpretation of such data remains largely limited to qualitative visualization or density-based assessment [11]. Systematic methods for transforming muon tomography outputs into structured, engineering-compatible representations, such as those required for BIM models, have received limited attention, highlighting an important gap between sensing capability and practical construction informatics applications [12].

This paper proposes a few-shot geometric calibration framework for processing muon tomography data to enable automated segmentation and reconstruction of internal building elements, with a focus on reinforcement bars. The method learns geometric priors from a limited number of annotated samples and generalizes to unseen configurations, reducing reliance on large labeled datasets. It is evaluated against existing instance segmentation approaches and demonstrates superior accuracy and robustness in rebar identification and reconstruction. The segmented elements are further converted into structured geometric representations suitable for BIM integration, supporting downstream applications such as structural assessment, defect detection, and digital twin development. The proposed framework advances muon tomography–based construction informatics and provides a practical pathway for as-built internal structure modeling.

2 Literature review

2.1 Internal Concrete structure reconstruction

Reconstructing the internal condition of concrete elements, including reinforcement layout and hidden defects, is fundamental to structural assessment and maintenance. Prior work has primarily relied on non-destructive testing and imaging techniques to infer internal features from indirect measurements. Among these, ultrasonic-based methods are widely adopted due to their practicality for field inspection. Early studies demonstrated the feasibility of ultrasonic testing and acoustic emission for characterizing damage in concrete elements [13] and summarized ultrasonic techniques for reinforced concrete evaluation [3]. To obtain volumetric representations, ultrasonic tomography has been developed and applied at structural scale, including full-scale reinforced concrete inspection [1] and broader reviews of nondestructive acoustic tomography methods for concrete [2].

A major challenge in ultrasonic tomography lies in the ill-posed inverse problem, which has motivated research into improved reconstruction algorithms and regularization. Iterative reconstruction approaches were explored early for ultrasonic imaging in concrete [14]. Subsequent work adopted algebraic reconstruction techniques and iterative solvers to enhance stability and image quality for reinforced concrete inspection [15]. More recently, network-based strategies have been investigated to improve ultrasonic tomography performance [16], while group sparsity has been introduced to reconstruct velocity field images of internal bridge structures [17]. In parallel, methodological advances have been proposed to refine the reconstruction mesh and improve ultrasonic tomography fidelity [18]. A systematic review further confirms the active development of reconstruction strategies and highlights persistent limitations in resolution, robustness, and deployment in complex concrete environments [19].

Beyond ultrasound, complementary modalities have been explored for internal concrete feature detection. Electrical resistance tomography has been used to locate reinforcement and visualize damage-related conductivity changes [4, 20]. Electromagnetic approaches such as microwave imaging have also been investigated for reinforced concrete inspection [5]. For high-resolution material characterization, X-ray and neutron tomography have been applied to reconstruct concrete microstructures and internal features [21], while CT-based 3D reconstruction has been used to analyze pore structures in concrete-related materials [22]. These approaches demonstrate strong imaging potential, but may be constrained by equipment requirements, data complexity, or applicability to field-scale construction scenarios.

Recent studies have also introduced learning-based components to improve internal condition detection, including deep learning applied to ultrasound arrays for two-step detection of internal concrete conditions [23]. However, across sensing modalities, existing work typically outputs voxel-level images or qualitative visualizations rather than explicit, engineering-ready representations of structural components. This creates a gap between internal imaging and downstream construction applications, particularly for workflows requiring component-level reconstruction and integration into digital models.

2.2 Muon tomography technique and construction applications

Muon tomography, also referred to as muography, is a passive non-destructive imaging technique that exploits naturally occurring cosmic-ray muons to investigate the internal structure of large and dense objects [7, 10]. Due to their high energy and strong penetration capability, muons can traverse thick materials such as concrete, rock, and steel, making them suitable for imaging structures that are inaccessible to conventional sensing methods [7, 9]. As muons pass through matter, their trajectories are altered through attenuation and multiple Coulomb scattering, with the degree of deviation dependent on the density and atomic composition of the traversed material [10]. By measuring the incoming and outgoing muon tracks using dedicated detector systems, three-dimensional density distributions of the inspected object can be reconstructed via tomographic inversion techniques [9, 7]. These characteristics have established muon tomography as a robust imaging modality in domains such as nuclear material monitoring, geological exploration, and underground structure inspection, providing a solid technical foundation for its extension to large-scale construction and civil infrastructure applications [7, 10].

In the context of construction and civil infrastructure, muon tomography has recently emerged as a promising technique for inspecting reinforced concrete structures that are difficult to assess using conventional non-destructive testing methods [8]. Early proof-of-concept studies demonstrated the feasibility of imaging the interior of reinforced concrete elements using muon tomography, showing that reinforcement layouts and internal features could be detected with a quality comparable to, and in some cases exceeding, that of ultrasonic and radar-based methods [8, 11]. These studies highlight muon tomography's potential to overcome the penetration depth limitations of traditional techniques when applied to large or densely reinforced concrete components [24].

More targeted investigations have focused on the detection and localization of reinforcement bars within concrete using muon scattering tomography. Simulation-based studies have shown that muon tomography can detect rebars of practical dimensions and distinguish between single and multiple reinforcement layers embedded at different depths [24]. Subsequent experimental and methodological developments further validated the capability of muon scattering tomography to identify reinforcement meshes within large-scale concrete objects and to resolve their relative spatial positions [11, 12]. These works demonstrate the viability of muon tomography for reinforcement detection and highlight its relevance for assessing ageing infrastructure where as-built documentation may be incomplete or unavailable [12].

Beyond reinforced concrete inspection, muon tomography has also been explored for broader infrastructure monitoring applications, including the structural health assessment of large civil assets such as dams. Field deployments have shown that muon-based density imaging can reveal internal deterioration and material loss within massive concrete structures, supporting its potential role as a complementary tool for long-term structural health monitoring [6, 7]. While these studies primarily focus on sensing feasibility and density imaging, they collectively establish muon tomography as a powerful technique for construction-scale internal inspection [9].

Overall, existing research confirms the potential of muon tomography for construction applications, particularly for imaging internal conditions of large reinforced concrete structures. However, most studies emphasize sensing principles, detector development, and qualitative density reconstruction [10]. The extraction of explicit structural components and their integration into engineering-oriented workflows, such as as-built modeling and digital twins, remains largely unexplored, motivating further research on advanced interpretation and reconstruction methods for muon tomography data [12, 6].

2.3 Research gaps

Existing non-destructive inspection methods for reinforced concrete (e.g., ultrasonic and electrical resistance tomography) support internal inspection, but their outputs remain image- or voxel-level and are difficult to convert into component-based models for scan-to-BIM and digital twin workflows [1, 25]. Muography offers high penetration for imaging dense reinforced concrete, yet current construction-oriented studies mainly focus on sensing feasibility and qualitative density reconstruction rather than automated extraction of discrete reinforcement elements for BIM-ready modeling [8, 12].

Few-shot segmentation enables recognition under limited labeled data, typically via meta-learning, but such paradigms rely on large pretraining datasets and are sensitive to domain shifts, making them less applicable to sparse and geometry-driven muon tomography data. Therefore, this study adopts a few-shot geometric calibration strategy, using limited annotated rebar exemplars to extract geometric priors and calibrate segmentation parameters for data-efficient and interpretable reinforcement extraction.

Meanwhile, conventional clustering or model-fitting methods may fragment or merge rebars in dense layouts, while fully supervised learning remains constrained by scarce labeled muon datasets. Thus, approaches that leverage geometric priors and limited supervision are needed to robustly extract reinforcement components and support BIM-oriented internal structural modeling.

3 Proposed method

This section presents an AI-enabled framework for internal structure reconstruction from muon tomography data, designed to enable robust segmentation and BIM-ready representation of internal structural elements, with a focus on reinforcement bars. Figure 1. provides an overview of the proposed framework workflow.

The proposed few-shot parameter calibration method identifies reinforcement bars from a large point cloud by leveraging a small number of labeled rebar examples as geometric references rather than relying on extensive supervised training. Each few-shot sample is first analyzed to estimate its principal axis, radius, length, and straightness using PCA-based geometric analysis. When the number of labeled points is insufficient, the sample is automatically augmented by retrieving geometrically consistent points from the full point cloud. These augmented few-shot examples are then used to compute representative

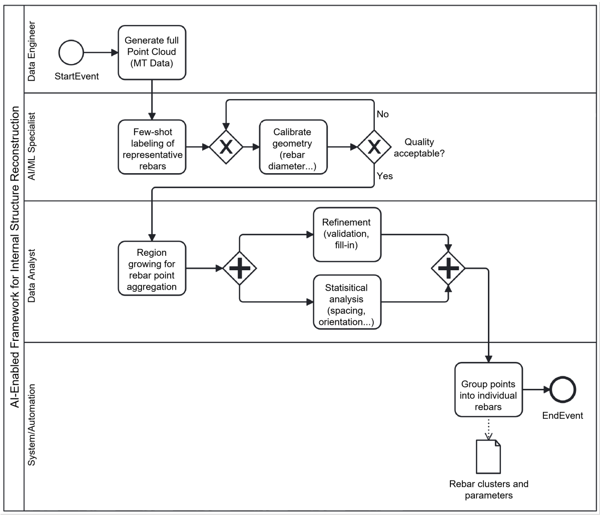

Figure 1. Enhanced workflow diagram of the AI-enabled framework

statistics, including typical rebar radius, axial variation, local orientation deviation, and radial noise. The proposed few-shot geometric calibration method identifies rebars in large point clouds using a small number of labeled rebar exemplars as geometric references rather than extensive supervised training. Each exemplar is analyzed via PCA-based geometric fitting to estimate axis, radius, length, and straightness, and is augmented with geometrically consistent points when necessary. Representative geometric statistics are then computed to derive calibration parameters controlling neighborhood size, angular consistency, radial deviation, and minimum rebar length. Using these calibrated parameters, a region-growing strategy is applied to segment rebar clusters, with seed selection based on local linearity and iterative growth under spatial and geometric constraints. Cluster geometry is periodically updated to refine axis and radius estimates. A subsequent fill-in step recovers missed but consistent points, and clusters are validated by size, straightness, and length criteria before extracting geometric descriptors for BIM-compatible output.

4 Implementation details

4.1 Dataset preparation

In this study, a simulated approach was first employed to generate volumetric data representing the internal structure, which were stored in the NIfTI (.nii.gz) format. The simulated data were subsequently processed using software provided by GSCAN, through which structural components, including reinforcement and concrete, were identified and encoded in the volumetric representation. The resulting .nii.gz files contain three-dimensional voxel-based data that describe material distributions within the structure.

The NIfTI data are characterized by high dimensionality and volumetric continuity, making them well suited for representing internal structural conditions but less convenient for direct geometric analysis. To facilitate subsequent processing and reconstruction tasks, the volumetric data were therefore converted into point cloud representations, enabling more efficient handling and geometric-based analysis in later stages of the workflow.

The experimental dataset consists of point cloud data representing reinforced concrete elements with irregular rebar layouts. The point clouds were acquired through simulated scanning generation, capturing variations in rebar diameter, curvature, spacing, and overlap. Ground truth geometric information was used only for evaluation purposes and not for training. Figure 2 presents representative reconstruction results obtained using the proposed framework..

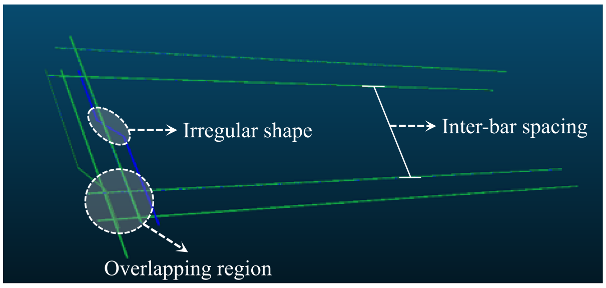

Figure 2. Labeled rebar data for training

4.2 Results of the proposed methods

This subsection presents the results of rebar segmentation from raw point cloud data. The proposed method effectively isolates rebar points from surrounding concrete and noise, even in cases of complex intersections and curved geometries. Quantitative and qualitative results demonstrate stable segmentation performance across different rebar configurations. Figure 3 shows representative examples of challenging rebar layouts, including dense arrangement, local overlap, and irregular spacing.

It is obvious that the segmentation results produced by the proposed AI-enabled few-shot calibrated method. Each reinforcement bar is identified as an individual cluster and visualized using a distinct color, demonstrating the method's ability to properly segment closely spaced rebars within a dense internal reinforcement layout.

As shown in the figure, the proposed approach successfully separates individual rebars even in regions with strong spatial proximity and complex intersections.

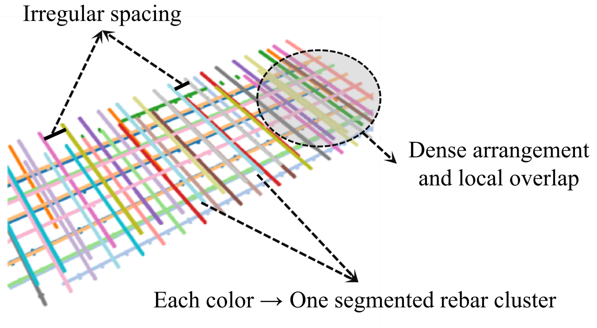

Figure 3. Segmentation results of using the proposed AI-enabled method

Importantly, rebars with irregular geometries and non-linear connections are also correctly identified as continuous structural elements rather than being fragmented or merged with neighboring bars. This indicates that the geometry-calibrated region growing process effectively preserves rebar continuity while maintaining clear separation between adjacent elements.

Overall, the results confirm that the proposed method can (1) accurately segment individual rebars from complex internal point cloud data and (2) reliably identify connected rebars with irregular shapes, providing structured outputs suitable for downstream applications such as BIM reconstruction, defect detection, and structural condition assessment.

4.3 Comparison with other segmentation methods

This research further compares the proposed method with commonly used instance segmentation algorithms for individual rebar identification, including DBSCAN, cylinder-model fitting, and region growing segmentation.

As shown in Figure 4, DBSCAN detects a large number of rebar instances, with 220 rebars identified. However, the results exhibit severe over-segmentation. Individual rebars are frequently divided into multiple clusters, and the algorithm fails to identify connected rebars with complex or irregular geometries. This behavior is mainly due to DBSCAN's sensitivity to point density and distance thresholds, which limits its robustness in dense reinforcement layouts.

Figure 5 presents the results obtained using cylinder-model fitting, where only 36 rebars are detected. Many rebars are missed due to the strict geometric assumptions of the cylinder model, and connected rebars cannot be correctly identified. This approach is particularly sensitive to incomplete or noisy data and struggles to represent irregular rebar shapes.

As illustrated in Figure 6, region growing segmentation detects 56 rebars but suffers from significant fragmentation, especially for vertical rebars. While region growing partially captures linear structures, it fails to maintain rebar continuity and cannot reliably identify connected rebars, leading to incomplete and fragmented segmentation results.

Overall, the comparison demonstrates that existing instance segmentation methods either over-segment rebars or fail to capture their connectivity and irregular geometry. In contrast, the proposed few-shot calibrated method achieves accurate individual rebar segmentation while preserving connected and irregular rebar structures, highlighting its robustness and suitability for construction-oriented applications.

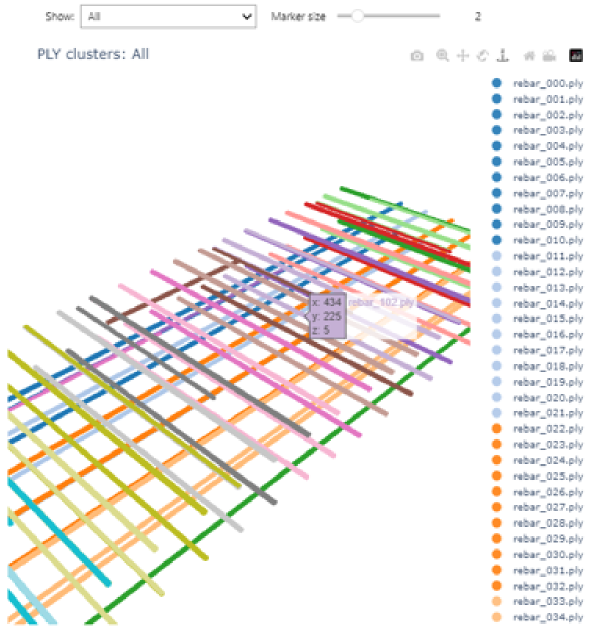

Figure 4. Segmentation results of using DBSCAN

5 Results and discussion

The experimental results demonstrate clear performance differences between the proposed method and commonly used instance segmentation algorithms for rebar identification, highlighting the challenges of density-based, model-based, and purely geometric approaches when applied to complex internal reinforcement layouts. DBSCAN detects a large number of rebar instances but suffers from severe over-segmentation. Individual rebars are frequently fragmented into multiple clusters, particularly under varying point density or close spatial proximity, preventing reliable identification of connected rebars and irregular geometries. Cylinder-model fitting exhibits the opposite behavior, detecting only a small subset of rebars. The method relies on strong geometric assumptions and is sensitive to incomplete data and deviations

Figure 5. Segmentation results of using cylinder-model fitting

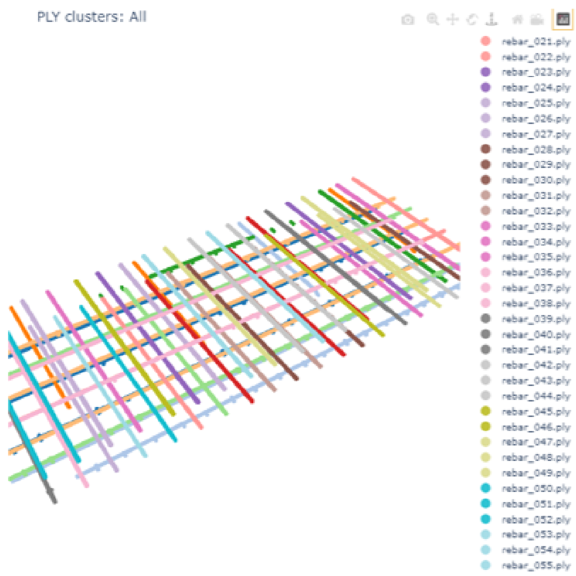

Figure 6. Segmentation results of using the region growing segmentation

from ideal cylindrical shapes, leading to missed rebars, under-segmentation, and incomplete internal structure reconstruction. Region growing achieves moderate detection performance but produces fragmented results, especially for vertical rebars. Although linear features are partially captured, the absence of calibrated geometric constraints prevents reliable identification of continuous and connected rebars. In contrast, the proposed few-shot calibrated method achieves accurate individual rebar segmentation while preserving continuity and connectivity, including irregular rebars embedded in structural components. This capability supports internal reinforcement modeling and downstream applications such as structural condition assessment, defect detection, retrofitting planning, as-built BIM generation, and digital twin development.

Several limitations of this study should be noted. First, standard quantitative instance segmentation metrics (e.g., IoU, precision, recall, and F1-score) were not reported, as no benchmark dataset was available for this evaluation. The current assessment is therefore based on manual observation and qualitative analysis. The current datasets are generated through simulation-based muon tomography, and robustness under real acquisition noise and reconstruction artifacts remains to be validated. Experiments were conducted on a limited range of reinforcement layouts and reconstruction settings; broader tests on varying densities and resolutions will be explored. Finally, while scan-to-BIM conversion is demonstrated, detailed evaluation of geometric parameter extraction and IFC/BIM generation accuracy will be investigated in future work.

6 Conclusions

Reconstructing internal structural elements remains a significant challenge in the construction industry due to the limited accessibility of concealed components. While muon tomography offers a promising non-destructive means of capturing internal structural information, its practical use in construction has been constrained by the complexity of the data and the lack of effective processing methods. Addressing this gap, this paper proposed a few-shot parameter calibration–based framework for the automated segmentation and reconstruction of internal building elements from muon tomography data, with a particular focus on reinforcement bars.

By leveraging a small number of labeled examples to calibrate geometry-driven segmentation, the proposed method generalizes effectively to unseen rebar configurations and reduces reliance on large annotated datasets. Comparative experiments demonstrate that the proposed approach achieves improved accuracy and continuity in rebar identification compared to commonly used segmentation methods. Furthermore, the reconstructed rebars are directly convertible into BIM-ready representations, enabling practical applications such as defect detection, structural condition assessment, retrofitting planning, and digital twin development for existing structures.

7 Acknowledgments

This research is part of the "Muon Tomography for Assessing Bridge Structures" (M-TABS) project, funded by Innovate UK (Project Ref: 10132366). The authors would like to thank their project partner GScan Ltd for their collaboration and support during this study. This research is partially supported by by the Center for Sand Hazards and Opportunities for Resilience, Energy, and Sustainability (SHORES), funded by Tamkeen under the NYUAD Research Institute Award CG013.

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