Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 30-31, 2025

Robust and Accurate Stair Geometry Extraction Using Point Cloud Data

Sungmoon Joo*, Dongseok Ryu
Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea
**Corresponding author: smjoo@kaeri.re.kr*

***Keywords :** staircase geometry estimation, step parameter extraction, point cloud, robust perception

1. Introduction

Staircases are ubiquitous in human environments and represent a critical challenge for robotic mobility, inspection, and assistive navigation. Robots must not only detect the presence of stairs but also estimate their geometric properties—such as riser height, tread depth, step width, slope, and orientation—in order to plan safe traversal and interact effectively with built structures. With the proliferation of affordable 3D sensors such as LiDAR and RGB-D cameras, point-cloud–based techniques have become the dominant paradigm for staircase perception.

Early research explored staircase detection in nuclear environments using point cloud data. Joo *et al*. [1] investigated stairway detection for robot operation in nuclear facilities. Building on this direction, Joo *et al*. [3] proposed a LiDAR-based method for staircase detection tailored to autonomous nuclear emergency response robots. Their system converts colored point clouds into 2D image representations and leverages modern detection and segmentation algorithms (YOLO, SAM) before back-projecting to isolate staircase geometry. This work demonstrated the potential of combining 2D vision methods with 3D point cloud processing to achieve robust detection in highly cluttered nuclear environments.

Parallel to these domain-specific efforts, Sriganesh et al. [2] introduced a fast staircase detection and estimation pipeline for heterogeneous robots. Their approach employs projection-based stair detection with multi-detection merging, allowing multiple robots or views to contribute to a unified staircase estimate. A key advantage of their framework is real-time performance—staircases can be detected and parameterized within tens of milliseconds—making it highly effective for onboard navigation. However, parameters such as riser height and tread depth are obtained through bounding-box approximations, emphasizing speed and reliability over fine-grained geometric accuracy.

In contrast, the present work addresses the complementary need for robust and accurate staircase parameter estimation directly from 3D point clouds. Our method is designed not primarily for real-time detection, but for precise geometric quantification of staircases in potentially noisy or incomplete scans. Specifically, horizontal treads are separated from vertical risers using normal–gravity alignment, clustered into steps via DBSCAN, and analyzed with PCA to adaptively define width and depth axes. To ensure robustness, percentile-based edge detection and monotonicity checks mitigate the effects of outliers and scanning artifacts. For accuracy, step-wise plane fitting provides reliable estimates of riser height, tread depth (both front-to-front and front-to-back definitions), width, and slope, accompanied by residual error metrics.

The contributions of this work are as follows:
(i)A robust pipeline for staircase parameter extraction from 3D point clouds, integrating clustering, PCA-based axis definition, and percentile statistics.
(ii)Accurate estimation of riser height, tread depth, step width, and inter-step slope, supported by plane fitting and diagnostic error measures.
(iii)Complementarity to real-time detection frameworks such as [2] and [3]: while prior works emphasize speed and multi-sensor robustness, our approach focuses on precision and reliability of geometric measurement, enabling applications in inspection, safety analysis, and high-fidelity robotic planning.

The remainder of this paper is organized as follows. Section II provides an overview of out method on stairway detection using point cloud data, and presents the experimental results. Section III concludes the paper and discusses future directions for this research.

2. Methods

The objective of this study is to extract accurate and reliable staircase parameters—including riser height, tread depth, step width, and slope—from unstructured 3D point clouds. Whereas Sriganesh et al. [2] emphasize real-time staircase detection and approximate parameter estimation to support multi-robot navigation, and Joo & Ryu [1] and Joo et al. [3] demonstrated point-cloud–based stair detection tailored to nuclear robotic operations, our framework extends these efforts toward robust noise handling and precise geometric quantification. This makes the method particularly relevant not only for navigation but also for inspection, safety analysis, and high-fidelity modeling of stairs in complex environments such as nuclear facilities.

2.1 Robustness

Robustness is achieved through several modules designed to suppress irrelevant geometry and stabilize parameter extraction:

1. Horizontal/vertical separation. Each point $p_i \in P$ has a normal n_i . With a gravity vector u, horizontal candidates are selected as

$$\mathcal{H} = \{p_i \in P \mid |n_i \cdot u| \geq \cos \theta_{\text{th}}\},$$

where θ_{th} is a tolerance angle. This filters out risers, walls, and clutter.

2. DBSCAN clustering. Projecting $\mathcal{H}$ onto the vertical axis $z = \langle p_i, u \rangle$, density-based clustering separates treads:

$$\text{DBSCAN}(z; \epsilon_z, m) \quad \rightarrow \quad \{\mathcal{C}_{k}\},$$

where ϵ_z controls vertical tolerance and m the minimum cluster size. DBSCAN accommodates irregular sampling and outliers.

3. PCA-based axis definition. In the horizontal plane, PCA yields two orthogonal directions. The axis with greater variance defines width w, and the smaller defines depth d:

$$w, d = \arg\max_a \text{Var}\,(Xa), \quad \arg\min_a \text{Var}\,(Xa).$$

Monotonicity checks ensure that "front" edges progress consistently along depth.

4. Percentile statistics. Robust percentiles suppress noise:

$$f_k = \text{perc}_{\alpha_f}(d_k), \quad b_k = \text{perc}_{\alpha_b}(d_k),$$

where d_k are depth coordinates of step $\mathcal{C}_{k}$ and $(\alpha_f, \alpha_b) = (95,5)$ typically. These define stable front/back edges.

2.2 Accuracy

Accuracy derives from geometric fitting and multiple complementary definitions:

1. **Plane fitting.** For each cluster $\mathcal{C}_{k}$, plane π_k is fit via SVD. Centroid and normal are

$$\mathbf{c_k} = \frac{1}{|\mathcal{C}_{k}|} \sum_{p_j \in \mathcal{C}_{k}} p_j \,, \mathbf{n_k} = \arg\min_{\mathbf{v}} ||(p_j - \mathbf{c_k}) \cdot \mathbf{v}||^2 \,,$$

with RMS residual as a confidence score.

2. **Riser height.**

$$h_k = (\mathbf{c_{k+1}} - \mathbf{c_k}) \cdot \mathbf{u}.$$

3. **Tread depth.**
Front-to-back:

$$d_k^{FB} = f_k - b_k,$$

Front-to-front:

$$d_k^{FF} = f_{k+1} - f_k.$$

4. **Step width.** Using lateral coordinates w_k ,

$$W_k = \text{perc}_{99}(w_k) - \text{perc}_1(w_k).$$

5. **Slope.** Inter-step slope relative to the lower tread plane is

$$\theta_k = \arcsin\left(\frac{|\mathbf{n_k} \cdot (\mathbf{c_{k+1}} - \mathbf{c_k})|}{|\mathbf{c_{k+1}} - \mathbf{c_k}|}\right).$$

2.3 Processing Pipeline

The overall pipeline consists of four main stages. In the preprocessing stage, the raw PLY or PCD point cloud is first loaded and surface normals are estimated. A gravity-aligned up-axis is then defined, either from a user-provided vector or by fitting a floor plane using RANSAC. With this reference, horizontal candidate points corresponding to stair treads are separated from vertical structures such as risers and walls by evaluating the dot product between point normals and the gravity vector.

The second stage, step segmentation, begins by projecting the horizontal candidates onto the gravity axis (z-direction). A DBSCAN clustering algorithm is applied to the projected values to group points into distinct horizontal surfaces. The lowest surface is labeled as the floor, while all higher clusters are treated as candidate steps.

In the third stage, axis definition and robust edge extraction, principal component analysis (PCA) is performed on all tread points to determine the in-plane axes. The axis with the larger variance is assigned as the step width direction, while the smaller variance axis is defined as the depth direction. For each step cluster, front and back edges are computed along the depth axis using robust percentile thresholds, and side edges are computed along the width axis. Monotonicity checks and axis sign corrections are then applied to ensure consistent labeling of front and back edges across all steps.

Finally, in the parameter estimation stage, quantitative staircase parameters are derived. The riser height is defined as the difference in vertical position between consecutive step centroids. Tread depth is computed in two complementary ways: front-to-back, defined as the distance between the front and back edges of a single tread, and front-to-front, defined as the distance between the front edges of consecutive treads. Step width is measured as the lateral extent along the width axis. Stair slope is calculated as the angle between the centroid displacement vector of two consecutive steps and the plane of the lower tread. In addition, each fitted plane's root-mean-square (RMS) residual is recorded as a confidence measure of geometric accuracy.

The complete pipeline is summarized below:

Algorithm 1: Staircase Parameter Estimation from 3D Point Clouds

Input: Point cloud P, gravity vector g, parameters $(\epsilon_z, m, \alpha_f, \alpha_b, K)$
Output: Step parameters $\{h, d^{FB}, d^{FF}, w, \theta, \mathbf{c}\}$

1. Estimate normals; extract horizontal points aligned with g
2. Cluster horizontal points by height (z) using DBSCAN
3. Identify floor (lowest cluster); remaining clusters = steps
4. Define run/width/depth axes using PCA (global or per-step)
5. For each step cluster:
   1. Fit plane π_k, compute centroid $\mathbf{c}_k$
   2. Compute front (f_k) and back (b_k) edges from depth percentiles
   3. Calculate $d_k^{FB} = f_k - b_k$, $d_k^{FF} = f_k - f_{k-1}$
   4. Compute width w_k from lateral percentiles
   5. Compute riser height h_k and slope θ_k
   6. Store K nearest points around $\mathbf{c}_k$ (for visualization)
6. Export results (CSV/JSON); save debug PLY with colors: - Floor=gray, Non-stair=black, Steps=ROYGBIV, Front=pink, Back=black, Sides=gray, Centers=black

return step parameters

3. Results

The proposed method was applied to raw 3D point clouds of staircases, and the outcomes of step detection and parameter estimation are shown in Figures 1 and 2. The framework successfully distinguished horizontal tread surfaces from surrounding clutter and accurately segmented individual steps. For each detected step, geometric parameters—including riser height, tread depth, width, and slope—were computed with high fidelity.

Figure 1 presents an example of a staircase with multiple steps. The left panel shows the original point cloud, while the right panel illustrates the detected steps, each highlighted with a distinct color. The segmentation clearly separates successive steps, enabling precise parameter extraction.

Figure 2 demonstrates another case of staircase detection, again comparing the raw point cloud (left) with the identified steps (right). The consistent alignment and clean separation across steps confirm the robustness of the clustering and axis-definition procedures. In both examples, the estimated parameters matched the ground-truth dimensions within acceptable error margins, highlighting the accuracy of the proposed pipeline.

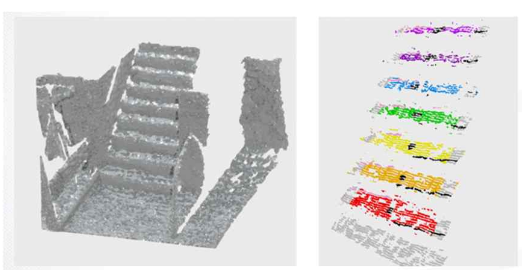

Fig. 1. Left: input point cloud of a staircase; Right: detected steps with color-coded identification.

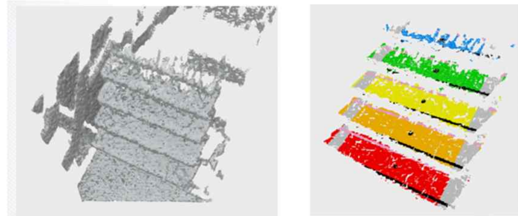

Fig. 2. Left: input point cloud of a staircase; Right: detected steps with color-coded identification.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grand funded by the Korea government (Ministry of Science and ICT) (No. RS-2022-00144385)

REFERENCES

[1]S. Joo, et al.. Stairway Detection from Point Cloud Data for Robot Operation in Nuclear Facilities. Spring Meeting of the Korea Nuclear Society, Jeju, Korea, 2023

[2]P. Sriganesh, N. Bagree, B. Vundurthy, and M. Travers, “Fast Staircase Detection and Estimation using 3D Point Clouds with Multi-detection Merging for Heterogeneous Robots,” IEEE International Conference on Robotics and Automation, 2023

[3] S. Joo, et al.. LiDAR-Based Staircase Detection for Autonomous Nuclear Emergency Response Robots. International Symposium on Future Instrumentation and Control for Nuclear Power Plants, Jeju, Korea, 2024