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Simulation of Stationary and Mobile Laserscanning with VRscan3D

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Abstract

Terrestrial and mobile laser scanning technologies have become essential tools in geoinformation, surveying, cultural heritage documentation, and construction. However, access to modern laser scanning equipment remains limited for many universities and training institutions due to high costs, logistical constraints, or disruptions caused by crises such as pandemics or military conflicts. The VRscan3D project addresses this challenge by developing a realistic virtual simulator for stationary and mobile laser scanning that supports education, training, and research.
VRscan3D is based on a game-engine environment that enables immersive interaction with virtual scanning devices and realistic 3D scenes. The simulator reproduces the physical parameters of real terrestrial laser scanners. Users can define scan stations, configure scanning parameters, and generate synthetic point clouds that incorporate realistic noise, intensity behavior, and beam characteristics. The platform also supports simulation of mobile scanning systems, including handheld scanners, mobile platforms, and UAV-based systems, allowing users to explore error propagation, scanning trajectories, and operator influence on data quality.
In addition to training purposes, VRscan3D enables the generation of synthetic point clouds with known ground truth for testing point cloud processing algorithms and training AI models. Ongoing research focuses on comparing simulated and real datasets to evaluate the accuracy and reliability of synthetic scanning data under dynamic conditions.

1. Introduction and objectives

1.1 Motivation and background

Terrestrial laser scanners (TLS) are now widely used in the fields of geoinformation, monument preservation, archaeology, construction, and surveying. Modern laser scanners also have integrated cameras that enable photogrammetric image processing or support registration processes. This technology allows for the rapid and precise 3D documentation of complex objects, from historical monuments to industrial plants. However, a significant barrier to widespread professional training is the high cost of equipment. Standard professional scanners typically price over €35,000, which is often beyond the budget of many universities, particularly in developing countries (Luhmann et al., 2022).

Mobile and handheld scanners are currently flooding the market, especially in the low-cost sector. Manual operation of mobile systems is much more sensitive to personal behavior and training skills, hence the quality of the resulting point cloud is strongly dependent on operation modes and user actions. Error propagation and noise is much more complicated than for stationary scanners, thus simulation of data collection can help to understand mobile systems and to develop better operational skills among users (Luhmann et al., 2024).

Beyond financial issues, recent global crises have highlighted the need for digital alternatives in education. The COVID-19 pandemic and the full-scale war in Ukraine have made traditional field practice difficult or impossible due to safety risks and restricted access to physical laboratories. Studies on higher education during military conflict indicate that engineering disciplines are among the most affected, since they depend strongly on laboratory infrastructure and access to measurement equipment that cannot easily be replaced by traditional online learning formats (UNESCO, 2024). In this context, digital twins and virtual simulation environments have emerged as critical tools. They allow students to learn how to plan surveys and operate complex instruments in a safe, cost-effective digital setting, ensuring that essential engineering competencies are maintained even under crisis conditions (Fig. 1). Recent studies highlight the significance of digital twins in engineering education, showcasing their ability to offer realistic simulations of industrial systems and processes, thereby enhancing student understanding of complex concepts (Chamorro-Atalaya et al., 2024).

Figure 1. A comparison showing a real-world scanning setup alongside its digital twin equivalent in the VRscan3D simulator.

1.2 Related work

The simulation of technical processes is a well-established method in engineering. In the field of LiDAR (Light Detection and Ranging), several specialized simulators already exist. HELIOS++ is a high-performance open-source framework used mainly for scientific research and generating large datasets for computer analysis (Winiwarter et al., 2022, Bechtold & Höfle, 2016). Another tool, BlenSor, is integrated into the Blender software and focuses on offline data generation for testing algorithms in areas such as autonomous driving (Kwitt & Uhl, 2011).

The project presented in this paper, VRscan3D, differs from these tools in its core philosophy. Instead of focusing only on data generation, VRscan3D is built on the Unreal Engine to provide a highly immersive and interactive experience. It is designed to feel like a real-life operation where the user navigates a virtual site as an avatar, interacts with realistic scanner interfaces, and experiences the physical challenges of fieldwork in real-time.

The closest in concept and approach to simulation is the DVocean Digital system – an educational simulation platform designed to reproduce hydrographic surveying workflows using a multibeam echo sounder (MBES) within an interactive virtual environment (Deggim & Kersten, 2023). The system integrates a digital model of a real survey vessel with a realistic 3D representation of the Hamburg port area, enabling users to simulate the full process of bathymetric data acquisition. In addition to the virtual environment, the platform models the operation of measurement sensors such as the multibeam echo sounder, GNSS positioning and motion sensors, allowing users to plan survey trajectories, perform simulated measurements and generate synthetic bathymetric datasets for further analysis.

Ríos-Otero et al. (2026) present a digital-twin LiDAR simulator for performance assessment of railway ballast geometry inspections, realistically replicating sensor behavior in real railway track environments.

These tools illustrate a spectrum in LiDAR simulation: from high-throughput scientific data generation (HELIOS++), offline algorithmic testing (BlenSor), and domain-specific workflow education (DVocean Digital), to targeted performance benchmarking in critical infrastructure applications (Ríos-Otero et al., 2026). VRscan3D occupies a distinct position in this landscape as the only tool combining real-time immersive interaction, emulation of multiple commercial scanner models, mobile scanning simulation, and a direct educational workflow orientation.

1.3 Research objectives and contributions

The primary objective of the VRscan3D project is to create a realistic “virtual laboratory” that replicates the entire laser scanning workflow, from setting up scan stations to exporting final data. This development aims to bridge the gap between theoretical study and practical experience without real field work or equipment. The specific contributions of this research include:

- **physics-based simulation**: implementing a point-cloud generation process based on mathematical raytracing, where virtual laser beams intersect with 3D surfaces to create accurate coordinates.
- **realistic noise and intensity modelling**: developing models that add Gaussian noise and simulate how different materials (like glass or metal) reflect laser light, creating the “messy” data typical of real-world sensors.
- **scanner interface emulation**: recreating the specific menus and controls of professional devices from manufacturers such as Leica, Faro and Trimble, allowing students to master the software logic used in the industry.
- **mobile and dynamic scanning simulation**: expanding the simulator to include mobile systems (handheld or vehicle-mounted) and dynamic scenes with moving pedestrians and vehicles to teach students how to clean data from unwanted moving objects.
- **AI and Machine Learning support:** providing a tool to generate high-quality synthetic datasets with known ground truth for training artificial intelligence to automatically recognize and segment objects in 3D point clouds.

Beyond individual training, the platform supports international capacity building and provides synthetic ground truth data for AI development – contributions with direct relevance to post-crisis reconstruction contexts such as Ukraine.

2. Methodology and system architecture

2.1 VRscan3D platform overview

The system architecture is built on a modular, subsystem-oriented design that ensures scalability and stability. The technical backbone consists of a C++ core combined with Unreal Engine’s Blueprint Visual Scripting system. This hybrid approach allows for efficient processing of data-intensive tasks – such as generating point clouds with billions of points – while maintaining the flexibility to update simulator modules without recompiling the entire codebase.

A central feature of the platform is its data-driven philosophy. Instead of hardcoding scanner behaviors, the system utilizes DataAssets to define scanner specifications, performance limits, and environmental settings. This enables users to quickly switch between different professional scanner models or create custom sensor profiles by simply swapping data files.

The platform’s functionality is organized into several independent subsystems, each responsible for a specific stage of the surveying process:

- **scanning subsystem**: manages the ray tracing logic and data collection from virtual sensors.
- **post-processing subsystem**: applies filters such as deduplication and noise reduction to raw scan data.
- **export/import subsystem**: handles the asynchronous conversion of data into industry-standard formats (e.g., E57, PTX, LAS) and its re-importation for inspection.
- **persistence subsystem**: ensures that user settings, projects, and scanner configurations are saved across sessions.

To facilitate professional interaction, VRscan3D includes an advanced User Interface (UI) system featuring over 60 modular widgets. The UI is fully responsive and guides the user through a structured workflow – from initial station setup and target placement to final data export. For detailed analysis, the platform provides a dedicated Visualization Room, where users can inspect reconstructed point clouds in an optimized environment isolated from the main scanning scene.

2.2 Sensor and noise modelling

The simulation begins by projecting an angular grid of virtual laser rays from the optical center of the instrument. Using a mathematical model of 3D line intersections (ray tracing), the system identifies the exact point where each ray hits a surface in

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the virtual environment. The result of this stage is an "ideal" point cloud, which represents the geometry of the digital twin with absolute precision. These data are stored within a dedicated data structure, which stores not only point positions but also extensive metadata, including material properties, angle of incidence, and signal return characteristics.

To bridge the gap between this idealized digital data and the "messy" data encountered in real-world fieldwork, the platform applies a series of stochastic noise models (Fig. 2). These models are designed to replicate the specific errors and imperfections of different sensors:

- **Gaussian noise**: adds random measurement deviations in distance and angular measurements based on the scanner's accuracy limits.
- **material-dependent noise**: adjusts the signal quality based on the optical properties of the surface, such as sandstone, steel, or concrete.
- **geometric noise**: accounts for the laser beam's angle of incidence, as measurements become less reliable when the beam hits a surface at a sharp angle.
- **temporal jitter**: simulates small instabilities in the sensor's rotation and timing during the scanning process.

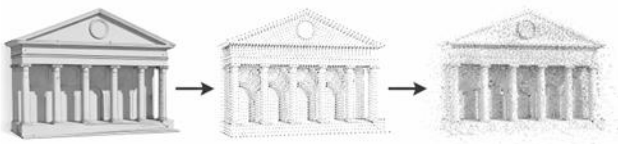

Figure 2. Transition from a perfect 3D mesh to an ideal point cloud, and finally to a noise-affected point cloud with realistic artifacts.

The parameters for these noise models are derived directly from the technical data sheets of real scanners. Users can interact with the same menus and settings – such as resolution, field of view, and scan quality – that they would find on the actual hardware.

Furthermore, the system simulates complex optical phenomena like intensity and signal reflection. For example, the simulator can replicate how a laser beam passes through glass or reflects off a mirror, creating "ghost points" or gaps in the data where the signal is too weak or over-radiated (Fig. 3). These artifacts are essential for teaching users how to recognize and clean problematic data during the post-processing phase.

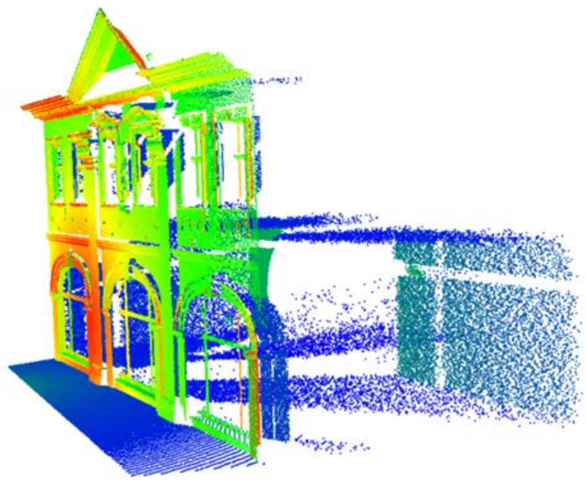

Figure 3. Example of simulated point cloud with intensity and artifacts from scanning through glass.

2.3 Environment customization

The effectiveness of the simulator as a training tool relies on the quality and realism of its virtual environments. These environments serve as digital twins – virtual replicas of real-world locations that allow students to experience the geometric complexity and physical constraints of actual surveying sites.

To ensure high fidelity, the project follows a Scan-to-BIM workflow for environment creation. This process begins by capturing a real building or site using high-resolution laser scanners. The collected data is then imported into Building Information Modelling (BIM) software, where the object is modelled with precision and enriched with material properties.

During the customization process, several technical aspects are optimized to maintain real-time performance:

- **level of detail (LoD):** training objects are typically modelled at LoD 300, which includes detailed architectural elements such as window frames and decorations. Surrounding objects are kept at LoD 200 to save computational resources.
- **performance constraints:** to prevent frame rate drops, the system recommends that main object models do not exceed 30,000 polygons. For special objects (e.g. complex heritage sites or complex models of historical monuments) it is possible to use models with millions of polygons, but such models need to be specially optimized within the game engine.
- **collision generation:** each building element is configured with simple collision meshes, ensuring that user avatars navigate the scene realistically without walking through walls or floating in the air.
- **coordinate precision:** the system uses a "local coordinates + global shift" approach to handle large coordinate numbers, preventing a loss of precision during the export to the game engine.

A vital part of environment customization is the assignment of physical materials within the BIM model. Instead of just applying visual textures, surfaces are assigned properties that represent real materials such as sandstone, concrete, or glass. The simulator's physics engine uses these assignments to calculate material-dependent intensity and noise.

To further enhance the flexibility of the platform, specialized tools for importing custom environments and user-defined 3D models are currently under development. However, it is important to note that the technical accuracy and realism of the scanning simulation – particularly the modelling of noise and intensity – are strictly dependent on how well the digital models are prepared. Since a significant portion of this preparation, including polygon optimization, collision mesh generation, and the assignment of physical material properties, must be performed directly within the Unreal Engine environment to ensure compatibility with the LiDAR pipeline, models imported independently by users will initially have certain functional limitations in the simulation.

3. Simulation modalities

3.1 Static terrestrial laser scanning

Static TLS is the primary simulation mode within VRscan3D, designed to replicate the traditional tripod-based surveying workflow. This modality is essential for teaching the fundamentals of 3D data acquisition, as it requires students to understand the geometric relationships between the scanner, the target objects, and the surrounding environment.

The simulator supports two main operational scenarios for static scanning. In the first scenario, intended for beginners, the user navigates the virtual environment as an avatar, selects a scanner position, and performs a scan before moving to the next station. In the second scenario, suited for more advanced users, the student plans the entire survey by placing all targets and scan stations throughout the site first, then triggers a batch scanning process where the simulator automatically executes all scans sequentially.

The technical workflow in this mode involves several interactive steps:

- **target management**: users can optionally select and place different types of registration marks, such as checkerboard targets or spherical targets, which can be attached to virtual walls and surfaces just as they would be in real life.
- **station placement**: by clicking on a point in the 3D model, the user defines a scan station. The system includes functional checks to ensure realistic placement; for instance, a station is rejected if it is placed too close to a wall (within 20 cm), or on a vertical surface.
- **instrument configuration**: access to settings is provided through realistic graphical user interfaces (GUIs) that emulate professional devices such as the Leica RTC360 or Faro Focus. Users can adjust parameters such as horizontal and vertical resolution, field of view (FOV), and scan quality.

The result of the static scanning simulation is a set of structured 3D point clouds, each referenced to its respective local station coordinate system. Once the virtual fieldwork is complete, the data is exported through the simulator's asynchronous pipeline into industry-standard formats, including ASCII (TXT), PTX, and E57.

This enables a seamless transition to the office phase of the project, where the synthetic datasets are imported into professional point cloud processing software such as Leica Cyclone, FARO Scene, CloudCompare, or Autodesk ReCap. In these external environments, students can practice the full processing workflow required for geodetic reconstruction: performing target-based or cloud-to-cloud registration, executing data cleaning and noise filtering, and eventually generating higher-level information such as BIM models, detailed architectural drawings, or maps. This end-to-end approach ensures that learners master the entire data processing chain, from initial capture to the final digital product.

3.2 Mobile and handheld scanning

Mobile laser scanning (MLS) and handheld mobile laser scanning (HMLS) systems are rapidly entering the market, offering significantly faster data capture compared to traditional static methods. These systems operate from moving platforms, such as drones, vehicles, backpack systems, or handheld devices, utilizing SLAM technology to reconstruct the environment as the operator moves. While MLS can survey large areas in a fraction of the time required for static scans, the data is typically noisier and subject to trajectory drift, which can lead to real-world accuracy discrepancies of 15–20 mm compared to 2–5 mm precision typically achieved by static terrestrial scanners.

To prepare students for these complexities, a prototype simulation mode for mobile mapping was developed. In this modality, the user navigates the virtual environment as an avatar equipped with a motion-based scanner. The simulator realistically replicates the physical experience of mobile surveying by modelling:

- **operator motion**: the system simulates the natural oscillations and hand movements of a person walking, where tilting or turning the virtual scanner directly alters the scan pattern and point distribution in real time.
- **platform variety**: the architecture supports several platforms, including handheld units, backpack systems, and vehicle-mounted scanners to demonstrate the scalability of the simulation (Fig. 4)
- **error modelling**: the simulation accounts for movement-specific challenges such as motion blur, insufficient overlap between areas, and trajectory errors caused by scanning too quickly.

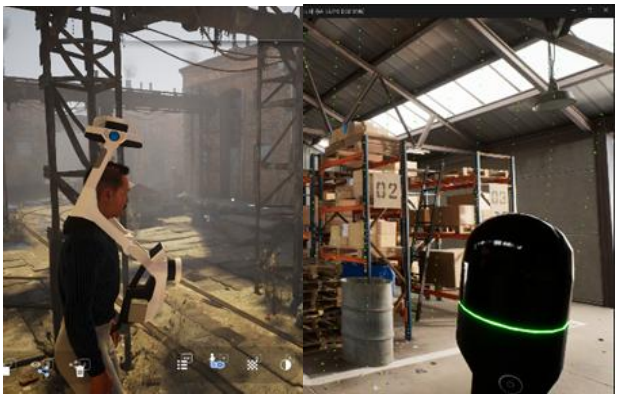

Figure 4. Mobile scanning simulation in VRscan3D: NavVis VLX backpack system (left) and Leica BLK2GO handheld scanner (right).

A unique feature of the mobile simulation is the scan path tracing system, which allows users to visualize and evaluate their full trajectory after a pass is completed. These traces are color-coded and remain visible, enabling students to compare multiple paths and identify "blind spots" or areas where the coverage is insufficient (Fig. 5).

Figure 5. Scan path visualization in VRscan3D during mobile scanning simulation with backpack system.

The integration of mobile scanning is a strategic objective of the DAAD-funded GeoRek project (Horkovchuk et al., 2026). Because mobile mapping is highly sensitive to user behavior, simulation provides a safe and cost-effective way for students to master the necessary skills before working with high-value physical hardware. This training focuses on teaching students how to balance the high production speed of MLS with the precision requirements of geodetic reconstruction, often emphasizing a hybrid workflow where mobile data is anchored to a high-precision static "skeleton".

3.3 Dynamic object scanning

Dynamic objects in the 3D scene are those that move during the scanning process. These include simulated vehicles or pedestrians that appear randomly in the scene which are also captured during scanning. They can be described as interfering objects and must be removed before subsequent analysis.
Furthermore, moving objects that constantly change due to their function may also be included, such as rotating wind turbines or machine parts. Since this usually leads to chaotic data when using static scanning in 3D mode, 1D or 2D modes of the scanner are primarily used for this purpose.
Fig. 6 shows the simulation example for a rotating wind turbine that is captured with four synchronous laser distance meters in 1D mode. The 3D coordinates on the rotor blade are generated when the blades pass the laser beam (Göring & Luhmann, 2023).

Figure 6. Virtual scanning of a wind energy system.

4. Data analysis and validation

Simulated point clouds generated within VRscan3D provide a valuable tool for data analysis and validation. Firstly, users can test and compare different point cloud processing methods, including filtering, segmentation, registration, and noise reduction. Because the true geometry is known, it is possible to assess the performance of algorithms, for example by computing deviations between processed results and the original reference model. Secondly, the simulated 3D data can be analyzed to determine how various factors influence point cloud quality, e.g. material-dependent intensity and noise, distance-dependent noise, resolution and beam divergence. By isolating and systematically changing these parameters, researchers can better understand error propagation mechanisms and select optimal settings.

4.1 Comparison of synthetic and real point clouds

To evaluate the fidelity of synthetic point clouds generated by VRscan3D, a controlled comparison was conducted using a university building in Bamberg as the test object. A real point cloud was acquired using the Leica BLK360 laser scanner from multiple stations, and a virtual scan was performed in VRscan3D using identical station positions, scanner model, and acquisition settings. Both datasets were co-registered and analyzed in CloudCompare across four criteria: object coverage and completeness, intensity and material reflection, scanner range and noise behavior, and geometric surface features.

As shown in Fig. 7, overall façade coverage of the two datasets is nearly identical – main building surfaces, window openings, and tower are captured to the same extent, and roof gaps appear in equivalent locations in both clouds, confirming that the station geometry was successfully replicated in the simulator.

Figure 7. Side-by-side comparison of real (top) and simulated (bottom) point clouds.

Differences are apparent in fine-scale object completeness. The real point cloud captures small urban features – wall-mounted lamps, drainage pipes, and a bicycle parking structure – that are absent from the simulated cloud, as these elements fall below the LoD 300 modelling threshold used for environment preparation.

Both datasets contain outlier points from dynamic objects – however their character differs: the simulated cloud captures more randomly generated pedestrians, whilst the real cloud additionally contains parked vehicles and other static street objects that were present during acquisition, resulting in considerably denser ground-level scatter.

Both point clouds display clear material-dependent intensity variation, confirming that the simulator successfully replicates the fundamental relationship between surface material and laser return strength. In the real point cloud, intensity varies within the same material class due to weathering, staining, and surface irregularities. In the simulated cloud, intensity is strictly tied to the material assigned in the BIM model, producing uniform values within each material class. This is a natural consequence of idealized material representation in the digital twin rather than a modelling deficiency.

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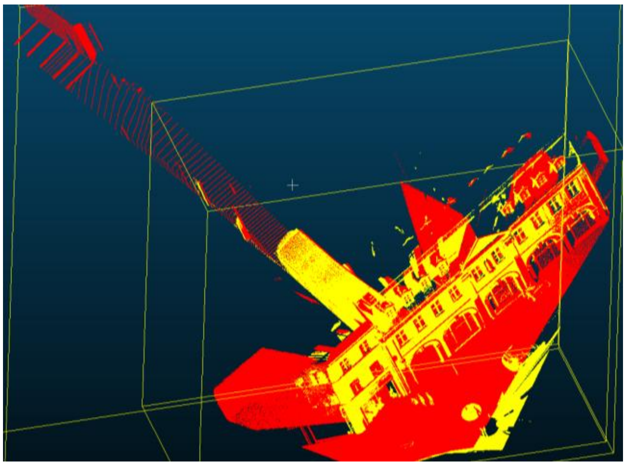

Figure 8. Single-station coverage comparison: real (yellow) and simulated (red) point clouds acquired from an identical position.

Comparison of single-station coverage (Fig. 8) reveals that the simulated point cloud achieves approximately twice the effective range at steep ground-level angles compared to the real dataset. While the simulation correctly models surface reflectivity, it does not account for atmospheric effects such as humidity, dust, and air turbulence, which reduce effective range in real acquisition conditions. It should also be noted that manufacturers typically report scanner specifications under optimal laboratory conditions, which rarely correspond to real field environments – meaning that even a perfectly calibrated simulation based on data sheet values will tend to overestimate operational performance. This difference between specified and operational scanner performance is a known limitation of the current simulation that should be considered when using VRscan3D data as a proxy for real acquisitions.

Noise behavior was assessed by comparing cloud-to-primitive distance distributions computed on planar surface regions selected from both datasets (Fig. 9). Both point clouds show zero-mean Gaussian distributions, confirming the absence of systematic bias. The real point cloud yields σ = 2.29 mm compared to σ = 2.03 mm for the simulated cloud — an 11% difference consistent with fine-scale surface irregularities and material variation present in real building surfaces but not represented in the BIM-derived environment model. The close agreement between the two distributions demonstrates that VRscan3D successfully replicates the noise magnitude and statistical character of real scanner measurements.

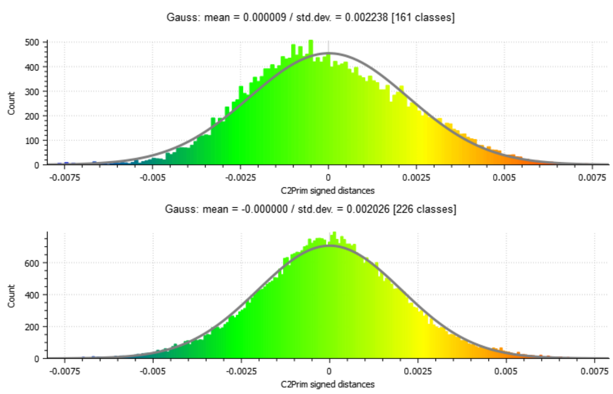

Figure 9. Noise distribution comparison between real (top) and simulated (bottom) point clouds acquired with the Leica BLK360.

Surface roughness was analyzed as a measure of local geometric irregularity, providing insight into how well the simulator replicates real surface texture. Roughness was computed in CloudCompare using a 5 cm neighborhood radius across all surfaces of both datasets (Fig. 10).

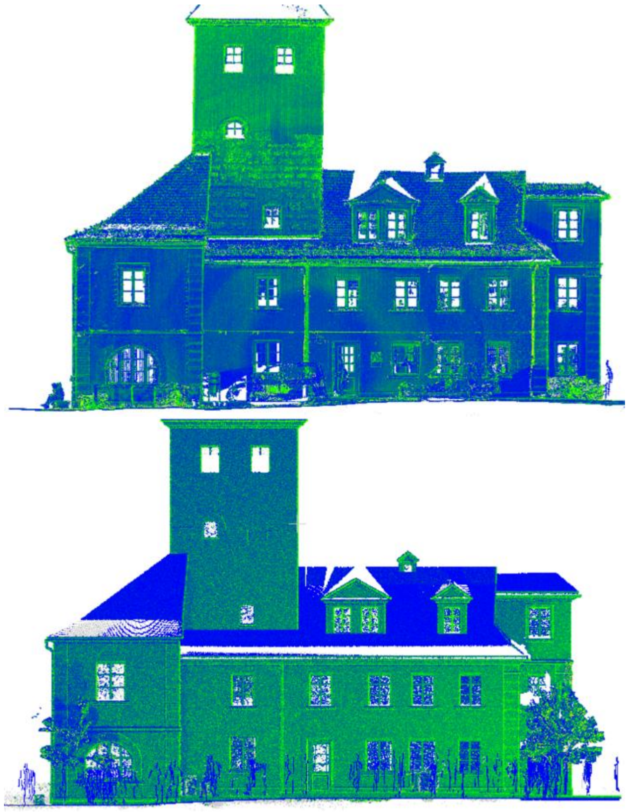

Figure 10. Roughness visualization of the real (top) and simulated (bottom) point clouds.

The overall roughness distributions of the two point clouds (Fig.11) are remarkably similar: the real point cloud yields a mean roughness of 3.43 mm (σ = 3.24 mm), while the simulated cloud yields 3.33 mm (σ = 3.36 mm) – a difference of less than 3%. Both distributions follow the same right-skewed form, confirming that the simulator's noise model produces surface irregularity at a scale consistent with real scanner measurements.

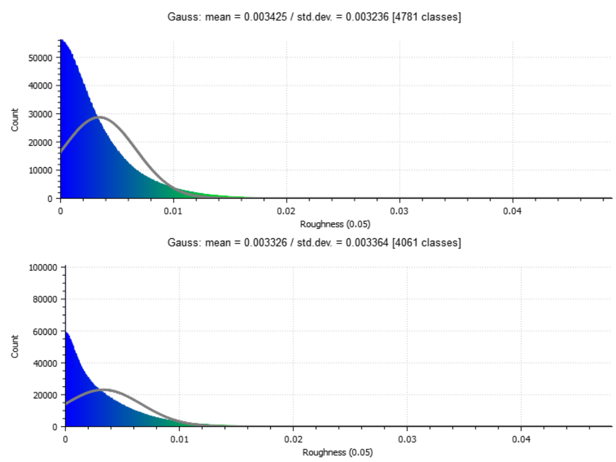

Figure 11. Roughness distribution histograms for the real (top) and simulated (bottom) point clouds.

A close inspection of the tower façade (Fig. 12) reveals an important qualitative difference: the real point cloud exhibits systematic vertical striping in the roughness scalar field, indicative of scan-line artefacts caused by minor mechanical irregularities in the scanner's rotational mechanism.

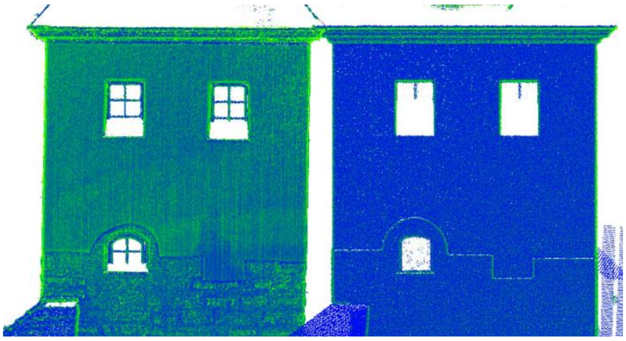

Figure 12. Close-up roughness comparison of the tower façade.

These periodic patterns, characteristic of phase-based or time-of-flight scanners operating at high angular resolution, are entirely absent from the simulated cloud, which shows a uniformly smooth surface. This finding highlights a category of systematic sensor behavior that is not yet modelled in VRscan3D and represents a direction for future simulation refinement.

4.2 Ground truth generation for AI training

AI-based processing of 3D point clouds is increasingly applied to tasks including automatic semantic segmentation (e.g. detection of walls, doors, and furniture), registration and fusion of multi-sensor point clouds, filtering and removal of dynamic objects, and detection of safety-critical elements such as pedestrians in autonomous driving scenarios. All of these approaches require large volumes of accurately labelled training data, which are often difficult or costly to obtain from real acquisitions (Xiao et al., 2022; Noichl et al., 2024).

VRscan3D addresses this need directly: because every point in a simulated dataset is generated from a fully defined scene, each point carries known object class, material properties, and geometric position by definition – without any manual annotation effort. Labelled point clouds can be generated either as geometrically ideal data or with stochastic noise applied, enabling controlled experiments at varying levels of data quality. Since ground truth is fully specified, the simulated data can be used both for AI training and for benchmarking the performance of trained models against known ground truth.

5. Educational implementation and evaluation

5.1 Integration into academic workflows

The integration of VRscan3D into academic curricula is a strategic objective of the DAAD-funded GeoRek project. Traditionally, practical training in terrestrial and mobile laser scanning requires access to expensive hardware, field logistics, and favorable environmental conditions. VRscan3D overcomes these limitations by providing a fully virtualized laboratory environment accessible independently of location and time.

Within university programs, the simulator can be integrated across multiple levels: from introductory courses covering coordinate systems and data-acquisition workflows, through advanced survey planning and hybrid static-mobile projects processed in external software such as CloudCompare or Leica Cyclone, to research-based learning in which students investigate the influence of scanning parameters on data quality. The platform equally supports remote and blended learning, enabling interactive assignments when physical laboratories are inaccessible.

5.2 User testing and feedback

User evaluation is an important component in assessing the effectiveness and usability of VRscan3D as an educational tool. Initial testing involved students and professionals in geodesy, photogrammetry, cultural heritage, and geoinformatics, with a focus on usability, learning outcomes, and perceived realism (Chizhova et al., 2021). Results indicated that users adapt quickly to the simulator's interface and workflow logic, primarily due to the realism of the emulated scanner controls. Participants identified the opportunity to experiment without risk, repeat scenarios, and visualize the consequences of their decisions as particularly valuable. User feedback also highlighted opportunities for improvement, such as providing more detailed information on scanning errors and quality metrics.

A follow-up evaluation was conducted in 2026 with an interdisciplinary student group enrolled in the Master's program 'Digital Technologies in Heritage Conservation' at the University of Bamberg. Of the respondents, 75% had a clear understanding of laser scanning principles whilst 25% were only partially informed. Approximately 50% had previous field experience with TLS equipment, and approximately 50% had prior experience with computer games. All respondents rated the software as user-friendly and found the help documentation easy to understand.

Navigation difficulties were reported by 25% of respondents, and a further 25% encountered problems with scanner positioning. These difficulties are attributed to the use of lower-specification laptops, as no options to adjust graphics quality settings were available at the time of testing. No difficulties were reported in selecting and positioning registration markers or target spheres. Respondents made several recommendations for future improvement: the teleportation function was found unintuitive, a sprint movement function was requested, and participants suggested that scan completion should be confirmed by providing direct access to the scanner's stored data. Overall, respondents confirmed that VRscan3D is an effective tool for gaining practical experience in 3D scanning workflows.

6. Conclusion and future work

TLS technology has become a cornerstone in geoinformation, heritage conservation, archaeology, and construction, enabling the rapid 3D capture of complex geometries. Modern sensors further integrate photogrammetric capabilities and sophisticated registration support. Simultaneously, the rapidly expanding range of mobile and handheld scanners introduces additional complexity – SLAM-based trajectory drift, movement-induced noise, and strong operator-behavior dependency – making simulation a vital tool for training users to maintain data quality in dynamic environments.

While LiDAR simulation frameworks such as HELIOS and BlenSor exist, VRscan3D differs fundamentally in its emphasis on real-time immersive interaction. Built on Unreal Engine, the simulator provides a digital twin environment where users navigate as avatars, experiencing the physical constraints of fieldwork such as placing targets on complex architectural monuments or managing line-of-sight obstructions. The system replicates laser reflection behavior and applies stochastic measurement noise based on material-dependent properties and scanner-specific parameters.

Beyond its pedagogical role, VRscan3D has evolved into a research platform for generating high-quality synthetic datasets with known ground truth, enabling controlled isolation of variables for AI training and algorithm validation. The quantitative comparison presented in this paper confirms that simulated point clouds closely replicate real scanner noise characteristics, whilst known differences in surface roughness is attributable to the geometric idealization inherent in BIM-based environment modelling rather than to simulation deficiencies.

With approximately 2,000 downloads, the platform has evolved from a proof-of-concept prototype into a modular, production-ready system. Future development will focus on completing the mobile scanner motion model, enabling user-importable custom environments with full noise and intensity modelling support, extending quantitative validation to mobile scanning scenarios, and implementing adjustable graphics quality settings to improve accessibility on lower-specification hardware.

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References

Bechtold, S., Höfle, B. (2016). HELIOS: A Multi-purpose LiDAR Simulation Framework for Research, Planning and Training of Laser Scanning Operations with Airborne, Ground-based Mobile and Stationary Platforms. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*., III-3, 161-168. doi: 10.5194/isprs-annals-III-3-161-2016.

Chamorro, O., Flores-Velásquez, C., Flores-Cáceres, R., Arévalo-Tuesta, J., Zevallos-Castañeda, M., Tomás Quispe, G., Aranda Dextre, C., Cruz-Telada, Y., Caller Luna, J., Alarcón-Anco, R. (2024). Use of Digital Twin Technology in the Teaching-Learning Process, in the field of University Education: A Bibliometric Review. *International Journal of Learning, Teaching and Educational Research*, Vol. 23, no. 2, 313-329, doi: 10.26803/ijlter.23.2.15.

Chizhova, M., Gorkovchuk, D., Kachkovskaya, T., Hess, M., Popovas, D., Gorkovchuk, J., Luhmann, T. (2021). Qualitative testing of an advanced terrestrial laser scanner simulator: users experience and feedback. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.,* XLIII-B5-2021, 29-35, https://doi.org/10.5194/isprs-archives-XLIII-B5-2021-29-2021.

Deggim, S., Kersten, T. (2023). DVocean Digital - A simulation prototype for hydrographic 3D measurements using multibeam echo sounder. *Journal of Applied Hydrography*, 24-30, Chapter HN126, https://doi.org/10.23784/HN126-04

Göring, M., Luhmann, T. (2023). Development of a Procedure for Torsion Measurement Using a Fan-Shaped Distance Meter System. *Sensors*, 23(20), 8603; https://doi.org/10.3390/s23208603.

Horkovchuk, J., Gorkovchuk, D., Trehub, M., Chizhova, M., Popovas, D., Sieberth, T., Luhmann, T. (2026). Modern online teaching formats for geodetic reconstruction methods in Ukraine. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.,* Toronto (accepted).

Kwitt, R., Uhl, A. (2011). BlenSor: Blender Sensor Simulation Toolbox. Advances in Visual Computing: 7th International Symposium, (ISVC 2011), Las Vegas, Nevada, USA, September 26-28.

Luhmann, T., Chizhova, M., Gorkovchuk, D., Popovas, D., Gorkovchuk, J., Hess, M. (2022). Development of a terrestrial laser scanner simulator. 3D Arch, Mantova, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*., XLVI-2/W1-2022, 329-334, https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-329-2022.

Luhmann, T., Chizhova, M., Popovas, D., Gorkovchuk, D. (2024). Simulation von mobilem und dynamischem Scanning im virtuellen Simulator VRscan3D. In: Luhmann/Sieberth (eds.): Photogrammetrie – Laserscanning – Optische 3D-Messtechnik. Beiträge der Oldenburger 3D-Tage und des BIMtages 2024. Wichmann, Berlin/Offenbach, 304–313.

Noichl, F., Collins, F. C., Braun, A., Borrmann, A. (2024). Enhancing point cloud semantic segmentation in the data-scarce domain of industrial plants through synthetic data. *Computer-Aided Civil and Infrastructure Engineering*, 39, 1530-1549. https://doi.org/10.1111/mice.13153

Ríos-Otero, E., Aldao, E., Fernández-Pardo, L.M., Fontenla-Carrera, G., Veiga-López, F., González-Jorge, H. (2026). A digital-twin LiDAR simulator for performance assessment of railway ballast geometry inspections. *Transportation Geotechnics*, Volume 58, 101922, https://doi.org/10.1016/j.trgeo.2026.101922.

UNESCO (2024). *Education under attack 2024*. United Nations Educational, Scientific and Cultural Organization. https://unesdoc.unesco.org/in/rest/annotationSVC/DownloadWatermarkedAttachment/attach_import_649cff13-21d0-4ee4-9fb9-a48496e31d9a?_=388803eng.pdf&to=32&from=1

Winiwarter, L., Anders, K., Schröder, D., Höfle, B. (2022). Virtual Laser Scanning of Dynamic Scenes Created from Real 4D Topographic Point Cloud Data. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. V-2-2022, 79-86. doi: 10.5194/isprs-annals-V-2-2022-79-2022.

Xiao, A., Huang, J., Guan, D., Zhan, F., Lu, S. (2022). Transfer Learning from Synthetic to Real LiDAR Point Cloud for Semantic Segmentation. Proceedings of the AAAI Conference on Artificial Intelligence. 36, 2795-2803. 10.1609/aaai.v36i3.20183.