

## Integrating Lidar and Virtual Reality for Safe Building Condition Assessment

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Material recovery tasks in buildings aimed at reducing Construction and Demolition Waste (CDW) require full access and accurate material inventories. However, the structural condition of these buildings may pose safety risks to inspectors, making it essential to minimize on-site exposure while maximizing data acquisition. In this context, LiDAR technology enables the rapid capture of precise 3D geometries, which can subsequently be inspected remotely. This work presents a framework for assessing building conditions through Virtual Reality (VR) based on LiDAR data. High-resolution point clouds acquired with a Handheld Mobile Laser Scanner are combined with virtual markers positioned using Mixed Reality device Microsoft HoloLens 2. Both datasets are registered within a unified reference system and rendered in a VR environment. In addition to true-color RGB visualization, a Multi Feature Synthetic Color technique is implemented to highlight geometric features of the point clouds, enabling the immersive evaluation of the condition of materials. The proposed method is tested in two case studies developed within the European project SUM4Re: a residential building in Longyearbyen (Norway) and a metro station in San Sebastián (Spain). The results show that VR is suitable for remote inspection based on point cloud data. Furthermore, synthetic color can complement original color visualization in immersive digital scenarios. However, tests highlight the importance of adapting the algorithms designed for 2D rendering to 3D environments.

*Keywords:* Digital Twin, Immersive Visualization, Structural Health Monitoring, Human-Computer Interaction, Augmented Reality, Sustainable Deconstruction.

### 1. Introduction

Traditional deconstruction inspections of aging infrastructure often rely on manual visual checks that require specialists to operate from lifts or scaffolding in hazardous environments. This conventional approach is inherently dangerous and time-consuming, frequently exposing workers to high-risk conditions where fatigue can compromise safety (Jiang et al. 2024). The gravity of these risks is evidenced by statistics indicating that in 2024, Spain recorded 14,252 accidents with sick leave in demolition and maintenance works (Ministerio de Trabajo y Economía Social 2024), while in the United

States, 77.6% of accidents during demolition were attributed to structural collapses (Ertaş and Sayıl Erdoğan 2017). By integrating intelligent monitoring technologies and automated diagnostic systems, critical structural defects can be identified with greater speed and accuracy (Vijayan et al. 2023). The transition toward these automated solutions is vital because minimizing worker exposure time in risk zones effectively prevents occupational accidents.

The inspection through 3D digital twins and Virtual Reality (VR) technology is transforming material recovery tasks and structural health monitoring by offering a

more objective, precise, and efficient alternative. By utilizing advanced methods like photogrammetry and LiDAR to generate damage-augmented digital twins, engineers can now perform detailed visual inspections and analyze complex pathologies, such as fine cracks, within a fully immersive and interactive digital environment (Yasin Yiğit and Uysal 2025; Salgado-Fernández et al. 2026). The primary advantages of VR environments include multiple remote collaboration without being physically present on-site, significant reduction in operation time and transportation expenses, and enhanced safety for personnel (Luleci et al. 2022; Catbas et al. 2022). However, previous digitization approaches focus exclusively on true-color visualization, which has limitations due to glare, reflections, and shadows (González et al. 2022).

The objective of this work is to propose a framework for the 3D building digitization for demolition based on the use of synthetic color based on geometries that allow both materials and defects to be identified. The proposed method consists of a LiDAR building digitization phase for the subsequent generation of an immersive VR environment for remote inspection, thus minimizing the exposure of inspectors in the field.

## 2. Methodology

This methodology is composed by the following sequential steps: First, the environment digitalization must be done, acquiring a point cloud to work with and visualize in a VR environment. Second, these point clouds must be colorized using the Multi Feature-Rich Synthetic Color (MFRSC) (Balado et al. 2023). Finally, the point clouds are placed in a virtual scene using Unreal Engine, which is then linked to a VR headset to assess the results and gain feedback from different users.

### 2.1. Digitalization

The first step is to acquire 3D spatial data suitable for subsequent analysis, visualization, and interpretation. This is carried out using two different mobile mapping systems: the CHCNAV RS10 (CHCNAV, n.d.) and the

Microsoft HoloLens 2 ('HoloLens 2 Hardware | Microsoft Learn', n.d.). The RS10 is a Handheld Mobile Laser Scanner (HMLS), selected due to its capability for fast data acquisition while maintaining a high geometric quality, making it suitable for this project indoor environments. The HoloLens 2 are a Mixed Reality glasses, used to label data in the real world through the placement of virtual tags using the Reality Mesher application (Navares Vázquez, n.d.).

Both the CHCNAV RS10 and the Microsoft HoloLens 2 rely on LiDAR-based sensing combined with Simultaneous Localization and Mapping (SLAM). With this, data acquisition can be performed in a continuous manner for both devices, without the need for discrete scans or registration of point cloud segments. The mobile nature of both systems allows unrestricted movement through the environments, with no specific constraints nor significant limitations beyond those inherently associated with each sensor.

A detailed technical comparison between the CHCNAV RS10 and the Microsoft HoloLens 2 can be found in (Navares-Vázquez et al. 2025). In this study, the scan is performed using both devices simultaneously, taking care to avoid mutual interference or obstruction. This ensured total geometric consistency.

The primary data product obtained from the scan is a 3D point cloud enhanced with virtual tags. No additional preprocessing steps are applied to the point cloud before colorizing them.

### 2.2. Synthetic coloring

Synthetic coloring is based on Multi Feature-Rich Synthetic Color (MFRSC) (Balado et al. 2023). The methodology begins with the selection and extraction of nine specific features from the input point cloud to enhance visual perception. These features are chosen based on perceptual descriptors such as edges, texture, shape, size, depth, and orientation. The nine features include: reflectance, inclination, depth, height, point density, linearity, planarity, and

scattering. Since the LiDAR sensor used does not provide the number of returns, this variable has been replaced by ones.

Given that the selected features have disparate ranges, normalization is mandatory to bound all values between 0 and 1. To visualize nine distinct features within the standard three RGB channels, a 9-to-3 reduction process is implemented. This is achieved by grouping features into sets of three and applying a grayscale conversion formula based on Eq. (1). In this context, the "F<sub>n</sub>" components of the formula are replaced by three specific point cloud features to produce a single value (g) for one RGB channel.

$$g = 0.299 \cdot F_i + 0.587 \cdot F_j + 0.114 \cdot F_k \quad (1)$$

### 2.3. VR environment generation

For the VR environment, Unreal Engine is used. This game engine is highly compatible with development for Virtual Reality (VR) devices. Along with it, Meta Quest 3 is the device we tested this workflow in, connecting it to a computer using Meta Horizon Link and a Wi-Fi connection. This is a modern device widely used in the VR industry. The app SteamVR is used to link both systems, acting as a bridge between Meta Quest 3 with Meta Horizon Link app and Unreal Engine. This simplifies the methodological workflow and optimizes compatibility with other devices. SteamVR plays an immersive scene simulated in a computer into the VR headset, increasing performance and speeding up testing.

Point clouds can be loaded directly into an Unreal Engine scene by using the LiDAR Point Cloud plugin, which is built-in with the software, and keeps RGB color.

For the VR interaction, Unreal Engine includes many tools that integrate the headset controllers into the virtual scene seamlessly. A pre-built template is used, due to the integration of all the control tools needed. On top of this template, the colorized point clouds are added. However, this template included multiple object interactors

which are not needed for our case. Therefore, all those unused elements were removed from the scene before testing. The total point render is also increased.

## 3. Results and discussion

### 3.1. Case Studies

The proposed method was tested in two real case studies. The first is a living room and kitchen in a residential building in Longyearbyen (Norway). The building will be deconstructed because the wooden foundations are rotting due to the increase in temperature and humidity caused by the permafrost thaw. The other case study is part of the hall of the Anoeta metro station (San Sebastián, Spain). The current building will be deconstructed for expansion. The point clouds obtained have 1.7 million points (Fig. 1) and 3.9 million points (Fig. 2), respectively.

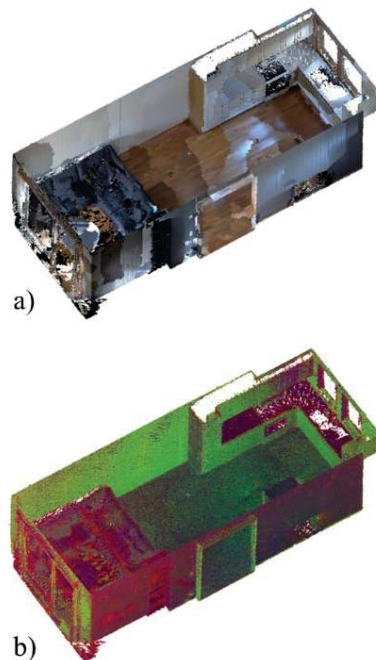


Fig. 1. Case study 1 in real RGB color (a) and MFRSC synthetic color (b).

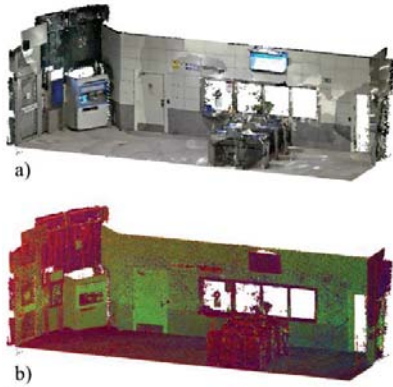


Fig. 2. Case study 2 in real RGB color (a) and MFRSC synthetic color (b).

### 3.2. Results on VR inspection

After preparing the virtual scene, the immersive experience was tested with the Meta Quest 3 device using the SteamVR app. The virtual environment ran in a laptop with an Intel Core i7-11800H 2.30GHz CPU, a NVIDIA GeForce RTX 3080 GPU and 40GB DDR4 of RAM. Fig. 3 and Fig. 4 show a similar point of view for original color and the synthetic-colored point clouds, respectively, from case study 1.



Fig. 3. Point cloud with original color visualized in the VR headset.



Fig. 4. Point cloud with synthetic color visualized in the VR headset.

The VR experience was completely immersive. The user could move around the environment as if present in the corresponding room, as well as approach any element for its inspection. The view stuttered sometimes due to hardware limitations. However, this did not affect negatively the overall experience in any of both case studies.

The VR visualization was tested by a total of 5 users with different levels of experience in point cloud assessment and VR environments. These users provided insight about the usefulness of synthetic color in VR immersive inspection.

According to the feedback provided, synthetic color enhances the perception of overall geometry. Large volumetric elements that were camouflaged with original color textures (due to color similarity or point cloud limitations) become more distinguishable when synthetic color is applied. This effect was especially noticeable in areas where the original color information was degraded or noisy, as synthetic color helped users better understand the shape and spatial extent of objects.

However, users also reported that small objects were harder to identify in synthetic color when compared to original color. While these elements generally remained visible, their semantic meaning was less evident, as synthetic color removes contextual cues provided by realistic textures, such as room use. Original color was generally valuable for object recognition.

The effectiveness of synthetic color was found to depend strongly on the physical parameters used for color mapping, as well as the color mapping selection. Using properties such as reflectivity, synthetic color successfully highlighted elements that differed from their surroundings, but hid others with similar values. This could be clearly seen in the Anoeta station, depicted in Fig. 5.

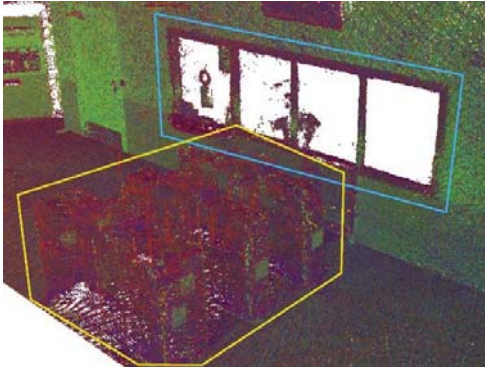


Fig. 5. In Anota case study, window frames stand out from the wall due to different reflective materials (blue shape), but gates blend with the floor (yellow shape).

### 3.3. Discussion

The results obtained from the VR inspection demonstrate that immersive visualization is a suitable medium for point cloud exploration and analysis. Although minor performance issues were observed, immersion allowed users to navigate freely within the scanned environments and properly inspect elements without being physically in the real-world place. This confirms that current consumer level VR hardware can support point cloud-based inspection workflows, providing a foundation upon which visualization strategies such as synthetic coloring can be meaningfully evaluated.

For synthetic coloring, one of the most relevant findings is the trade-off between geometric perception and scene understanding. Synthetic color generally improved the perception of overall geometry, particularly for large volumes. This suggests that synthetic color can be effective in revealing spatial structures that are otherwise difficult to perceive due to texture similarity, lighting conditions, or inaccuracies in original color. However, this geometric enhancement was accompanied by a loss of semantic detail, especially for small objects. The removal of realistic textures reduces contextual cues that are essential for identifying the function or nature of certain elements that may not have enough detail in the scan.

The discussion of depth perception further highlights the specificity of VR-based visualization. Users consistently reported that depth-based synthetic coloring provided little to no additional benefit in VR. Unlike desktop visualization, immersive environments already provide depth information through stereoscopic vision. Consequently, adding depth to the colorization algorithm is redundant in this context. This finding indicates that visualization strategies for non-immersive environments, such as regular monitors, should be reconsidered before being transferred to VR, since some characteristics that were useful for 2D visualization may result in inappropriate 3D representation.

The effectiveness of synthetic color in material identification was also proved to depend strongly on the physical parameters selected for color mapping and on the associated color scale design. Parameters such as reflectivity proved useful for highlighting certain elements with clear differences but also introduced new forms of visual ambiguity when materials with similar properties were present. This dual behavior shows that the usefulness of synthetic color depends on careful configuration. Inappropriate parameter selection or poorly designed color scales may influence negatively the information presented to the user.

It is important to mention that the results do not support a clear superiority of either original or synthetic color visualization. Instead, both were, in general, perceived as complementary. Original color was found to be more effective for scene understanding and object identification, while synthetic color was better suited for emphasizing geometric structure and visible material differences. The fact that some users reported limited benefit from synthetic color reinforces the idea that its usefulness is task-dependent and user-dependent. In this sense, synthetic color should be applied selectively, based on the inspection objectives and the characteristics of the environment.

#### 4. Conclusion and Future Work

Data acquisition is an important step for material recovery and inventory. However, it is frequent that the building's conditions propose a risk for the workers. For this reason, VR inspection using LiDAR data can be seen as a viable alternative for off-site inspection.

Additionally, synthetic coloring helps remote inspection tasks by implementing multiple measured features into the point cloud information. This work assessed how MFRSC is applied to VR experiences and what changes are needed to optimize inspection.

Future work will identify new parameters more appropriate for VR inspection and how they will be mapped into the color information. Another valuable future contribution will be to evaluate how switching between the original and synthetic colors helps users understand the scene and recognize objects. Therefore, adding support for dynamic adaptation of synthetic color parameters will be investigated.

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