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Original Research Article

3D DATA PROCESSING FOR VR VISUALIZATION: A CASE STUDY IN THE "PODGÓRZE" URANIUM MINE

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Abstract

VR technologies are playing an increasingly important role in the visualisation of hard-to-reach places, such as underground environments, which is important for the documentation and protection of cultural heritage. The digitisation of such objects allows the creation of a faithful digital twin and its dissemination in the form of immersive experiences. In this study, a comprehensive workflow for the creation of 3D virtual models was developed and illustrated using the part of Podgórze uranium mine as an example. The process included data acquisition, point cloud processing, 3D modeling, optimisation, and integration and integration into a game engine for VR applications. The results show that the obtained models achieved high accuracy, the cloud-to-mesh (C2M) mean errors within ± 14 mm and standard deviations up to 58 mm relative to the input data. Despite the lack of original textures, realistic approximations have been used to enhance authenticity. Interactive elements further enhance the user experience. The results support the preservation of historical sites and its popularisation in educational and tourist applications. The proposed workflow is highly adaptable, making it applicable to other historical and industrial sites.

Keywords: 3D data, 3D visualization, VR, TLS, historical mine

1. INTRODUCTION

The use of Virtual Reality (VR) technology is so widespread and growing that it was necessary to expand the definition of virtual reality. Currently, VR can be described as a type of computer-based system that presents an interactive, participatory environment that could maintain multiple remote users

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sharing a virtual place. VR can present or simulate the illusion of participation in a synthetic or work-mapped environment rather than external observation of this environment. It is based on, most commonly, a collection of controllers and 3D displays that track head movements - head-mounted displays (HMDs), hand/body tracking, and binaural sound [1]. VR has attracted significant attention in recent years, emerging as one of the most innovative and rapidly developing areas of technology. Today, the use of VR is much broader than it was just a few years ago, when it was only associated with the gaming and entertainment industries [2, 3]. VR is used in numerous fields such as medicine [4], mechanics [5], education [6, 7], the mining sector [8], marketing [9] and construction [10]. Other sectors such as real estate, architecture, and tourism have also recognised the huge potential of VR technology and have started to actively use it [11, 12]. This has made it possible to visit and view locations remotely. In the literature, it is also described as virtual environments [3], virtual worlds [13], or micro-worlds, depending on the concept and the tools used. This system allows the fusion of information from multiple sources, a three-dimensional view, sound, and dynamic interaction with the virtual environment to immerse he users in the environment to the extent that they have the impression of 'being there'. to the extent that they have the impression of 'being there'.

The concept of virtual reality the basis in the 1960s [14]. The original systems were based on disconnecting the user from the real world and were created for military and aerospace purposes [15]. Over the years, HMDs have become increasingly accessible and affordable. It is possible to have HMDs in households at a low cost in terms of money and hardware. Among the most common are the Oculus Quest, HTC VIVE Focus and Apple Vision [16]. More advanced virtual reality system, most used for engineering applications, can additionally use haptic gloves, suits, omnidirectional treadmills or other devices that enhance the immersive experience [17].

Due to the unlimited variety of VR applications, it is now possible to build new universes or to map real objects using tools to measure the geometry of specific objects. Developing a virtual environment suitable for these purposes requires a specific workflow that integrates a variety of strategies from research, measurements, 3D modeling and virtual navigation [18].

To achieve a high level of fidelity in the representation of the actual geometry of an object, two main approaches are commonly used: LiDAR-based and image-based methods. LiDAR (Light Detection and Ranging) can operate based on different principles: (i) Time-of-Flight (ToF), where the distance is calculated by measuring the time it takes for the laser beam to travel between the emitter, the object, and the receiver; (ii) phase-based measurement, which determines depth information by analysing the phase shift of the returning laser pulse; and (iii) triangulation, where the distance is derived from geometric relationships within a triangle. In addition to recording spatial coordinates, LiDAR also registers intensity, which provides additional information about the reflective properties of the scanned objects or surfaces. There are various types of laser scanners that differ in scanning parameters such as measurement range, accuracy, precision, laser wavelength, field of view, scanning speed, as well as hardware specifications - physical size, weight, portability, ability to integrate with external devices or systems. The choice of scanning method depends mainly on the expected accuracy, type and size of the object to be measured, as well as the available equipment, budget and time required for the measurement. The second approach, image-based solution, allows the simultaneous retrieval of shapes and colours from high-resolution images or even from archival data [19, 20]. Typical photogrammetric processing is based on a computer vision approach – the well-known Structure from Motion (SfM) method [21].

The second classification for obtaining geometric information from the environment is based on the measurement instrument used and its operational range: TLS (Terrestrial Laser Scanning), MMS (Mobile Mapping Systems), or UAS (Unmanned Aerial Systems). TLS is a technology that provides high scanning density while maintaining millimetre accuracy. TLS scanners are typically mounted on ground platforms, such as tripods, or other stable platforms, and are often equipped with additional components such as cameras and Global Navigation Satellite System (GNSS) receivers to support data georeferencing [22]. Another widely used technology for collecting 3D data is the Mobile Mapping System (MMS), in which sensors such as laser scanners and/or cameras can be mounted on a variety of platforms, including handheld devices [23, 24], backpacks [25], robots [26] or ground vehicles [27]. These systems are typically equipped with GNSS sensors and inertial measurement units (IMUs). In the absence of GNSS, Simultaneous Localization and Mapping (SLAM) algorithms are often used to ensure accurate positioning and mapping [24]. The MMS solution, due to its mobility and size, allows mapping processes in areas where measurement areas are complex, and access is limited in a short time [28]. The third advanced technology used to collect spatial data is UAS. In this technique, sensors such as RGB cameras, multispectral cameras, or laser scanners are mounted on drones that perform autonomous flights [29]. One of the most popular methods for the processing of aerial images is the Structure-from-Motion method [30].

Reconstruction of surfaces from unstructured point clouds obtained from laser scanner or photogrammetric measurements is a very difficult case that is currently described widely in the literature and problematic with incomplete and noisy data [31]. Point clouds are intended to represent the external surfaces or the overall 3D geometry of an object. An important step in the creation of the virtual environment is the processing of the raw point clouds from the measurement and the 3D modeling stage [31]. The laser beam is exposed during measurement to the properties of the measured object, the processing method and a dynamically changing environment, so there are possible gaps or noise in the final point cloud. Therefore, the first step is to eliminate noise in the form of unnecessary objects, excessively reflective surfaces, and to leave behind the necessary prisms for subsequent work. Depending on the laser scanning method, the positioning of the subsequent stations from which the measurement is taken can be done based on an inertial measurement unit (IMU) or by connecting the point cloud to an existing reference system and/or carrying out registration using targets to create a geodetic network [33]. The result is a 3D model in the form of a single, coherent point cloud, consisting of multiple point clouds, at different positions [34]. Subsequently, a reconstruction of the surface of the object is carried out. The mapping can be done in many ways, for example, manual modeling based on point clouds, using a set of RGB images or using a depth map [35-37]. During the transformation of a point cloud into a mesh model (i.e. a surface composed of polygons), the density of the polygons can be controlled. The density of the mesh can be adjusted depending on how detailed and realistic the model has to be (visual quality), or how large an area or scale is needed. In mapping real objects, the most difficult task is to maintain the proper balance between data quality (e.g., weight, number of faces) and its portability on devices, simplicity of data processing and visualisation.

A specific case of surveying and 3D representation is the environment of both operating and tourist mines. Using VR technology, in which the real mining environment is implemented, better management of mining and post-mining operations is possible. The use of VR technology can guide the planning of mining operations and support, in a continuous system, the selection of appropriate mining operations and observe changes in the mining environment [38]. Simulation of mining processes using VR technology allows for much better planning and monitoring of mining operations, considering formal, legal, environmental, and economic issues [39]. The use of VR is also important in the context of demonstrating the principles of sustainable mining practices [40]. This is aimed at the use of post-mining sites for tourism, among other applications. VR influences policy-making and is fast becoming an important means of tourism marketing [41, 42], including mines tourism. Planning and management, marketing, entertainment, education, accessibility, and heritage conservation are six areas of tourism where VR may prove particularly valuable. Part of the possible usefulness of VR as immersion tool is due to its potential to create virtual experiences that tourists may accept as substitutes for real visits to endangered sites [43]. This is particularly important in mining sites where the environment is hazardous.

In addition, mining infrastructure is a valuable input for the presentation of cultural heritage. Its implementation into a virtual environment allows the user to be moved to the time of the mining operation and reinforces the awareness of the mining activities conducted. The integration of history with state-of-the-art technology in immersive environments has the potential not only to preserve and manage cultural heritage, but also to enrich the visitor experience and subsequent engagement with history [44]. Additionally, it is possible to view interactive mine models almost anywhere there is an internet connection and access to the location where the model is stored [39].

This study investigated the acquisition, processing and modeling of 3D data, and the implementation of these models in a computer game engine and virtual reality technology for the visualisation of historic mining facilities. The case study focused on a historic uranium mine, which is an example of a distinctive industrial heritage site. The presented scenario is unique and atypical because it includes different objects - both elements of the underground environment, such as tunnels and their structures, and tourist objects, such as a model of an atomic bomb. The creation of a VR model for this site is essential for the preservation of its industrial heritage. By reconstructing the active period of the Podgórze mine, the VR model offers a valuable insight into its historical context and enhances appreciation of its cultural and industrial significance. This digital representation allows virtual tours of the site at any time, regardless of physical accessibility, thus promoting virtual tourism. The approach proposed in the papier is characterised by a high degree of universality, allowing the proposed methodology to be applied to different historical and industrial objects.

2. STUDY SIDE - PODGÓRZE MINE

The research site is located in the southern part of Kowary - one of the key historical mining towns in SW Poland. The Podgórze mine was in operation for only 8 years in the 1950s, later the mine tunnels were used as radon inhalation facilities and today an underground tourist route runs there (Fig. 1).

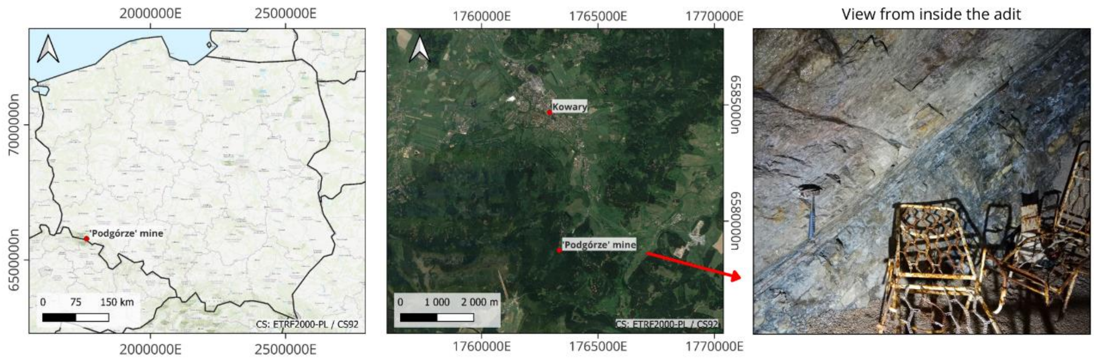


Fig. 1. Localization of the Podgórze mine and view of one of geological sites on the sightseeing route

The mine is also a unique research and training site for geological education. The vein deposit, mineralised mainly by uraninite, was located within a large shale lens surrounded by gneisses. At present there are approximately 3,300 metres of workings, including two very long adits, the remains of the mine workings and an undershaft zone.

3. METHODOLOGY

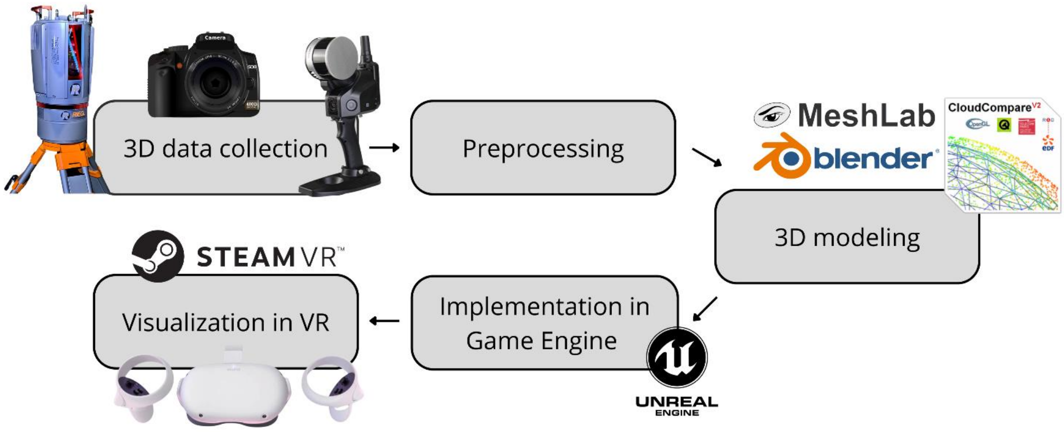
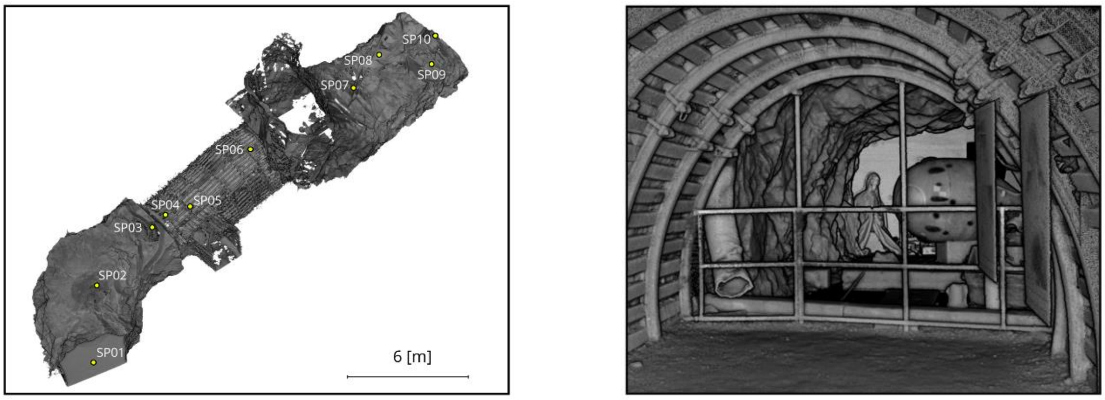


Fig. 2. Workflow of the proposed methodology for processing 3D data for visualisation in VR

This research proposes a five-step workflow (Fig. 2) to accurately reconstruct a real underground tourist environment in VR. The first step involves the acquisition of 3D data. It can be carried out using a variety of techniques and sensors, depending on the availability of measurement instruments, the object under investigation, and the expected accuracy of the final model. Different technologies will be used for outdoor objects versus indoor objects with limited space. The resulting raw data, in the form of a point cloud, will require a customized approach and appropriate processing. In the presented case study, the acquisition of 3D data was performed with a Riegl VZ-400i terrestrial laser scanner. This instrument offers a measurement accuracy of up to 5 mm at 100 m. Other important parameters include a laser pulse repetition rate of up to 1200 kHz and a measurement rate of up to 500,000 measurements per second, within a field of view of 100° (vertical) × 360° (horizontal) [45]. The fragment of the adit used in the study, approximately 25 m in length, was collected from 10 scanner stations (Fig. 3a). The raw point cloud consisted of approximately 117 million points.

The acquired data were processed using the RiSCAN PRO software. First, the point cloud was filtered by adjusting the reflection, amplitude and deflection parameters accordingly. Registration and alignment were then performed using the Multi Station Adjustment (MSA) method. For each point cloud, the algorithm generates sets of planes and iteratively aligns them by minimizing the distance between corresponding planes, applying rotations and offsets during the process [47,48]. The registration and alignment process achieved a deviation error of 3 mm. In the final pre-processing step, the point cloud was unified by resampling to a spatial resolution of 1 cm, which reduced the point cloud to approximately 4 million points. An example view from inside the point cloud is shown in Fig. 3b.



(a) (b)

Fig. 3. Point cloud view of: (a) part of the 'Podgórze' mine and (b) a detailed inside view

The 3D modeling stage is the most time-consuming step in the methodology. Segmenting the point cloud into individual objects is essential for processing data accurately and eliminating errors and noise that can affect the quality of the final model. In the analysed area, numerous objects cannot be modeled without segmenting them initially. In the case of objects that are smaller and more detailed, such as an atomic bomb, it was necessary to add missing points to the point cloud and then reconstruct the surface. In the case of larger objects, such as tunnels, it was necessary to clean them of all internal objects in order to obtain a coherent point cloud that was free of noise. Segmenting the point cloud into smaller objects is also key to accurately matching the textures to the relevant areas of the 3D model. In the analysed case study, the extracted objects were the skeleton of a tunnel and tourist attractions, including among others a cart with mining materials, a mock-up of an atomic bomb, and a mock-up of a bomb operator. Each of these objects was individually detailed to create a digital twin that faithfully reflected the real object. This was done using open-source software: CloudCompare to work with the point cloud, MeshLab to create a 3D mesh, and Blender to refine the 3D model. These steps are key to ensuring a high level of data detail while maintaining rendering performance.

The modeling phase was divided into two approaches depending on the groups of objects to be reconstructed. For the first group of objects, the initial approach involved creating MESH model from larger objects by isolating them from their surroundings and segmenting them into smaller components. An example of such object is a surface representing the geometry of tunnels. Creating the surface of these objects Poisson surface reconstruction method was used. This technique is particularly effective for generating consistent and closed models, especially when working with dense, high-resolution point clouds. Due to the high level of detail of the given environment and the many places where the laser beam was unable to reach, gaps were created in the final point cloud. To correctly create the model, it was necessary to fill in the gaps created. Filling the holes was done by fitting planes into empty spaces and generating new points. To prepare the point cloud for the MESH model, an additional processing step was employed for the scan fragment connecting the two chambers. The section illustrates the creation of a distinctive ceiling enclosure. In order to ascertain the geometry of the ceiling itself, it is necessary to classify and extract the points belonging to the ceiling and the enclosure. A point cloud generation approach was implemented to map this section of the point cloud in accordance with the edges of the tunnel cross-section. This step made it possible to generate a synthetic point cloud of the selected tunnel section based on the edges representing the ceiling [46].

Second group of objects are additional objects, including mining equipment, technical infrastructure and exhibits. These objects were modeled using two approaches. The first one involved the conversion of point cloud data into MESH models by applying adapted parameters in MeshLab using Poisson surface reconstruction method. The second approach combined basic geometric elements with advanced modeling tools to create 3D representations based on accurate real-world dimensions. In particular, tools such as sculpting and smoothing in Blender were utilized to shape and refine the models. This process was carried out using both Blender and MeshLab software, which facilitated the precise modeling and refinement of these models to ensure fidelity to the original structures. This method is characterised by a higher level of object generalisation, while allowing the use of sculpting tools to incorporate distinctive features into the model. It gives the creator greater flexibility and creative control over the representation of the object, allowing the inclusion of its characteristic elements. The resulting mesh model consisted of approximately 9 million triangles.

The next stage of the project focuses on implementing the prepared 3D models in Unreal Engine 5 (UE5). The Unreal Engine environment is one of the most popular and respected tools for developing computer games and interactive applications. A game engine is a software framework designed for the creation and development of video games for consoles, mobile devices and personal computers. The core functionality typically provided by a game engine includes a rendering engine for 2D or 3D graphics to display textured 3D models (spatial data), a physics engine or collision detection (and collision response) for the interaction of objects, an audio system to emit sound, scripting, animation, artificial intelligence, networking, streaming, memory management and localisation support.

To map the mine tunnels into gaming environment, created MESH models are first imported into the environment content as components and textured to ensure their visual accuracy and readiness for the environment. The texturing process includes several approaches: using pre-made materials from a library, creating custom materials by defining attributes such as color, reflection, transparency, and relief, or generating textures from real images. In the study, due to the impossibility of taking photographs of each object, ready-made textures from the Unreal Engine 5 library were used, which best reflected the actual appearance. Once this stage is complete, the environment setup is constructed, with careful placement of models, addition of lighting, configuration of physics simulation and interactive elements to increase realism. Unreal and other game engines such as Unity are platforms that allow the generation of realism-enhancing tools using physically-based rendering. On this basis, installing multiple lights, water and other objects in the environment that change in real time gives the impression of being in the real world. One example of the use of elements that enhance the realism of the environment is the use of fluid mechanics in the form of water filling the cavity in the tunnel. The water features in Unreal Engine 5 integrate the shading and mesh rendering pipeline, offering surfaces that enable physics-based interactions and fluid simulations during gameplay.

A crucial part of creating a virtual environment is defining the game mechanics, which defines the rules for how the user functions in the built environment. Game mechanics are the foundation of the user experience, as they determine how the user can move, interact with objects or react to changes in the environment. This includes a variety of locomotion options, such as teleportation and smooth movement, ensuring accessibility and comfort for a wide range of users. The game mechanics in Unreal Engine 5 are implemented using the so-called C++ Blueprints, a pictorial programming language, or directly using the C++ language.

In the case study, the following user interaction mechanisms were implemented:

- Teleportation-based locomotion – this functionality enables users to navigate the virtual representation of the tourist mine complex, allowing for exploration from multiple perspectives.

- Dynamic button interaction – a pressure-sensitive button triggers the display of graphical content, replicating informational posters present in the real mining environment.

The following interactions were programmed in Unreal Engine 5 using the native Blueprints C++ visual coding tool. Finally, the finished environment in Unreal Engine 5 is being adapted for VR integration through the Steam VR platform, allowing users to fully interact with the virtual space and enjoy a responsive, immersive experience.

4. RESULTS

As a result of the research, 3D mesh models were created and implemented into the gaming engine environment. To evaluate the accuracy of the models, they were compared to the cleaned point clouds by determining the cloud-to-mesh (C2M) distance. The results of these comparisons are shown in Fig. 4. As shown, the mean error values fluctuate in the +/- 14 mm range, and the standard deviations are up to 58 mm. These low error values confirm the high fidelity of the reconstructed mesh models.

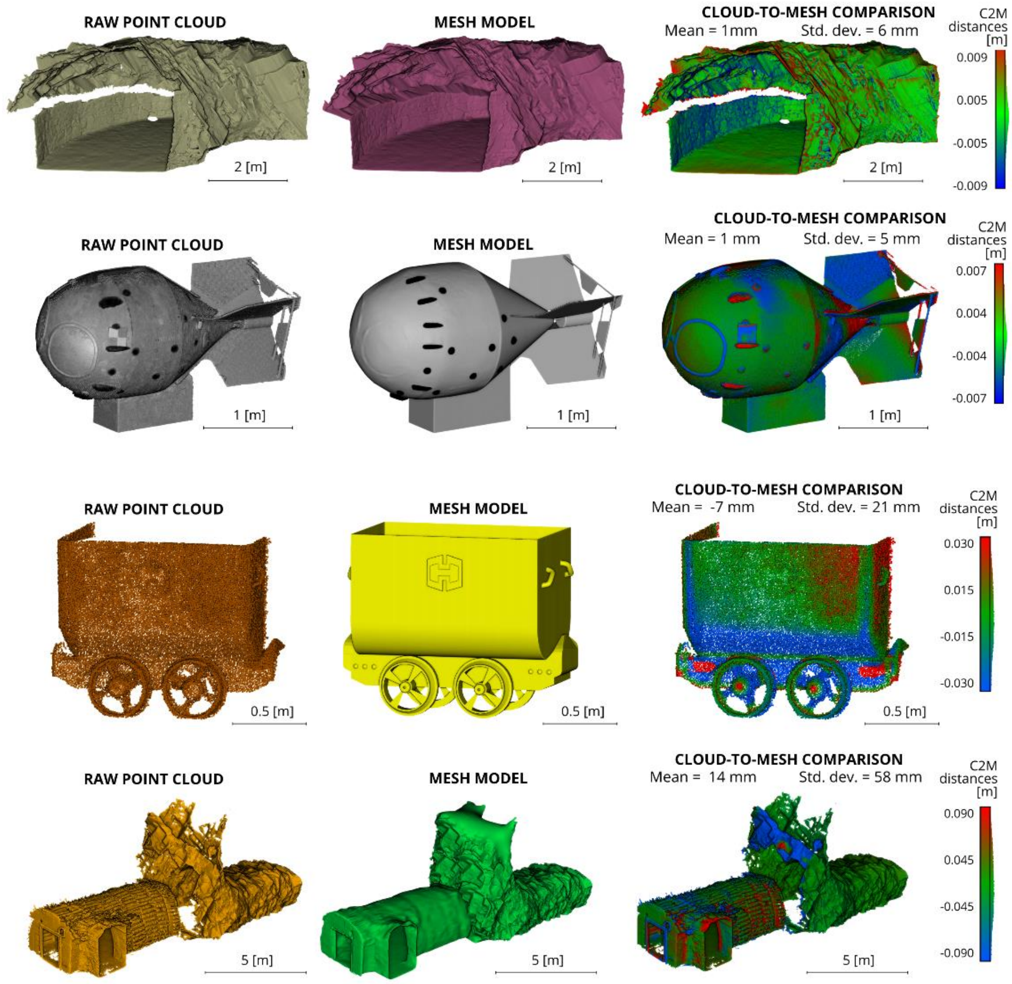


Fig. 4. C2M comparison of raw point clouds and processed mesh models ready for implementation in VR environment

Following the modeling and validation of the accuracy of the 3D mesh models through cloud-to-mesh distance analysis, the next phase of the study focused on their application in a gaming engine environment. Integrating the models with the Unreal Engine framework, it is possible to create an interactive environment that improves the viewer's spatial perception and experience of being in the presented virtual environment, superior to traditional 2D representations. Analysis of the resulting models was carried out based on C2M statistics.

In the case study, reconstruction was performed for all objects that were in the selected section of the tunnel. Different approaches were used in modeling the point clouds depending on the type of object. Fig. 5 shows the reconstruction of a simple object and Fig. 6 shows the approach chosen for large data structures.

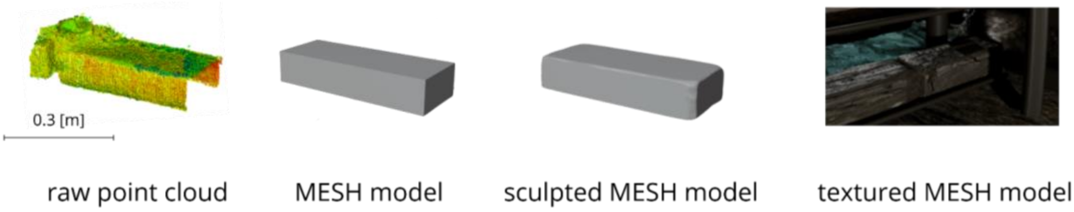


Fig. 5. Steps in creating and implementing models from components

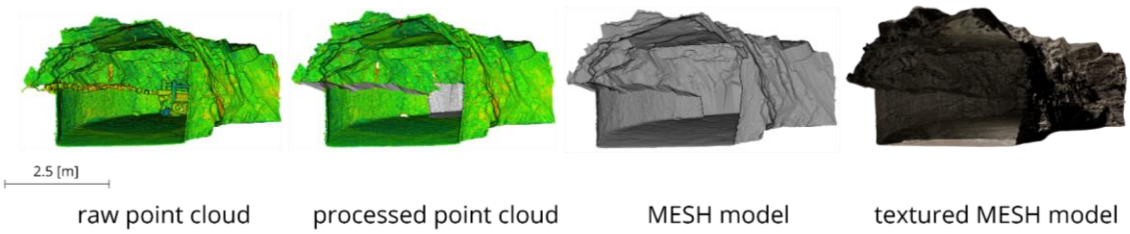


Fig. 6. Steps in creating and implementing models from larger objects

Due to the lack of photographs taken at the time of the survey, it was not possible to accurately represent the texture. To make the representation as close as possible, the texture that most closely resembled the actual condition was used. A section of the selected texture on the MESH models was appended to the Fig. 7.

(a) (b)

Fig. 7. Example of: (a) utilizing ready-made textures and (b) the actual view of the study site

The VR environment incorporated teleportation for locomotion, allowing the user to navigate the tourist mine and explore it from different perspectives. In addition, interactive mechanics, such as a pressure-sensitive button, were implemented to display graphical content, such as posters from the real mine.

The results demonstrate the successful development and implementation of detailed 3D models of mine infrastructure, equipment, and exhibits within a gaming engine environment with the use of VR technology. The resulting reconstructed 3D scene shows good quality due to the high resolution of the reconstructed data and real effects, which ensure the realism of the objects. Most objects are well-defined and easily recognizable. In our study, the final stage was the implementation of a VR module into the scene, but further development of the environment is possible. Figures 8 and 9 illustrate the results of the study. Figure 8 shows the perspectives from each segment of the tunnel, while Figure 9 is a three-dimensional representation of the primary exhibit of bomb in a defined area of the Podgórze mine.

(a) (b)

(c) (d)

(e) (f)

(g)

(h)

Fig. 8. Created environment in Unreal Engine 5 showing (a-b) part one of the tunnel in a vintage mining truck, (c-d) part two with the casing and (e-h) part three with the atomic bomb

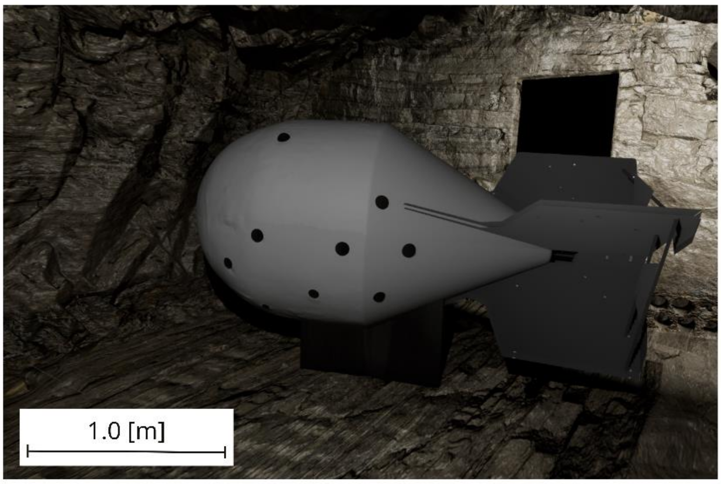


Fig. 9. Atomic bomb representation in Unreal Engine 5

5. DISCUSSION

Virtual reality is an alternative environment that simulates reality or creates new spaces. This form of visualisation can bring numerous benefits to many fields, from education to tourism to science. In education, it enables students to learn more effectively through enhanced visual experiences. What's more, they can safely carry out experiments and simulate events that would pose a risk in real life. In tourism, VR not only provides entertainment but also contributes to the preservation of cultural heritage. It makes it possible to remotely visit tourist sites and view monuments in minute detail without being physically present. VR is particularly useful for underground mines, which are usually inaccessible to non-miners or those with mobility limitations. In the mining engineering field, the implementation of VR is commonly used in health and safety issues. It is most widely used to enhance training programmes with simulations of emergency response, operating autonomous vehicles and practising the execution of daily work but it is important to remember that VR representation relies on collected and modeled data, therefore it is impossible to represent dynamically changing environments.

In research, VR demonstrates the need for accelerated and automated modeling of 3D objects. The present research focuses on the application of VR in the field of tourism, presenting an abandoned underground mine that has been transformed into a tourist route. Universal processing steps were proposed, starting with 3D data acquisition using different methods. Then the point clouds were processed individually for each site and mesh models were created. The final step was to implement the models in a VR environment, adapting the mechanics of user interaction.

The research has developed a universal methodology for processing 3D data for visualisation in a VR environment but requires an individual approach depending on the specific object and measurement conditions. A key step is the choice of measurement technology, depending on factors such as working environment, object size or required accuracy. In subterranean environments, such as underground mines, terrestrial laser scanners are the optimum solution, enabling precise mapping of object geometries with millimetre accuracy. In the case studied, a section of a 25 m tunnel was mapped with a resolution of 1 cm, ensuring realistic visualisation in VR and efficient implementation of the models. Mobile laser scanners could be used to speed up data collection for extensive underground systems stretching for kilometres. However, it should be noted that SLAM systems based on IMU may be used, and the final model could be distorted due to the inability to closure the loop when measuring long tunnels. At the same time, the resolution of the models would need to be optimised to meet the requirements of VR and the limitations of hardware processing power.

3D modeling is one of the most difficult steps in the proposed methodology. It requires an individual approach depending on the size of the object, its shape and the completeness of the data collected during the measurement. The first step is the segmentation of the object. Due to the complexity of the scanned environment and the irregular shapes of the solids, this process was carried out manually. Although accurate, this approach is time consuming. In the future, there are plans to automate this step using AI algorithms, which could significantly speed up the work. Another challenge is filling in gaps in the point clouds. Where this was possible, a plane fit to adjacent points was used to fill in the missing parts of the model. In more problematic cases, such as objects with complex and/or irregular structures containing many characteristic elements, they were created from scratch using geometric primitives and relying on real-world dimensions. This approach optimises the data by reducing the number of polygons. The use of a precise method of mesh generation from point clouds ensures high accuracy in the representation of the shape of objects. However, this can have a negative impact on user performance and fluidity in VR. A key element in this process is optimising resolution and adjusting face sizes to achieve a balance between accuracy and performance.

The created mesh models were compared with the raw point cloud using the Cloud-to-Mesh method to evaluate modeling accuracy. The mean C2M distance was a few millimetres, with a standard deviation of up to 6 cm. However, not all elements and parts of the tourist site were fully captured during the 3D data acquisition stage. During processing, gaps had to be filled, or where data was significantly incomplete, solids were modeled from scratch based on visual inspection of the actual object. This approach resulted in simplified objects and higher standard deviation values in the C2M comparison results. In summary, when data is incomplete, maintaining the correct scale and proportions of objects is a significant challenge. In such cases, additional field measurements are required to accurately capture the true dimensions and ensure realistic modeling.

Texturing is a key step in the process of creating objects for implementation in a VR environment. For object modeling, the optimal approach is to use the recorded RGB values from the cameras as textures for the models. However, objects from underground environments, especially mines, pose significant challenges due to limited access to power sources and light, and often no light at all. In such situations, it is necessary to develop custom textures or use off-the-shelf materials from available libraries. In this study, existing textures were used to replicate the actual colours and characteristics of the objects as closely as possible.

There are several problems with implementing ready-made models in a game engine, in this case Unreal Engine 5. This engine does not support geodetic coordinate systems, so objects lose their georeference and must be manually placed in virtual space. Another challenge is scale. Once the models have been implemented in the engine, the lack of preserved scale, which is crucial for the faithful representation of objects, is a major difficulty. In the studies, the positions and scales of objects were adjusted manually.

6. CONCLUSION

The methodology developed in this research provides a flexible and effective approach to recreating real-world environments in virtual reality. Through careful processing and implementation of 3D data, the resulting digital twins closely mirror their physical counterparts, providing users with even better visualization and interaction capabilities through VR. This approach not only improves the understanding of complex environments but also opens new possibilities for exploration and analysis.

The methodology shows considerable potential for overcoming the challenges of representing environments with complex detail or limited accessibility, making it a powerful tool for both academic and practical applications. Moreover, by presenting environments in a virtual setting, this methodology fosters broader engagement, allowing users to explore and appreciate unique objects that might otherwise remain inaccessible.

Future work will focus on automating parts of the 3D modeling process, in particular filling in gaps in point cloud data and using pre-designed solid models. These advances are expected to streamline and accelerate the reconstruction of larger environments, making the process more efficient for a variety of applications.

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