

Digital models of caves for exploration in virtual reality

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Abstract

This work addresses the applications of Terrestrial Photogrammetry in the generation of digital and virtual models of natural caves for immersive exploration in an interactive environment, which are useful tool in the education of Earth Sciences subjects. Two photogrammetric surveys were carried out in the Letreiro and Furna Nova caves, both within the Furna Feia National Park, northeastern Brazil. The methodological approach followed the photogrammetric acquisition protocol, and subsequent processing in the Agisoft Metashape Photoscan software through the Structure from Motion (SfM) algorithm, resulting in the generation of 3D digital models of referred caves. The models were then transferred to interactive 3D viewers (Unreal Engine Software), and a human avatar, in real scale, was inserted allowing the user to control the movements inside the virtual cave environment. In addition to this, a second mode of virtual exploration was related to virtual reality, as the models were uploaded in VR-type goggles (MetaQuest 2). Both forms of visualization allow users to move and explore the cave environments in an immersive and interactive way. This technology is a promising tool for the virtual presentation and exploration of natural environments, such as caves, which are frequently difficult to access.

1. Introdução

Caves are usually remote and low-light environments, which pose challenges regarding their access, mapping and exploration in the field. With the increasing use of digital mapping of natural spaces, the virtual exploration of caves then becomes a promising way of democratizing the knowledge about these spaces, as it enables any user, through an immersive experience, to explore them in virtual reality. The objective of this work is to report the application of virtual reality in facilitating general access to two caves located in the Brazilian semi-arid region. These caves (Furna Nova and Letreiro) were digitally reproduced for insertion into virtual reality. In addition to virtual exploration, the integration of advanced technologies in 3D modelling for education of Earth Sciences subjects has the potential to promote interactive and inclusive learning. In this regard, the manipulation of technological objects allows students to experience immersion, interaction, and imagination through Virtual Reality (ŠVEDOVÁ; KUBÍČEK, 2021; AZZURI et al., 2024). Technologies such as landscape visualization in VRs with 3D immersion goggles are resources

that support the learning of complex concepts, as they offer immersive and hands-on experiences that allow students to explore and interact with representations of natural phenomena and environments in a more tangible way (FISHER et al., 2019; LAMPROPOULOS; KINSHUK, 2024).

Recent studies highlight the positive impact of these technologies, including augmented reality and virtual reality, gamification, and 3D landscape models, on new knowledge acquisition and student motivation, in addition to the inclusion of students with special needs (SILVA; MARTINS; ROCHA, 2025). This is particularly useful in the teaching of Geography and Cartography (CARRUBA; CALCAGNO; COVARRUBIAS, 2023).

In view of this, technological applications using Virtual Reality as a educational tool in lessons related to Earth Sciences, especially Geomorphology, were the focus of this work. The aim was to promote the visualization of geomorphological data in 3D digital models of landforms (caves).

2. Surveyed Area

The surveyed area is located in the state of Rio Grande do Norte, in northeastern Brazil, and comprises two caves (Furna Nova and Letreiro) within the Furna Feia National Park. The caves are carved in carbonate rocks of the Jandaíra Formation, which corresponds to the post-rift

section of the Potiguar Basin. The exposed carbonates of the Jandaíra Formation tend to show a high level of karstification, with large fields of limestone pavements, collapse dolines, and numerous caves.

3. Materials and Methods

Photogrammetric surveys and subsequent processing result in the generation of three-dimensional virtual models of the natural objects being imaged, allowing for its manipulation, visualization, and data

acquisition outside the field.

In caves, the technique employed is digital photogrammetry, which encompasses of two main stages, the first being the image capture

in the field (Figure 1). In this stage, sequential photographs are taken following the photogrammetric parameters of lateral and vertical overlap of at least 60%. For this work, about 2000 photos were captured with a Sony DSC-Hx300 digital camera, with a focal length of up to 215 mm. The photographs are taken sequentially and must cover 360° (acquisition globes, Figure 1A). Artificial white light is an essential factor for acquiring photos in this case, and this procedure is repeated along the length of the cavity. It is important to note that the camera's light meter should be set to "Low Light" to maximize the light capture on the sensor inside the cave. To assist the generation of homologous points during the cloud processing (e.g., identifying differences in the texture of the object), control points with different geometric shapes are positioned along the acquisition path inside the cave.

The subsequent processing steps - similar in both photogrammetry and aerial photogrammetry - result in the construction of the three-dimensional model with submetric resolution. The processing is performed in Agisoft Metashape Photoscan software (Geomorphology Laboratory - UFC) using the Structure from Motion (SfM) algorithm, which creates a computational model of points based on digital stereoscopic effects. The workflow consists of: adding photos and defining the geographic coordinate system (SIRGAS 2000); aligning figures; generating a point cloud. Afterwards, 3D models are generated from the interpolation of the point clouds, giving a high-resolution texture of the terrain. This

visualization can be merged with the aligned photos in the model, giving a real appearance of the outcrop in the 3D model (Mesh). Subsequently, the Digital Terrain Model (DTM) and georeferenced orthomosaic are exported, and can be manipulated in other 3D data visualization and GIS (Geographic Information System) softwares.

These virtual models are adapted for three purposes: visualization of the model in open-source software (Cloud Compare), also used to obtain geometric data and production of virtual reality scenarios. After being generated in Agisoft Metashape, the models go through a process of mesh and texture optimization, where an algorithm (Optimize Alignment) is applied, which uses kriging to interpolate the points with gaps to reduce the number of artifacts in the product. This helps adapt the application to the graphical limitations of Meta Quest 2 devices (virtual reality headsets), without compromising visual fidelity to the real model. The Unreal Engine software, a 3D graphics engine, is employed to develop the interactive application, allowing for real-time exploration of the models. To ensure a smooth experience, gamification resources and graphic optimization techniques are used, ensuring interactivity and user immersion (COSTA, 2020; Figure 2C). These techniques involve rendering the models and their textures using Nanite technology, making the manipulation of heavy, high-resolution models easier, and also providing a more dynamic and realistic interface for viewing the immersive three-dimensional landscapes.

4. Results and Discussion

The resultant 3D models for exploration in virtual environments evidence the applicability of using virtual reality as an immersive experience, which can be utilized for various purposes.

In educational contexts, this immersion in the virtual environment contributes to a more direct interaction with subjects involving natural spaces. In this context, research has pointed out that virtual classroom activities allow students to develop conceptualizations of the environment in which they are immersed. Activities involving virtual reality learning environments (VRLE) enable immersion, interactivity, and imagination, as the virtual environment allows them to move and interact with the created environment (in this case, using the controls), stimulating the formulation of concepts

and interpretations about the object they are engaging with (Figure 1).

Virtual reality (VR) and the use of immersive virtual environments (IVEs) provide a spatial experience that promotes the understanding and visualization of complex three-dimensional natural objects and a sensory experience of complex concepts, such as terrain formation and the climatic processes associated with cave genesis.

Virtual reality with 3D immersion headsets can be used both in Geoscience education and for scientific outreach purposes. Thus, virtual fieldwork using VRs not only constitutes methodologies that support traditional fieldwork but also becomes a potential tool for accessibility to anyone interested in experiencing an immersive cave experience.



Figure 1: Cave scenario with a manipulable avatar in virtual reality, based on the gamification of the digital model generated by photogrammetry. This scenario is the view of the user with MetaQuest 2 glasses, where the user is the avatar, represented by a man in a blue jumpsuit and a yellow helmet, artificially inserted into the digital model for gamification. The avatar can move through the cavity using commands on the glasses' controller.

A: Furna Nova Cave.

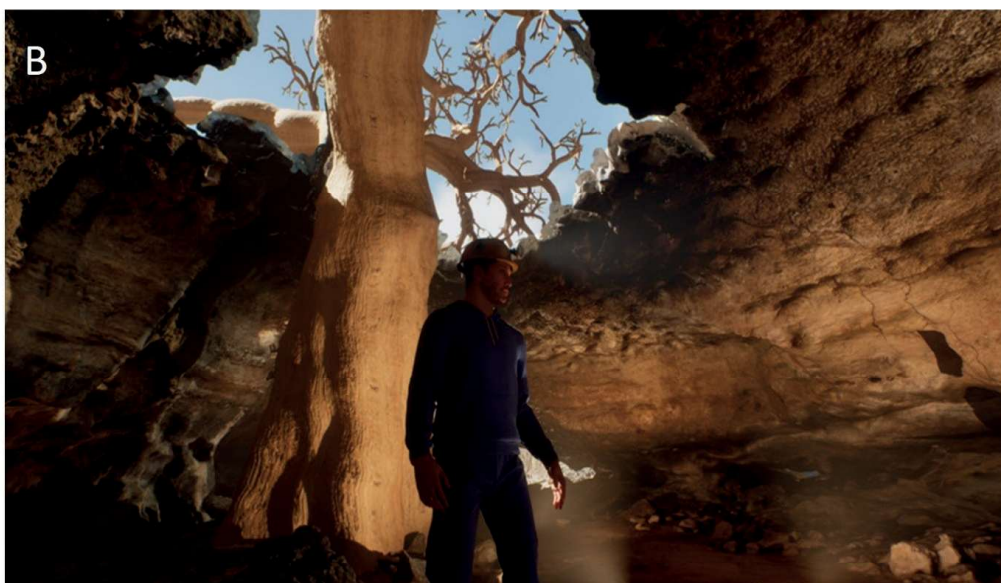


Figure 2: Cave scenario with a manipulable avatar in virtual reality, based on the gamification of the digital model generated by photogrammetry. This scenario is the view of the user with MetaQuest 2 glasses, where the user is the avatar, represented by a man in a blue jumpsuit and a yellow helmet, artificially inserted into the digital model for gamification. The avatar can move through the cavity using commands on the glasses' controller.
B: Letreiro Cave.

5. Conclusion

The use of virtual immersion in 3D models of cave environments can have a wide application and is a promising resource both in education and scientific outreach. Currently, technologies such as digital photogrammetry are becoming increasingly accessible, and their use for various purposes, including educational ones, has proven to be an efficient tool, especially allowing access and immersion in remote en-

vironments such as caves. We encourage the digitalization of caves and the availability of 3D for exploration in both digital and virtual modes, in order to expand knowledge and provide a more realistic immersive experience in caves. We highlight that these techniques can also foster the conversation of these relevant natural spaces.

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