



360° VIRTUAL TOURS OF CAVES: AN INNOVATIVE TOOL FOR CAVE CADASTRE AND PUBLIC ACCESSIBILITY

360-STOPINJSKI VIRTUALNI OGLEDI JAM: INOVATIVNO ORODJE ZA KATASTER JAM IN JAVNI DOSTOP

Michele POTLECA^{1*}, Nicola CREATI¹, Paolo MANCA², Alessio MEREU³,
Alessandro PAVAN¹, Paolo STERZAI¹ & Paolo PAGANINI¹

Abstract

Michele Potleca, Nicola Creati, Paolo Manca, Alessio Mereu, Alessandro Pavan, Paolo Sterzai & Paolo Paganini: 360° virtual tours of caves: An innovative tool for cave cadastre and public accessibility

Recent technological advances have opened up new possibilities for collecting, analysing and sharing information about speleological sites. This study explores the integration of 360° spherical imagery and Virtual Tours (VTs) to document five hard-to-access natural caves in the classic karst region. These immersive VTs experiences were embedded in the official speleological cadastre of the Friuli-Venezia Giulia Region, Italy (<https://catastogrotte.regione.fvg.it/>).

The Autonomous Region of Friuli Venezia Giulia has officially integrated underground VTs into its institutional cave registry. This innovation not only improves the functionality of the cadastre but also sets a precedent for how immersive technologies can be effectively utilized within public geological and environmental databases.

We analyse the benefits of integrating 360° VTs into a regional cave cadastre from the perspective of scientific documentation, promotion of speleological heritage, knowledge dissemination and public engagement. We also address the technical challenges that have been encountered during acquisition and post-processing and provide guidelines and future perspectives for the application of these technologies in cave research and digital documentation.

Keywords: speleology, virtual tours, 360° panoramic photography, cave cadastre, digital heritage, accessibility.

Izveček

Michele Potleca, Nicola Creati, Paolo Manca, Alessio Mereu, Alessandro Pavan, Paolo Sterzai & Paolo Paganini: 360-stopinjski virtualni ogledi jam: Inovativno orodje za kataster jam in javni dostop

Nedavni tehnološki napredek je omogočil nove možnosti za zbiranje, analiziranje in izmenjavo informacij o speleoloških najdiščih. V tej študiji se proučuje združitev 360-stopinjskih sferičnih posnetkov in virtualnih ogledov za dokumentiranje petih težko dostopnih naravnih jam na območju klasičnega kraša. Te poglobljene izkušnje virtualnih ogledov so bile vključene v uradni speleološki kataster dežele Furlanija - Julijska krajina v Italiji (<https://catastogrotte.regione.fvg.it/>).

Avtonomna regija Furlanija - Julijska krajina je podzemne virtualne ogledne uradno vključila v svoj institucionalni register jam. Ta novost ne le izboljšuje funkcionalnost katastra, ob tem tudi ustvarja precedens za to, kako se lahko tehnologije poglobljenega doživetja učinkovito uporabljajo v javnih geoloških in okoljskih podatkovnih bazah.

Analiziramo prednosti vključitve 360-stopinjskih virtualnih ogledov v regionalni jamski kataster z vidika znanstvene dokumentacije, promocije speleološke dediščine, širjenja znanja in vključevanja javnosti. Obravnavamo tudi tehnične izzive, s katerimi smo se srečali med zajemanjem podatkov in naknadno obdelavo, ter podajamo smernice in obete za prihodnost za uporabo teh tehnologij pri raziskovanju jam in digitalnem dokumentiranju.

Ključne besede: speleologija, virtualni ogledi, 360-stopinjska panoramska fotografija, kataster jam, digitalna dediščina, dostopnost.

¹ OGS, National Institute of Oceanography and Applied Geophysics, Borgo Grotta Gigante 42/C, 34010 – Sgonico, Italy

² Direzione centrale difesa dell'ambiente, energia e sviluppo sostenibile - Servizio geologico RAFVG, via Sant'Anastasio 3, Trieste, Italy

³ Divulgando S.r.l., V.le Miramare, 15, Trieste, Italy

* Corresponding Author, e-mail: michele.potleca@ogs.it

1. INTRODUCTION

Caves are unique natural laboratories rich in geological, biological, and archaeological value (Ford & Williams, 2007; Williams, 2008). However, their documentation presents major challenges due to limited accessibility, poor lighting conditions, and the fragile nature of underground environments. Conventional methods such as topographical surveys and 2D photography are often insufficient to capture the full spatial complexity and immersive experience of subterranean spaces (Sordoni et al., 2021).

The documentation of cave environments has undergone substantial evolution over the past two decades, driven by the development of high-precision three-dimensional surveying technologies. Among these, terrestrial laser scanning (TLS) and LiDAR systems mounted on terrestrial or aerial platforms represent the current standard for generating dense 3D point clouds with high geometric accuracy. TLS/LiDAR systems routinely achieve centimetric to sub-centimetric precision, enabling detailed morphometric analyses, deformation monitoring, volumetric assessments, and the geometric modelling of complex underground spaces (Soudarissanane et al., 2011). Their application in karst environments is well established, providing quantitative datasets that complement traditional topographic surveys and geomorphological observations, as demonstrated in large-scale, high-resolution cave mapping applications (Gallay et al., 2015).

In parallel, Structure-from-Motion (SfM) photogrammetry has emerged as a powerful and cost-effective method for 3D reconstruction based on multi-view imagery. SfM has proven particularly effective in cave environments, where irregular geometries, low illumination, and constrained spaces pose significant challenges (Westoby et al., 2012; James & Robson, 2012). When combined with artificial lighting and high-sensitivity cameras, SfM can produce high-resolution 3D models that are often comparable to TLS outputs, although limitations remain in areas with poor texture, reflective surfaces, or insufficient photographic coverage.

Alongside these metric techniques, a distinct class of approaches focuses on visual documentation and communication, rather than strict geometric measurement. In recent years (Cardona et al., 2023; Rodríguez et al., 2025), 360° virtual imaging technologies and VTs have emerged as powerful tools for realistic and immersive remote documentation (Angeloni, 2023; Aricò et al., 2024; Bassier et al., 2018; Harun & Yanti Mahadzir, 2021; Rahaman et al., 2023; Stappung et al., 2023). Relying on omnidirectional cameras to acquire panoramic imagery through spherical projection, VR360 imaging does not

produce georeferenced point clouds or 3D models, nor does it allow spatial measurements. Instead, its strengths lie in rapid acquisition, minimal equipment requirements, low operational cost, and high accessibility of the resulting content. These characteristics offer new opportunities for scientific study (Napolitano et al., 2018; O'Connor et al., 2019; Savini et al., 2024), while making VTs particularly suitable for preliminary documentation, inclusive access, public outreach, and accessible tourism (Iftikhar et al., 2023; Lu et al., 2022; Petousi et al., 2023; Stappung et al., 2023), where immersive visualization and heritage communication are more relevant than metric accuracy.

From a technical perspective, VTs should therefore be understood as complementary to high-precision 3D survey methods. TLS/LiDAR/SfM remain essential for rigorous spatial analysis, morphometric characterization, and monitoring, while VTs provide an intuitive and immersive representation of underground environments that enhances spatial understanding and remote exploration. This complementarity is especially relevant in speleological cadastres, where rapid visualization tools can improve communication among researchers, cave managers, and the general public, without replacing the metric techniques required for scientific analysis.

Although individual caves have previously been documented with Virtual Tours (Ciocchetti, 2025; Han et al., 2019; Farabollini & Bendia, 2022; Stucchi, 2025; Vannini et al., 2015), these initiatives were not integrated into structured, official speleological cadastres, and therefore lacked standardized formats, comprehensive metadata, and long-term accessibility for research, education, and territorial management. This gap highlights the potential value of combining immersive VT technologies with institutional cadastres, providing both rich visual experiences and verified geospatial information in a unified system.

The establishment and continuous updating of official cave cadastres play a crucial role in supporting territorial knowledge and governance. These databases represent not only inventories of underground voids but also geospatial information systems that integrate geomorphological, hydrological, and biological data essential for land-use planning, environmental monitoring, and risk management (Del Vecchio et al., 2015; De Waele, 1999). By providing verified and accessible data, cave registers enable public administrations, researchers, and emergency services to make informed decisions regarding groundwater protection, infrastructural development, and heritage conservation.

To date, over 8,000 caves have been catalogued. The registry entries include detailed descriptive information, topographic surveys, photographs, and in some cases 3D models obtained through laser scanning. The archive is continuously updated thanks to the active participation of speleologists, who play a central role in the ongoing development of the registry. They make a significant contribution to the understanding of the territory through research, environmental monitoring, exploration, and topographic surveying of karst phenomena.

In this context, the introduction of 360° VTs represents a major innovation. This technology transforms the CSR from a static archive into an interactive platform, enabling immersive spatial exploration of caves and enhancing the dissemination and valorisation of speleological knowledge for researchers, schools, and the general public.

This article presents the results of a pilot project in

which five caves were documented using 360° imaging and VT technologies and subsequently integrated into the cadastre's public web platform. The project was conducted in the Friuli Venezia Giulia Region (northeastern Italy), a classical karst area with numerous speleological sites of high scientific and cultural significance. Five caves were selected as case studies based on their morphological complexity, limited accessibility, and relevance for documentation and dissemination.

To our knowledge, this is the first instance in which a public administration has adopted immersive underground VTs within an institutional speleological cadastre. By bridging the gap between previous standalone VTs and a structured cadastre, this initiative not only demonstrates technical feasibility but also opens new perspectives for the digital transformation of public environmental records, promoting transparency, accessibility, and a deeper understanding of karst landscapes as dynamic components of territorial systems.

2. MATERIALS AND METHODS

2.1 INSTRUMENTATION AND SOFTWARE

Several types of photographic equipment were employed, depending on the specific needs of each cave environment (Table 1).

A Nikon D610 DSLR with a panoramic head was used with wide-angle (16 mm focal length) to capture overlapping frames suitable for stitching. This camera, thanks to full manual control of exposure and aperture, provided high image quality, broad dynamic range, and flexibility in challenging lighting conditions (Chiesi & Pani, 2003). The combination with a panoramic head minimized parallax errors, ensured seamless stitching and produced higher-resolution panoramas, especially in caves with larger chambers.

A Ricoh Theta Z1 360° panoramic camera was the primary instrument for spherical imagery used for most of the documentation due to its compact design and ability to capture high-resolution images. Its portability and structural features made it particularly effective in narrow passages and humid environments. This device, equipped with dual ultra-wide lenses (180° each), automatically captured full panoramas with reduced stitching complexity. This prosumer model was preferred due to its capability to shoot in RAW format, HDR (High Dynamic Range) and 4K–8K resolution, which ensured high-quality outputs even in low-light environments (Ricoh Theta Z1, 2025).

To complement the terrestrial data, a DJI Mini 2 drone was utilized to capture the external context of the cave entrances. These aerial 360° images were acquired to document the immediate surroundings and the specific geomorphological setting of the access points, providing a visual transition between the external landscape and the subterranean environment (Figure 1).

Both systems were mounted on Tripods and mounting systems, essential for image stability during long exposures (Figure 2). Adjustable tripod legs allowed stable placement on uneven surfaces, while small flexible tripods supported auxiliary flashes. In vertical shafts, custom aluminium brackets were anchored to fixed bolts to stabilize the camera, later digitally removed during post-processing.

A Panoramic head Nodal Ninja 3 was used for DSLR/mirrorless setups to ensure correct rotation around the optical nodal point, minimizing parallax errors during stitching. Careful alignment and a minimum overlap of 30 % between successive frames were applied to guarantee seamless stitching.

Lighting equipment included both continuous LED systems and remotely triggered flash units. Backlighting techniques were applied to enhance depth and texture of speleothems, while HDR bracketing compensated for extreme contrasts near entrances.

Protective cases, spare batteries, and high-capacity

Table 1: Technical specifications and primary functions of the equipment employed for 360° cave acquisition.

Equipment	Model	Acquisition Role	Technical Notes
360° Panoramic Camera	Ricoh Theta Z1	Primary tool for spherical imagery; general cave documentation	RAW (DNG) + HDR support; compact for narrow passages.
DSLR Camera	Nikon D610 + panoramic head Nodal Ninja 3	High-resolution panoramas in large chambers	Wide-angle lenses (16 mm); nodal-point alignment
UAV (Drone)	DJI Mini 2	Capture of external 360° panoramas at cave entrances.	Lightweight for field transport; 12 MP RAW imagery for spherical stitching of entrance contexts.
Tripod & Brackets	Tripod & Custom Brackets	Stabilisation in chambers and vertical shafts	Adjustable legs for uneven terrain; custom aluminium mounts for shafts.
Lighting Systems	LED Panels & Remote Flash Units	Illumination of dark galleries and textural enhancement.	Remote triggers; backlighting used to emphasize speleothem depth.

storage devices were carried to address the logistical challenges of extended underground operations.

After the images were captured, the panoramic images were carefully processed and stitched together using Kolor Pano suite software (Autopano giga and Panotour). This specialised software package was crucial for transforming individual spherical images into interactive, virtual environments with multiple nodes. Kolor Panotour's robust features allowed for precise stitching of images, seamless navigation between different "nodes" or viewpoints within the VT and the integration of various interactive elements such as information hotspots,

embedded media and navigation maps. The software's capabilities were critical to creating a fluid and immersive user experience that accurately depicts the spatial relationships within the caves.

2.2 FIELDWORK PLANNING AND IMAGE ACQUISITION

Capturing high-quality 360° images in underground environments requires careful planning of fieldwork. The unique challenges of cave systems, including their often dangerous and physically demanding conditions, require a thorough understanding of the site beforehand. Famil-



Figure 1: Screenshot of the Fontanon di Goriuda VT interface. The image displays an aerial panorama of the cave entrance environment, acquired via Unmanned Aerial Vehicle (UAV).

ilarity with the terrain is critical to ensure that the team is aware of potential geological hazards, hydrological features and pre-existing conservation issues.

To maximise image quality and ensure scientific utility, several strategies were systematically applied. One of the most important was the use of HDR bracketing to address the strong contrast between cave entrances and zones exposed to external light, where the coexistence of bright daylight and deep shadows can otherwise compromise image readability (Jusof et al., 2014). By acquiring a sequence of underexposed, correctly exposed and overexposed shots, later combined in post-processing, it was possible to obtain images that retained detail across the entire tonal range (Jusof et al., 2014; Peteva, 2022), particularly useful for accurately representing transition zones. Another key strategy was the inclusion of human figures within selected panoramas, which provided an intuitive sense of scale and spatial reference. Their careful positioning ensured that the most significant morphological and geological features remained visible while enhancing the perception of the true dimensions of passages, chambers and formations. Lighting was also deliberately managed using backlight flash, which enhanced depth and texture by creating contrasts and emphasising the three-dimensionality of speleothems such as stalactites, stalagmites and flowstones, as well as the fine textures of surfaces that would otherwise have remained indistinct. Finally, all photographs were captured in RAW format to preserve the maximum amount of sensor data. This choice ensured extensive post-processing flexibility, allowing fine control of exposure, colour balance and noise

reduction in the particularly challenging lighting conditions of caves. The image stations, or recording points, were carefully selected and generally spaced every 20–30 metres for large cave systems to ensure comprehensive coverage while minimising redundancy. For smaller caves or more complicated passages, fewer stations were often sufficient, with spacing adjusted according to the line of sight and complexity of the environment. Great care was taken when positioning the camera tripod on stable, dry surfaces to avoid movement during image capture and to protect the equipment from moisture. In addition, deliberate care was taken to avoid dripping or standing water, not only to protect the equipment, but also to avoid unwanted reflections or distortion in the final spherical images.

2.3 POST-PRODUCTION AND IMAGE PROCESSING

The post-production phase was critical for ensuring chromatic consistency and the systematic elimination of visual artefacts resulting from complex subterranean imaging conditions. The workflow (Figure 3) commenced with RAW file processing, aimed at mitigating colour shifts induced by the coexistence of heterogeneous light sources, such as natural light filtering through entrances and artificial LED or strobe illumination. To resolve the spectral discrepancies between these sources, rigorous white balancing and local colour grading were performed, ensuring that mineralogical textures and speleothem pigmentations were reproduced with scientific accuracy.



Figure 2: Photographic equipment used for the acquisition of the VT imagery: (a) Ricoh Theta Z1 360° camera, (b) Nikon D610 DSLR camera.

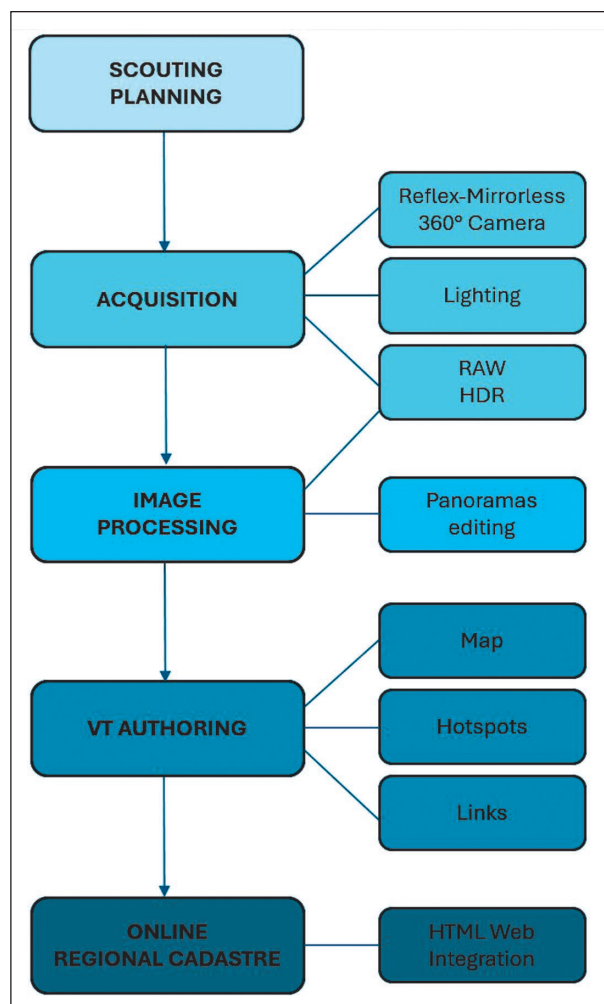


Figure 3: Methodological workflow for the development of the photographic VT. The diagram outlines the sequential phases from initial data acquisition to final web-based integration.

To manage the extreme contrast ratios inherent in karst environments, HDR blending algorithms were applied. By merging bracketed exposures, the system preserved high-frequency details in deep shadows while simultaneously preventing pixel saturation in highlight areas. Parallel to radiometric optimization, a meticulous digital cleaning operation was executed to remove technical elements extraneous to the natural context. Using selective masking tools and advanced cloning techniques, tripods, mounting brackets, and lighting supports were digitally removed from the Zenith and Nadir points of the spherical projection. This complex technical intervention resulted in a fully immersive, artefact-free 360° equirectangular projection, providing the user with a natural and uninterrupted representation of the subterranean environment.

2.4 VIRTUAL TOUR AUTHORIZING

The final phase of creating the interactive cave experiences involved the creation of VT, which were expertly executed using Kolor Panotour software (Figure 4). This powerful platform allowed us to transform individual edited panoramic images into a cohesive and navigable virtual environment. A key feature of these tours is the implementation of hotspots, strategically placed interactive points within each panoramic node that allow seamless navigation between different viewpoints. This creates a fluid "walk-through" experience that mimics the exploration of the cave in real time.

To enhance orientation and contextual understanding, detailed maps with embedded navigation points and compass orientation have been carefully integrated into each tour. These navigation aids give the user a clear sense of where they are within the cave system and in which direction they are travelling. Beyond simple navigation, the VTs have been enriched with a variety of ad-

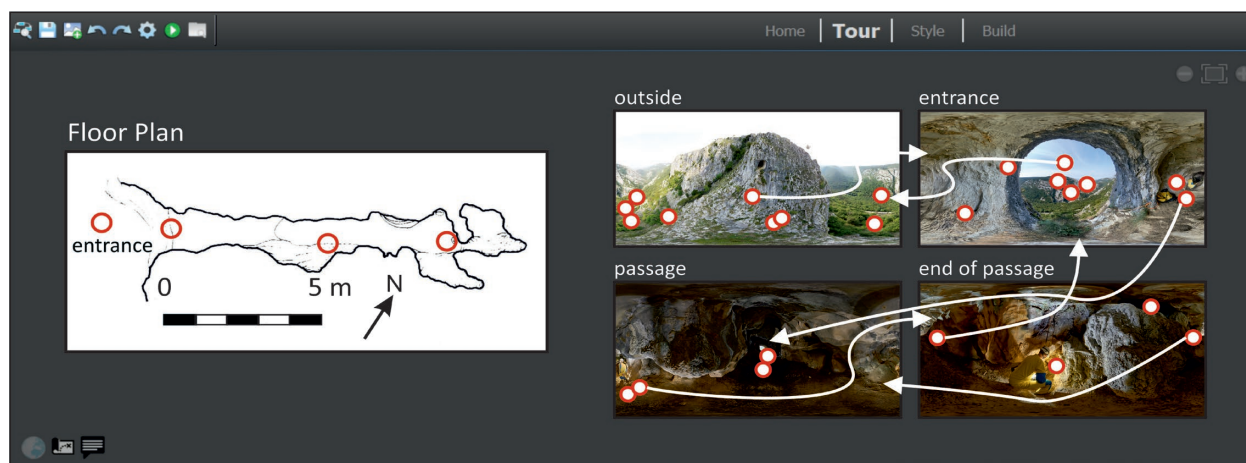


Figure 4: Graphical User Interface (GUI) of the software employed for the VT authoring. The upper panel illustrates the topological network of interconnected panoramic nodes; the lower panel displays the cartographic plan of the cave with georeferenced image acquisition stations.

ditional content designed to provide deeper educational and scientific insights:

- Text annotations: These pop-up descriptions provide concise information about specific geological formations, historical details or ecological observations relevant to the immediate viewing area.
- External links to scientific databases: To encourage further research and provide access to authoritative information, direct links to relevant scientific databases and research papers have been embedded to connect the visual experience with academic resources.
- Embedded PDFs: For more comprehensive information, entire PDF documents (e.g. geological reports, historical documents).

2.5 INTEGRATION INTO THE REGIONAL CADASTRE

An important result of this project was the successful integration of the completed VTs into the website of the Regional Speleological Cadastral Register of Friuli Venezia Giulia (Figure 5). With this step, the VTs were no lon-

ger just used as stand-alone applications, but embedded directly into an official, publicly accessible speleological information system. Each VT was directly linked to the corresponding cave entry in the cadastral database. Users can now access these fascinating experiences via a dedicated "Virtual Tour" button displayed on each cave's profile page, making them easy to find and access for all visitors to the CSR.

This integration effort was not only a technical upload, but also a significant coordination with the regional public administration. This collaboration is a rare and remarkable example of how immersive technologies are being integrated into official geological information systems. It underlines the proactive approach of public authorities in the Friuli Venezia Giulia region to utilise state-of-the-art digital tools for cultural heritage management and public engagement. This initiative shows a viable way to improve public digital infrastructure with new media, sets a precedent for other public authorities and demonstrates the potential for VTs as a standard component of environmental and cultural heritage databases.

The screenshot displays the web interface of the Regional Speleological Cadastre. The header includes the logo of the Regione Autonoma Friuli Venezia Giulia, the language selector (English - EN), and a Login/Register button. The main title is "Regional Speleological Cadastre" with the subtitle "Central Directorate for Environmental Protection, Energy and Sustainable Development - Geological Service". A search bar is located on the right. The navigation menu includes Home, Speleological Cadastre, Help, Tools, News & Events, and Contacts.

The main content area shows the profile for "20 | Fontanon di Goriuda". It includes a table with the following data:

Main name	Fontanon di Goriuda
Cadastral number	20
Local cadastral number	1 FR
Total number of entrances	1

Below the table are buttons for "Complete record", "Map", "Search nearby", "Save", and "Virtual Tour". To the right of the table is a 360° virtual tour image showing a cave interior with green lighting.

The "Main entrance" section includes a table with the following data:

Position reliability	Correct
Nameplate presence	Yes
Geographic area	Julian Alps
Municipality	Chiusaforte
Provincial area	Udine
Lat. WGS84	46,39159998
Lon. WGS84	13,4357724
East RDN2008/UTM 33N	379736.251
North RDN2008/UTM 33N	5138747.252
Entrance altitude (a.s.l.)	861 m

The "Map" section shows a topographic map with a red pin indicating the location of the cave entrance. The map includes a scale bar (100 m) and a "Plan" button.

Figure 5: Web interface of the Regional Speleological Cadastre database. The image illustrates the integration of the VT access point directly within the cave's metadata record.

Within less than two years, the VTs have surpassed 3,000 views on the website of the Regional Speleological Cadastre, confirming their value as an excellent tool for

public outreach and for enhancing knowledge of the territory.

3. BENEFITS OF 360° VIRTUAL TOURS IN CAVE DOCUMENTATION

360° VTs are an innovative tool for comprehensive documentation, providing a visually rich, spatially accurate and deeply interactive representation of the cave interior. Unlike traditional photographic methods, these immersive tours capture every corner of a subterranean space and provide a complete visual record. In this way, intricate morphological features such as delicate shells, various speleothems (such as stalactites, stalagmites and flowstones) and complex erosional forms can be studied with remarkable precision. Explorers and enthusiasts can "walk through" the cave and examine details, zoom in on specific formations and gain a holistic understanding of the geology and geomorphology of the cave, all from a remote location. This detailed and interactive documentation greatly expands the scope and depth of information available for study and conservation.

One of the most profound impacts of VTs is their ability to provide access and engagement to some of the Earth's most hidden wonders. A wide audience, including people with disabilities who need to overcome physical access barriers, students and general tourists, can now virtually explore caves that are otherwise inaccessible. This opportunity not only extends the reach of these unique environments, but also serves as a powerful medium for environmental education. By enabling virtual exploration, these tours promote a deeper understanding of underground heritage and highlight its ecological, geological and cultural significance. They can be used in classrooms to bring lessons to life, in museums to create engaging exhibitions, and in private homes to inspire curiosity about the natural world and

overcome the physical restrictions that traditionally limit access to caves.

Beyond access and education, VTs serve as permanent, invaluable digital records of the state of the caves. This important function directly supports conservation and monitoring efforts. By capturing a precise visual snapshot at a point in time, these tours provide a baseline against which future changes can be accurately identified and tracked. This is particularly useful in the management of sensitive or endangered cave environments where the direct presence of humans can cause irreversible damage. Scientists and conservationists can use successive VTs to monitor subtle changes in speleothems, water levels, sediment accumulation or even the impact of human visitation over time. This enables proactive management strategies to protect these fragile ecosystems.

The spatially resolved images provided by VTs are of great benefit for scientific analysis. Researchers from various disciplines, including speleology, geology and geomorphology, can remotely access detailed visual data on an unprecedented scale. This means that professionals can carry out initial investigations, identify areas of interest or even take detailed measurements without the need for repeated, costly and potentially burdensome site visits. In addition, VTs can be repeated indefinitely for longitudinal studies, allowing scientists to compare the state of a cave at different points in time. This temporal dimension is invaluable for understanding dynamic geological processes, monitoring environmental changes and conducting in-depth research that contributes to a more comprehensive understanding of subterranean systems.

4. TECHNICAL CHALLENGES AND SOLUTIONS

Working in caves poses a major technical challenge due to their specific characteristics. Caves are usually cold, damp and always dark, which creates dangerous conditions for both personnel and sensitive electronic equipment. The high humidity can lead to condensation, while cold temperatures can affect battery life and camera performance. Dripping water, muddy floors and slippery surfaces pose a risk of falls and equipment damage.

Overcoming these limitations requires careful planning and specialised equipment. Proper sealing of all electronic equipment, including cameras, lighting and power sources, is essential. In addition, the use of protective equipment for operators — such as robust helmets, suitable footwear and hardwearing clothing — is essential to ensure safety and comfort during prolonged operations in these challenging conditions.

Achieving high-quality 360° images without natural light is a major hurdle. Artificial lighting is essential, but it needs to be carefully controlled to avoid harsh glare and distracting shadows that can obscure details and create an unnatural look. Our solution was the strategic use of diffused LED lighting to illuminate the scene evenly and minimise hotspots and dark spots. The use of HDR techniques, already described in our methodology, played a crucial role. By taking multiple exposures and blending them together, we were able to achieve an even exposure across the entire scene, preserving detail in both brightly lit areas and deep shadows, which is crucial for a realistic representation of the cave interior.

The unique geometry of cave environments, with their confined spaces, irregular surfaces and often reflective surfaces (such as wet rock or crystalline formations), often leads to errors when stitching individual images into a seamless 360° panorama. These errors can manifest themselves as visible seams, distorted perspectives or duplicate elements. To minimise these problems, careful tripod positioning was of paramount importance. Parallax errors were reduced by selecting a stable, flat surface and accurately aligning the camera node. In post-production, selective masking and advanced blending algorithms were used to carefully correct any remaining stitching artefacts. This included manual adjustment of overlaps and the use of imperfection hiding tools to ensure a smooth and visually continuous VT.

In Kolor Autopano, the main blending algorithm is based on the multiband blending technique, which combines the details and colours of overlapping images to create a seamless transition. The specific algorithms and presets include Multiband Blending. This is the most powerful and widely recommended method. It works by blending pixels based on colour and luminosity frequencies, creating soft, natural transitions that avoid ghosting (semi-transparent or duplicated objects) and differences

in brightness between images. Other blending presets used are the anti-ghosting, simple and exposure fusion algorithms. Anti-ghosting is specifically designed to eliminate artefacts caused by moving objects (such as people or vehicles) in overlapping areas. It combines multiband blending with intelligent pixel selection to remove moving elements that would appear in multiple images. The 'Simple' preset provided a faster blending method, useful for a quick preview, but which can leave visible seams. Exposure Fusion is useful for HDR panoramas: it blends differently exposed shots to balance light and dark areas and capture a wide range of tonal details.

The integration of the high-resolution, interactive VTs into existing cadastral systems was associated with various technical considerations. Key challenges included web compatibility, managing large amounts of data associated with high-quality panoramic images and supplementary media, and ensuring an intuitive user interface (UI) within the cadastre. The embedding of each VT into the Regional Speleological Cadastre was implemented using JavaScript and jQuery technologies. This approach made it possible to dynamically adapt the embedded viewer to different devices and screen orientations, ensuring an optimal viewing experience both on desktop and mobile. By leveraging JavaScript, the system can automatically detect window size and device type, resize the VT iframe accordingly, and maintain full responsiveness without requiring page reloads. jQuery further streamlined cross-browser compatibility and simplified the handling of events such as orientation changes. This technical choice ensured smoother interaction, better usability, and a more reliable presentation of the VTs across a wide range of platforms.

This approach considered data handling, ensured broad compatibility with web browsers and provided a smooth user experience, demonstrating a robust method of extending existing digital platforms with rich, interactive media.

5. CASE STUDIES

During the experimental phase aimed at developing underground VTs, photographic tests were carried out in more than ten caves with different morphologies and lighting conditions, in order to assess the effectiveness of various solutions for 360° panoramic photography in complex subterranean environments.

The investigated sites include Fontanon di Goriuda (Ricoh Z1), Grotta dell'Orso (Nikon D610), Grotta Azzurra (Nikon D610 and Ricoh Z1), Jama Cotarjova (Ricoh Z1), Caverna Pocala (Nikon D610 and Ricoh Z1), Pozzo tra Gabrovizza e Sgonico (Ricoh Z1), Grotta delle

Porte di Ferro (Ricoh Z1), Caverna degli Zingari (GoPro MAX), Grotta del Dio Mithra (Ricoh Z1), Grotta Tartaruga (Ricoh Z1 and GoPro MAX), and Grotta di ghiaccio del Monte Leupa (Ricoh Z1).

Following the tests, five VTs were selected and published in the Regional Speleological Cadastre of Friuli Venezia Giulia, focusing on caves of archaeological, geological, and naturalistic significance (Table 2).

A prominent case is the Fontanon di Goriuda, a powerful perennial resurgence that collects the waters of the Canin plateau's channels then into the Val Raccola-

Table 2: List of selected caves integrated into the FVG Regional Cave Registry and technical metrics for the 360° VTs. Legend: N: Number of stations; S: Average spacing between stations; L: Approx. development of the VT path / Total development of the cave; T: Processing time per tour (including stitching and multi-node authoring); D: Total dataset size optimized for web integration.

Cadastral ID & Cave Name	Municipality	Camera(s) used	N	S (m)	L (m)	T (h)	D (MB)
20 Fontanon di Goriuda	Chiusaforte (UD)	Ricoh Z1 Mavic Mini 2	13	15	250 /767	8	160
151 Jama Cotarjova	Sgonico (TS)	Ricoh Z1	7	10	80/24	4	65
173 Caverna Pocala	Duino Aurisina (TS)	Nikon D610 Ricoh Z1	9	15	140/140	6	80
211 Pozzo tra Gabrovizza e Sgonico	Sgonico (TS)	Ricoh Z1	5	10	40/40	4	56
504 Grotta delle Porte di Ferro	San Dorligo della Valle - Dolina (TS)	Ricoh Z1 Mavic Mini 2	4	5	28/28	4	35

na. The VT was carried out along the 150 meters that can be explored without diving equipment (https://catastogrotte.regione.fvg.it/vr/vr/20-Fontanon_di_Goriuda). The inner spaces, poor in speleothems but rich in erosional and corrosional features caused by flowing water, were documented together with 360° aerial images showing the spectacular external waterfall (Figure 1). Due to its hydrogeological value, the site has been classified as a geosite of national interest.

Special attention was dedicated to three difficult-to-access caves of great prehistoric and archaeological importance: Jama Cotarjova (<https://catastogrotte.regione.fvg.it/vrdoc/cotarjova.html>), located on fenced private

property and therefore not accessible; Caverna Pocala (https://catastogrotte.regione.fvg.it/vr/vr/173-Caverna_Pocala), notable for its rich speleothem formations and abundant remains of *Ursus spelaeus* (Figure 7); and the Grotta delle Porte di Ferro (https://catastogrotte.regione.fvg.it/vr/vr/504-Grotta_delle_Porte_di_Ferro), of interest both for its prehistoric deposits and for modifications to the entrance dating back to Roman times. In this latter case, in addition to the internal documentation, an external panoramic view was produced to highlight the scenic position of the entrance on the Monte Stena cliff face and the natural setting of the Val Rosandra.

A distinctive case is the Pozzo tra Gabrovizza e Sgo-

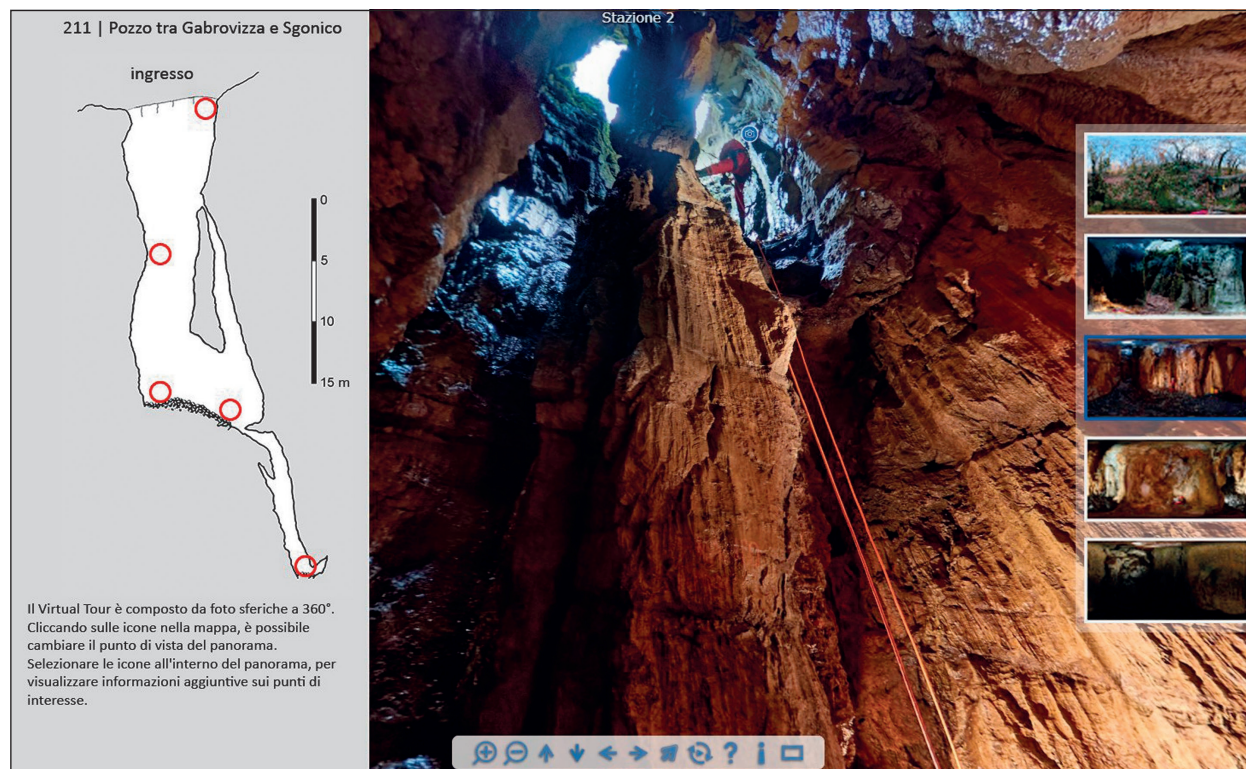


Figure 6: Screenshot from the VT of Pozzo tra Gabrovizza e Sgonico. The acquisition setup involved custom aluminium brackets (1/4" screw mount) for vertical positioning, which were digitally Zenith/Nadir-patched during the editing of the RAW spherical images.

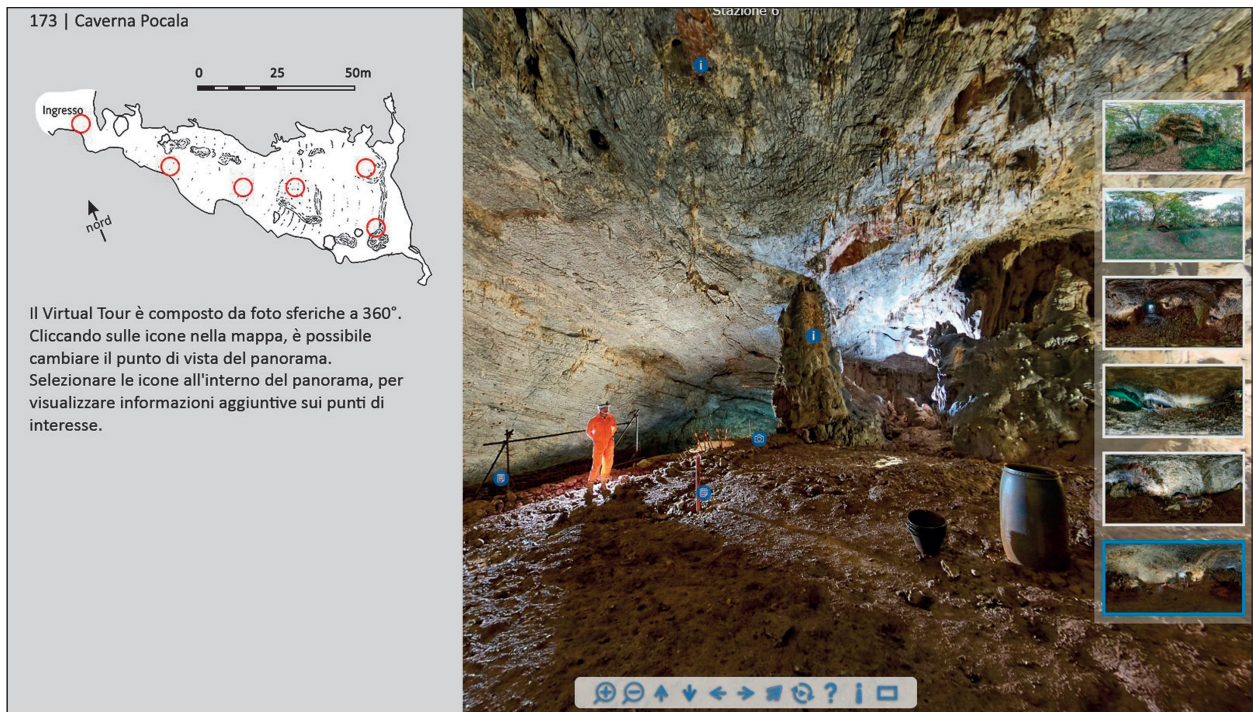


Figure 7: Screenshot of the Caverna Pocala VT. The lighting strategy utilizes backlighting on both the human subject and the speleothems to enhance the perception of spatial depth. To accommodate the low-light conditions and long exposure times (>1 s), a tripod-mounted acquisition was employed, requiring a static subject to prevent motion blur.

nico (Figure 6) the only vertical cave documented with a VT (<https://catastogrotte.regione.fvg.it/vrdoc/carsiana.html>). The shaft, 40 meters deep, opens within the Carsiana Botanical Garden (owned by the Autonomous Region of Friuli Venezia Giulia). In this case, to ensure stable image capture with long exposures and bracket-

ing sequences, special aluminium brackets anchored to bolts on the cave walls were specifically designed. Each tour includes topographic maps with clickable hotspots, orientation tools, and embedded scientific and cultural content.

6. FUTURE PERSPECTIVES

The rapid evolution of immersive technologies offers highly promising prospects for the future of cave documentation and heritage valorisation. The integration of Virtual Reality (VR) and Augmented Reality (AR) represents a significant step toward a new way of exploring and understanding underground environments. VR headsets will enable fully immersive experiences, allowing users to perceive spatial depth, scale, and atmosphere in a way that traditional 360° VTs cannot replicate. Such immersive environments can be used not only for public outreach and museum displays, but also as training and planning tools for speleologists, improving safety and situational awareness prior to physical exploration (De Pisapia et al., 2024).

At the same time, AR applications will open new

opportunities for on-site interpretation. By using tablets or AR glasses, visitors could view real-time digital overlays providing geological, historical, or biological information, reconstructing paleoenvironmental contexts or visualizing extinct fauna that once inhabited the caves. This combination of physical and digital layers can transform underground visits into dynamic, interactive experiences, greatly enhancing their educational and touristic value. A comparative study has shown that VR and AR heritage applications significantly influence visitor emotions, motivation and engagement (Banfi et al., 2024).

To ensure the widespread and consistent adoption of these immersive techniques, standardization and professional training will play a crucial role. Speleologists, survey specialists, and heritage professionals will need

specific training not only in the technical aspects of 360° image acquisition and processing but also in the pedagogical design of effective and accessible immersive experiences. Regional and national cave registries are ideally positioned to define shared quality standards regarding image resolution, metadata structure, accessibility features, and long-term data storage. The establishment of such guidelines will form the foundation for a reliable and interoperable digital archive of subterranean heritage.

The long-term sustainability and scalability of VT initiatives will depend heavily on strong institutional support. Active involvement from public authorities, universities, museums, geological surveys, and funding agencies is essential to ensure continuity. Cultural and environmental institutions should recognize the strategic value of immersive technologies as tools for education,

conservation, and dissemination, providing financial and logistical support for equipment acquisition, staff training, and digital infrastructure maintenance. Likewise, collaborations between academic research and public institutions can stimulate innovation in immersive methodologies and digital platforms, while museums and regional agencies can serve as key interfaces between science and society. A framework study has highlighted key features of XR (AR/VR) technologies that plausibly favour their adoption in cultural heritage contexts, while also identifying unresolved issues relating to user experience and deployment in the field.

From this perspective, the underground VT should not be seen merely as a documentation tool, but as a bridge between research, education, and conservation, combining scientific accuracy with interactive public engagement.

7. CONCLUSIONS

The widespread adoption of 360° VTs marks a transformative moment, shifting the paradigm in cave documentation and heritage management. When these tools are thoughtfully designed and strategically integrated into official cadastres, they establish a forward-looking model for environmental governance and digital archiving. This approach is far more than a simple technological upgrade; it fundamentally shifts how we understand, preserve, and share these unique underground environments, enhancing both transparency and accountability.

The value derived from this innovation is multifaceted. VTs are an essential asset for research and preservation, providing invaluable baseline data for environmental monitoring and enabling detailed analyses without the physical intrusion that risks fragile ecosystems. This non-invasive methodology is critical for safeguarding the long-term health of subterranean habitats. Furthermore, the immersive quality of the tours dramatically improves accessibility, democratizing access for a diverse audience,

from global researchers to individuals with mobility impairments and educational institutions. By transforming abstract geological and historical concepts into engaging learning experiences, VTs transcend geographical barriers, connecting the public with these restricted wonders.

Ultimately, the integration of these immersive underground tours into public databases represents a powerful investment in the future. By championing this innovative model, public administrations set a strong precedent, demonstrating their commitment to modernizing heritage databases and safeguarding the lasting legacy of our natural and cultural treasures. This progressive step paves the way for a more accessible, comprehensively documented, and protected future for underground habitats worldwide, ensuring a responsible custodianship of these delicate natural wonders.

In conclusion, the results highlight a novel approach to public speleological data management through the use of immersive underground VTs.

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