

# Experiences from the Creation of a Virtual Tour through a Stalactite Cave with VR Gear

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*Abstract: This paper describes the 3D survey of an Austrian stalactite cave and the derivation of a Virtual Reality (VR) tour through the data set with the Game Engine Unity. The survey of such a cave beholds many challenges like narrow passages, abstinence of light and scan obstructions in the large stalactite fields.*

*Documenting this huge cave-network required several scanning sessions since the year 2016. The limitations of a cave survey have been overcome by the usage of a broad spectrum of sensors, geodetic total stations, different types of static terrestrial and kinematic laser scanners, SLR cameras and even DJI Mini drones.*

*However, the different surveying techniques deliver varying texture qualities and point accuracies which resulted in inhomogeneous 3D data. Combining these data sets in a common coordinate system and merging them into a single 3D mesh required a solid geodetic reference frame and postprocessing in commercial software products from the laser scanning industry, structure from motion solutions and applications from the entertainment sector.*

*The final 3D model is presented in a VR application as the complexity of the geometry exceeds the capability of the conventional 3D viewers. The user can move along the mesh, has to duck in narrow passages and handles a torch for the exploration of the dark underground. This way students and school pupils get an immersive impression of the dimensions of the cave while they learn about the 3D survey.*

## 1 Introduction

The Katerloch is a major Austrian cave with very diversified terrain properties, as presented in figure 1. It is not only famous for an immense density of stalactites in several stalactite fields throughout its entire structure, but also for its large network of huge domes and narrow passages. The cave's entrance opens up in a huge hall, which leads to a 45m deep shaft that ends in a large underground dome with one of the largest stalactites in Austria. A big part of the cave is accessible for visitors, who can climb down the cave with ladders through the narrow corridors to experience the stalactite fields and even an underground lake that lies 140 m below the entrance hall.

The main challenges for surveying sessions in caves, are the accessibility with equipment (dimensions and weight of the gear), the abstinence of light (camera-based systems) and the limited freedom in the setup design due to the dimensions of the cave and safety reasons. Also, the measurement of the massive number of topological features (stalactites) requires high accuracy and high resolution from the used instruments. Although simple ruler measurements and hand-drawn maps are still best practice in conventional cave exploring, there are already good examples of the usage of laser scanner in underground scenarios like the scanning of the *Eisriesenwelt* in

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Austria (BUCHROITHNER & GAISECKER 2020), *Skocjanske* cave in Slovenia (WALTERS & HAJNA 2020) or a Messinian gypsum cave in Italy (DE WAELE et al. 2018).

In comparison to these surveys, there are some features of the survey in the Katerloch that makes this project special. First of all, the solid geodetic reference frame with millimetre accuracy on which the whole survey is based on. The coordinate system was established in 2011 by a geodetic traverse, that was executed with total station measurements throughout the whole structure. Therefore, not only the relative performance of the applied methods could be investigated, moreover the overall accuracy and systematic errors of the surveying techniques could be assessed.

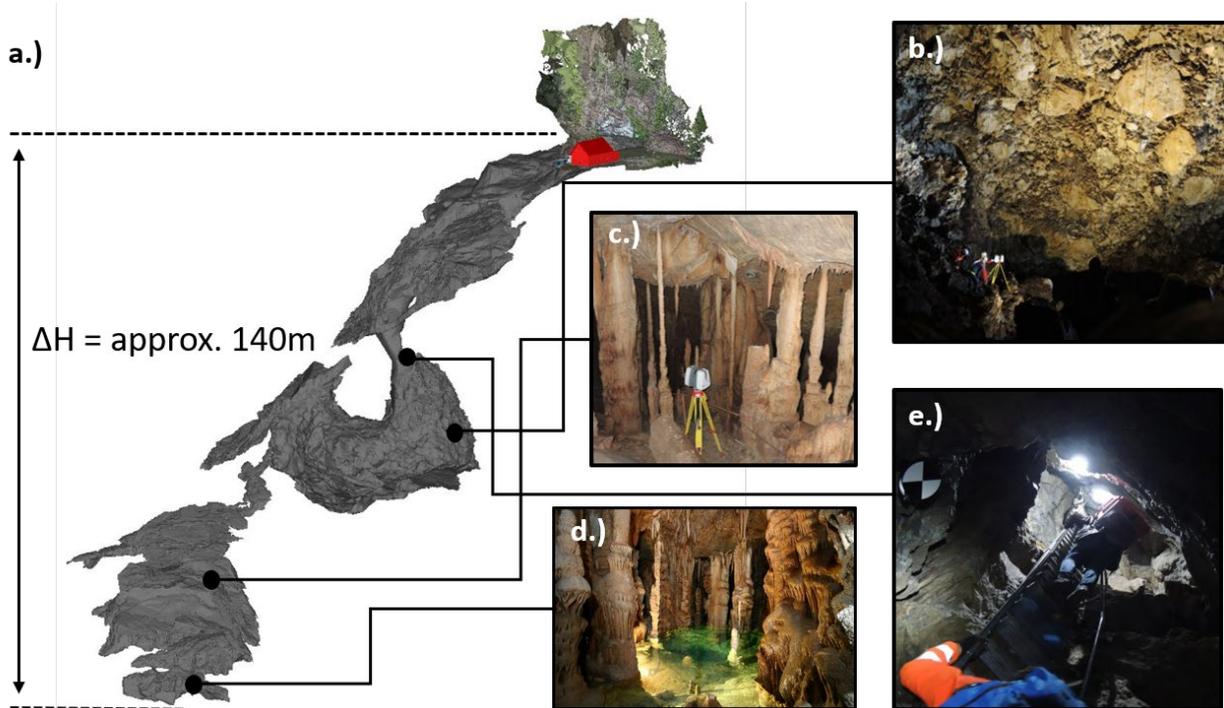


Fig. 1: a.) 3D model of the cave b.) Marteldome c.) stalactite field d.) underground lake e.) corridor with ladders

Furthermore, a big selection of different geodetic sensors has been used. Due to the huge extend of the cave and the challenges of several sections, the effort was too large for a single surveying session. Therefore, since 2016, it has been a training ground for surveying students of Graz University of Technology (TUG) and six measurement campaigns have been executed on a yearly basis. During these campaigns the equipment has been updated and adjusted to the current state of the art in laser scanning. Therefore, the data sets do not only compare different methods but also represent the advances in the technologies over the last years. With the establishment of commercial laser scanners in the late 90s (GEOFFREY 2020) it still can be counted as a relatively new technology, in comparison to tachymetry or photogrammetry. Due to vast changes in the computer industry regarding CPUs and graphic-cards the possibilities of software products for point cloud processing are rapidly increasing. Even in the short period of time since the start of the campaigns in 2016, paradigms in laser scanning have been shifted. With the upcoming of on-board registrations and the increased usage of cloud to cloud approaches in software solutions, the trend is heading towards smaller and mobile solutions like the RTC360 or the BLK series (LEICA

GEOSYSTEMS 2020). The availability of massive high-resolution point clouds has affected also the software processing behaviours of 3D data and geodetic software solutions. Here, a lot has been learned from advances in the entertainment sector regarding texturing of meshes and automatic meshing algorithms.

In order to cover a wide range of settings for the students the main objectives have been changed in every surveying campaign. Special focuses have been placed on the performance of handheld laser scanners, the absolute performance of the registration of static laser scanners in the stalactite fields or the scanning through water to capture the ground level of the underground lake. The investigation of the current state of texture quality provided by all the systems, has been a constant aim through the campaigns and a lot has been learned of what does work in this environment and which approaches have failed.

## 2 From 2D plans to 3D models and gameful design with VR

At the beginning of the 19<sup>th</sup> century (GEISLER 2023), adventurers and explorers have started to document the Katerloch with hand-drawn sketches (figure 2a) and the first 2D maps. The initial aim of the 3D survey was to update these historic maps, to accurately determine the volume of the underground domes and the capture the dimensions of the most prominent stalactites, as it can be seen in figure 2b.

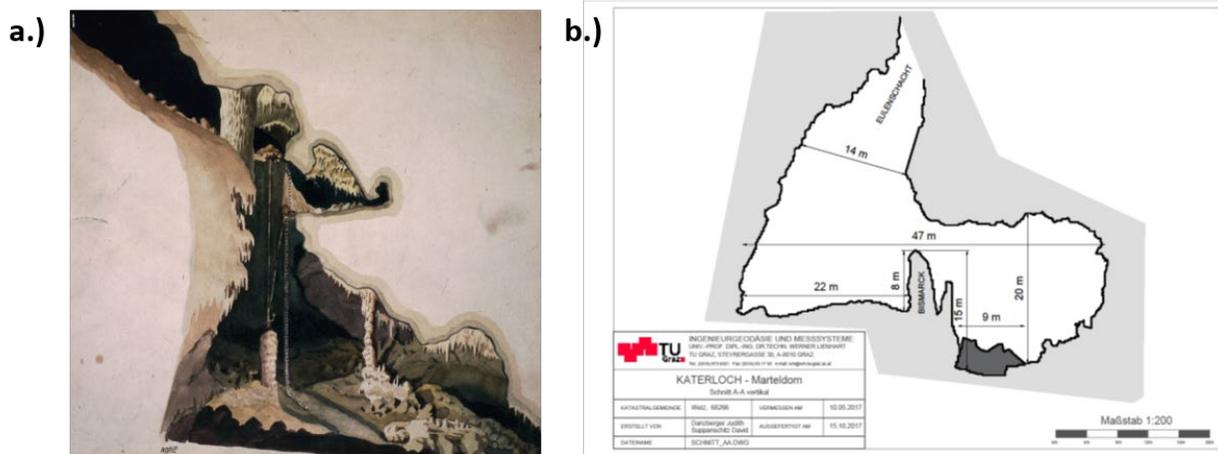


Fig: 2: a.) Sketch from Adolf Mayer 1899 (GEISLER 2023) and b.) plan of the Marteldome from TUG 2017

However, soon it became obvious that 2D plans are no suitable representation of the complex geometry of the cave anymore and that new approaches had to be found for the presentation of the 3D data to the scientific community as well as to students and school pupils.

Beside attempts of 3D printing selected cave parts and producing 3D PDFs as giveaways, the presentation of the data set with Virtual Reality gear was a very promising approach. The Virtual Reality technology originates from the entertainment sector and has been around since the early 1960s. However, the industry received a real boost only in the last decade, when advances in home computing enabled manufacturers like HTC or Oculus to produce VR headsets for the mass market (VIRUTALREALITYSOCIETY 2017). With the establishment of VR devices on the consumer market,

it became also an established tool in the scientific world for 3D data visualisation. The benefit of the technology is the ego-perspective of the user. The user can access the data set from inside and has no complexity limits in visualisation, which exceeds the capability of conventional 3D viewers. The process of integrating video game elements in a non-game context is summarized as Gamification by the definition given by DETERDING et al. (2011). This term has gained popularity in the last years and is often mentioned in the context of digitalisation and technical VR applications. However, for the beneficial adaption of software approaches for technical applications the more precise term gameful design (DETERDING 2015) is more adequate to describe the developed geodetic software presented in this paper.

### 3 Applied surveying methods

When the survey started in 2016 with the Leica P40 scanner [range noise = 0.4 mm @ 10 m, (LEICA GEOSYSTEMS 2016)] it was best practice to register each scan individually with at least four target plates with known coordinates. Therefore, scan setups have been treated like total station setups, which have been registered via free stationing in the Leica Cyclone software. This required a very dense and highly accurate reference frame throughout the whole cave. The reference frame was created in 2011 by a local surveying company and densified by TUG within the following campaigns. The registered P40 data sets from 2016 and 2017 cover the major caverns of the cave and provide a highly accurate and homogenous data set.

Although the free stationing of scanners has been mostly replaced by cloud to cloud approaches and redundant network configurations, these P40 scans are still the most reliable data foundation in the Katerloch data set.

However, the major back-draws of high accuracy scanners like the P40 scanner or other comparable devices in cave surveys, are their weight, their dimensions and their scanning time. This makes them unhandy and hard to operate in narrow passages. For the smaller corridors the BLK360 [3D point uncertainty = 4 mm @ 10 m (LEICA GEOSYSTEMS 2023a)] provided a more mobile and lightweight solution, although the measurement precision is decreased and the noise in the point cloud is increased. Small scanners are mainly designed for agile cloud to cloud matching, which improves the onsite operation, but the uncertainty in the measurement setups accumulates very fast and is prone to systematic deviations without the usage of external reference information. In order to sustain a high accuracy in the overall model the BLK360 setups have been used in combination with the P40 measurements, just to fill gaps in the existing point cloud. The BLK360 setups for each corridor has been co-registered with cloud to cloud-matching, merged together and furthermore transformed as rigid objects onto the existing P40 point clouds. The transformation parameters have been investigated and for most of the parts deviations below one centimetre have been established. This has been also verified at additional terrestrial target signs in the scene. This workflow is demonstrated in figure 3.

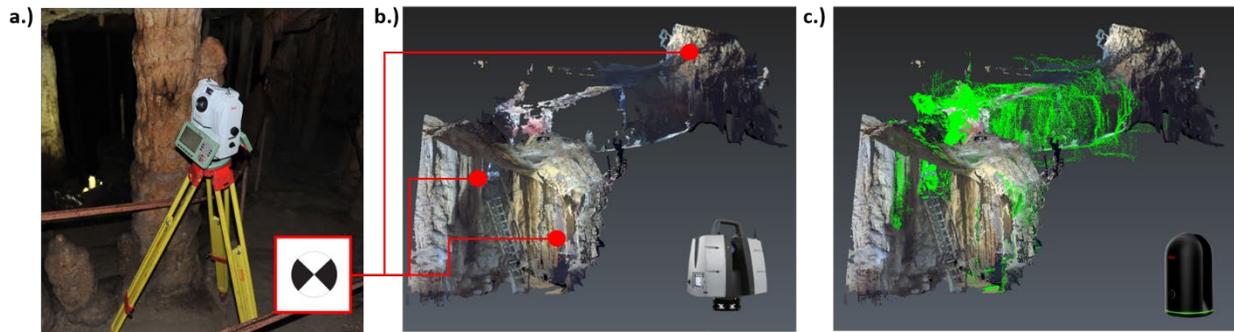


Fig. 3: a.) Leica MS60 for reference measurements, b.) registered P40 point cloud and c.) transformed BLK360 point cloud

Two vertical corridors linking the major stalactite fields are only accessible with ladders, which made also the use of the BLK360 in a tripod setup nearly impossible. These passages have been scanned with the handheld BLK2GO device [range noise = 3 mm; accuracy = 10 mm (LEICA GEOSYSTEMS 2023b)]. The registration of the BLK2GO does not support conventional target signs, because the scan resolution is not sufficient for the detection of these in any software. Therefore, the registration has been also carried out with cloud2cloud-matching of the BLK2GO data onto the existing P40 point cloud. The challenge here was the drift of the BLK2GO in the trajectory of the device, because the implemented GrandSLAM algorithm relies on camera and laser based odometry. For the observation area hardly any light sources were available, therefore the positioning algorithm could only rely on the laser-based slam algorithm and faced a loss in positioning accuracy. It was not possible to manually postprocess the trajectory of the BLK2GO and to optimize the resulting point cloud. To minimize the significant drift in the data set, the observation area has been divided into separate shorter runs. The transformation on the P40 data revealed deviations up to several centimetres for the both corridors (25m and 50m long), which was sufficient for the determination of the passages in the overall model.

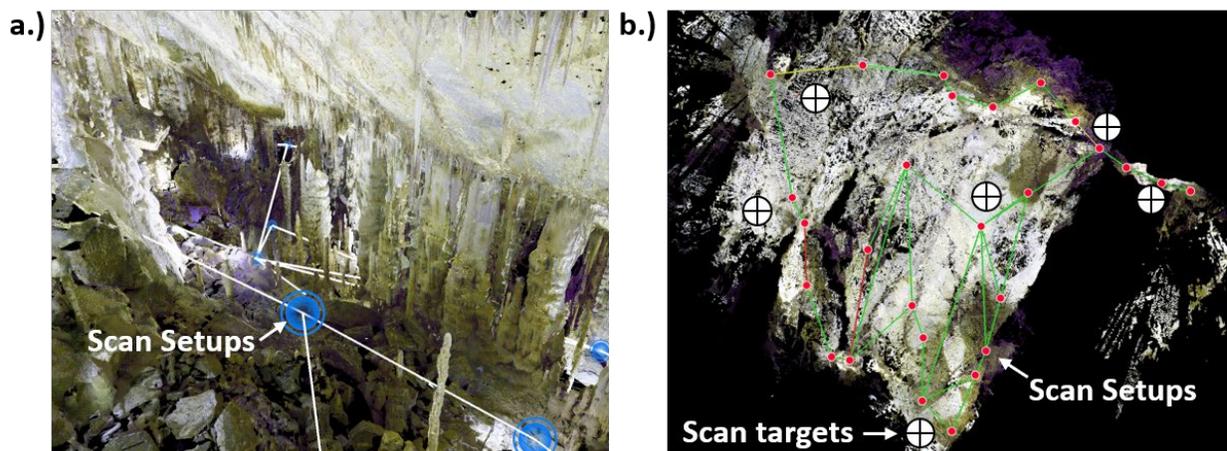


Fig. 4: a.) 3D point cloud with scan setups and b.) 2D network configuration in a stalactite field

The medium range scanner Leica RTC360 [3D point uncertainty = 1.9 mm @ 10 m (LEICA GEOSYSTEMS 2018)] provided a good balance between accuracy and mobility for the capturing of

the huge stalactite fields. The massive number of features required an increased number of setup points and due to obstructions by stalactites an obstacle free line of sight to four target plates was not possible. With the Leica Cyclone Register 360 the point clouds of the RTC360 have been registered on the bases of cc-matching in a redundant network configuration, which is optimised and geo-referenced by the coordinates of the few visible ground control points in the scene. The georeferenced point cloud has been compared to the P40 point cloud in overlapping areas and the differences of a few millimetres were not significant for the survey.

For some selected parts of the cave also structure-from-motion approaches have been tested with small DJI Mini 2 drones and SLR cameras and few ground control markers. The results have been compared to the scanner measurements. Due to the limitations of the pathways, no solid setup geometry could be established in the camera locations and also there was limited possibility for application of ground control markers for supporting the bundle adjustment to preserve the stalactites. Therefore, vast systematic deviations have been revealed in the comparison to the P40 measurement and only laser-based techniques have contributed to the geometrical documentation of the cave.

## 4 3D modelling and mesh creation

The registered point cloud for the Katerloch survey is only an intermediate result. The point cloud can serve for visualisation purposes and software products like the Leica Cloudworx plug-in can easily derive 2D plans out of it. Regarding VR applications a very common approach is a simple fly-through through the raw point cloud. This interaction method is not only of high risk of motion sickness (CHANG & KIM 2020), but also the experience depends strongly on the resolution of the point cloud because the user sees more or less only a fixed wallpaper.

More sophisticated 3D model interactions require the transformation from the raw point cloud into a triangulated mesh. Due to additional topological information of a mesh (e.g. surface normals) it supports 3D printing, complex mathematical operations like volume calculations, more stable deformation analysis with C2M or M2M (HOLST et al. 2016) and better integration into graphic software products, because point clouds are no native data type in the entertainment sector. By meshing the data set the user can move along the mesh in a VR application and interact with the cave in a more immersive manor. The user has to duck to pass narrow corridors or and has to stretch in order to look over an obstacle.

Automatic meshing operations are a basic feature of every point cloud processing software. They have been improved a lot over the last years and such functionally can also be found in open source products like CloudCompare or Meshlab. For the creation of the Katerloch mesh the commercial software 3DReshaper (and the new version: Leica Cyclone 3DR) have been used as they support every processing step, from point cloud filtering, 3D meshing up to mesh cleaning and postprocessing in a single working environment. Different modelling strategies can be found in GEIST et. al. (2018).

For the automatic meshing algorithm, the point cloud has been filtered and resampled to avoid artefacts and degenerated triangles. Blunders in the point cloud caused by visible surveying gear and inattentive crew members have been removed manually in advance. The original resolution of

the point clouds varies from a few millimetres to a few centimetres depending on the sensor type. Therefore, the whole data set has been resampled and smoothed to an average triangle size of 1-2 cm. This was a compromise between performance (size of the mesh) and level of detail. In this configuration the overall mesh resulted in a total size of 5 GB and the shape of the single stalactites was still properly represented, as it can be seen in figure 5.

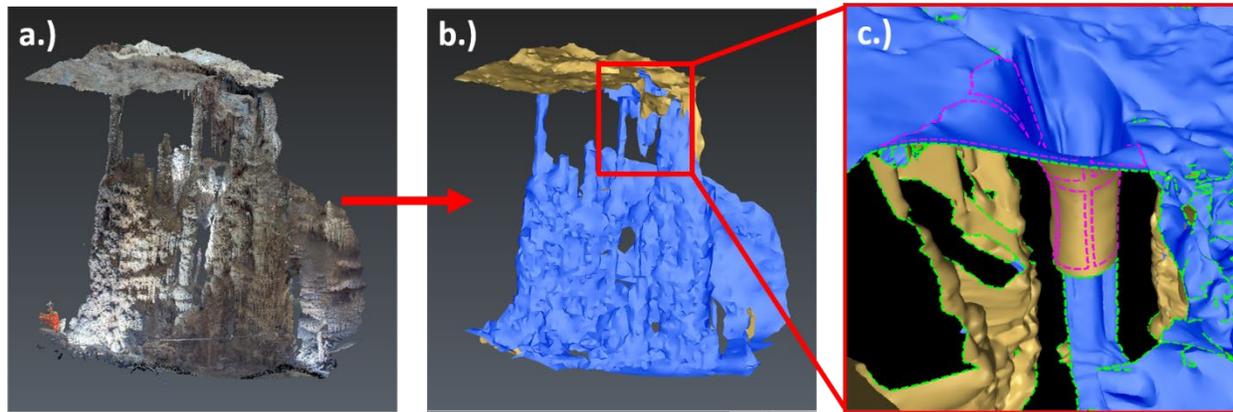


Fig. 5: a.) raw point cloud b.) automatic generated mesh c.) manual hole filling and cleaning process

Defining the triangle size significantly affects the quality of the automatic meshing algorithm, because it indirectly defines the size of holes that are automatically filled and which features are merged. Due to the massive amount of features the decision, if a hole in the mesh is a scan obstruction or separate stalactites, cannot be easily generalized for the whole data set and false classifications can never be avoided, which have to be corrected manually. Therefore, every automatic meshing approach in every state-of-the-art software product is only semi-automatic because the scan data requires a lot of manual cleaning, hole filling and reconstruction of obstructed areas. For the stalactite fields the ratio of fieldwork to postprocessing can be assumed with 1:15, meaning one day of cave scanning will result in three working weeks of mesh modelling. This takes also into account that the few geometric features with sharp edges like stairs, handrails or doors have to be separately modelled within Revit or comparable software products.

## 5 Texture and surface properties

Although the dimensions of the Katerloch would be impressive enough, it is the colourful appearance of the stalactites and the game of light and shadow in the caverns that attracts most visitors. White lime, brown clay and rusty iron ore shine together, when hit by a light source. This is such an important feature and therefore it was always an important aim of the survey to find an appropriate measurement device to document also the different surface properties of the stalactites. However, the complex light situation in the scene, consisting only of few light spots from the tourist paths and scattered torch light, was challenging for the texture quality of the scanning devices. Figure 6 shows the same location in the cave captured with three different devices under comparable circumstances. It can be seen in figure 6, the internal camera of the BLK2GO has no internal brightness correction and the resulting panorama images give the point cloud only a very dark and inappropriate texture. The internal camera of the P40 has a comparable quality, therefore

an external camera system (Istar) has been used for texturing the point cloud at the setup locations. The Istar camera delivers 360° HDR images and it can be seen that the brightness is improved a lot and single features can be easily identified and the colours in the panoramas have a good saturation.

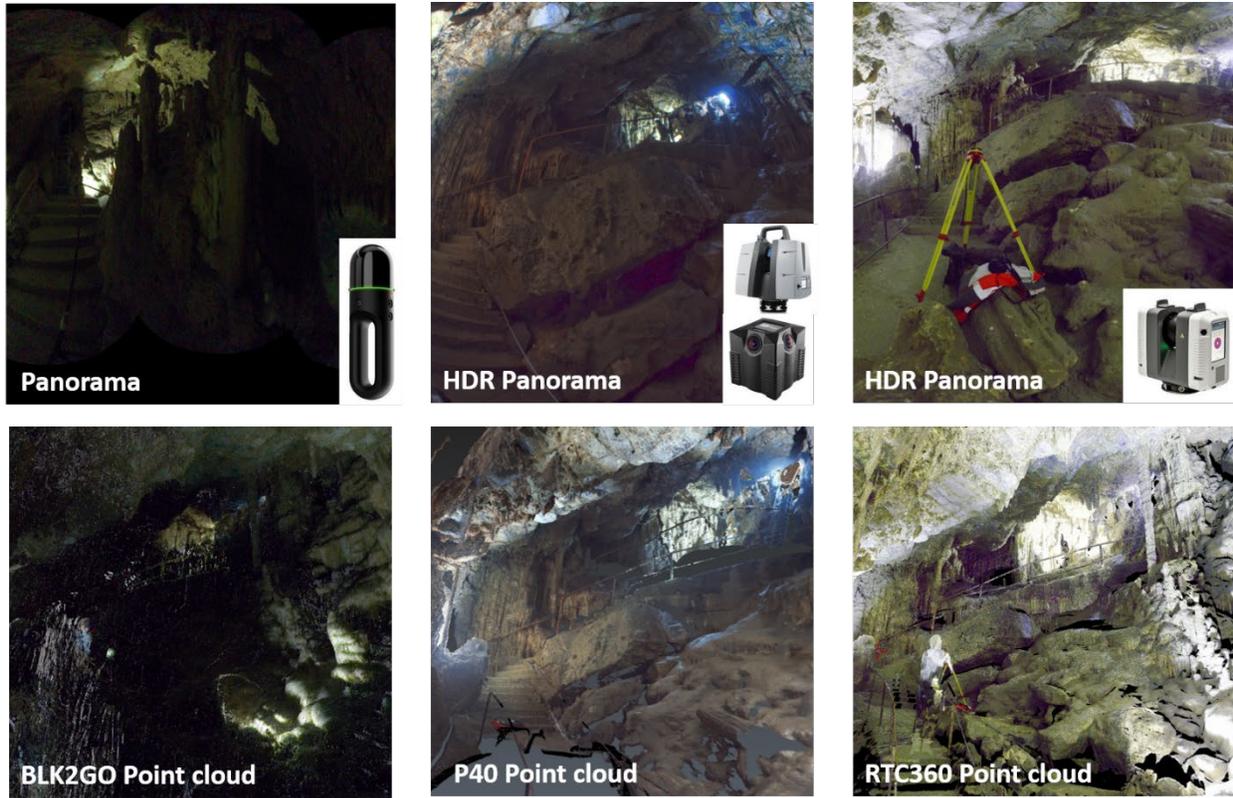


Fig. 6: Different panoramas with the P40, RTC360 and BLK2GO and the resulting textured point clouds

The RTC360 has internal HDR cameras that are automatically linked to the point cloud. The derived panorama images have only a slightly lower resolution compared to the Istar system (Istar 10000×5000 pixels and RTC: 8192×4096 pixels) but a better brightness correction, therefore single features come out better. However, the colour saturation is worse compared to the Istar system and true-colour-accuracy is lower.

Both systems delivered suitable panoramas for the texturing of the point clouds with a minimum of scattered light in the scenes. However, the brightness correction depended strongly on the setup location, therefore huge differences in the colour brightness can occur between overlapping point clouds of adjacent scans. The data quality was sufficient for the texturing of simple scenes as the plane rock surface of the entrance hall, because single panoramas cover big parts of the mesh and the image consistence in the texture is preserved. Whereas the resulting texture of the stalactite fields with the RTC was unsatisfying, due to the resolution of the scans and the inconsistent visibility and brightness of the panoramas caused by the complex scene and the obstructions by the stalactites.

In section 4 it was already mentioned that the structure-from-motion approach failed for the geometric reconstruction due to accuracy reasons. However, the quality of the RTC panoramas

was sufficient enough to enable a combined processing approach for the external SLR images and RTC360 point clouds with the panoramas. The software RealityCapturer was used to combine these two data sources with feature matching of the high resolution SLR images and the HDR panoramas (figure 7a). This way images from the scanner with known position (from the registration process of the scanner) have been introduced into the bundle adjustment as a constraint. Therefore, the camera locations of the SLR images have been forced onto the high accurate RTC point cloud, which enabled the texturing of the RTC360 mesh with the SLR images, as seen in figure 7b.

This procedure was tested only at selected sites of the cave yet. Capturing larger parts of the cave with SLR images and DJI drones for a combined processing with the RTC360 will be the aim of further surveying campaigns in the next years.

## 6 Virtual Reality application

Commercial VR viewers of point cloud data are provided by several laser scanner manufactures. Faro provides VR functionality within Faro Scene and Leica has updated its Cyclone VR viewer into the TrueView VR viewer. However, these products offer only basic fly throughs through point cloud data.

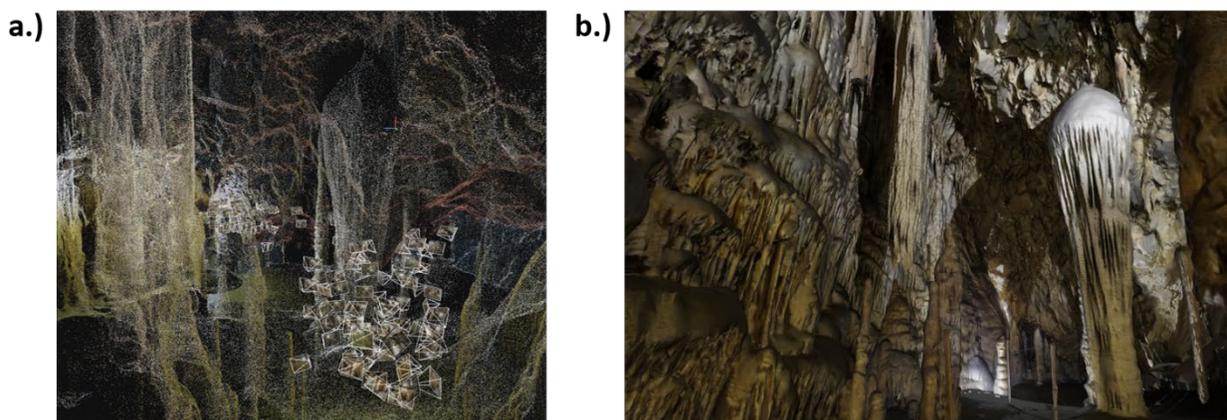


Fig. 6: a.) Screenshot from Reality Capturer with camera locations and b.) mesh with photorealistic texture of the Denkmalstein

To implement more sophisticated data interaction and visualisation options like adjusting of lighting, more immersive navigation and also basic story telling features, a custom VR application has to be made up for such occasions. Appropriate development environments are provided by game engines. These software kits were originally designed for the creation of videogames but provide a state-of-the-art 3D-object-oriented environment for numerical simulation and data interaction. Basic physic engines and light engines support the creation of realistic simulations. Due to their close relation to the video game market the implementation of VR devices into the application can be established with open source plug-ins.

Several game engines can be found on the market like Unity, Unreal or the cry engine. Although the Unreal engine supports point clouds and has advantages in photorealistic texturing the

application for the Katerloch was made up in Unity. Here, the creator can build the application from custom C# routines like in any other coding environment, which gives the environment a huge degree of freedom and a big support of the community. As an exchange format between geodetic software and Unity and other graphic software the obj-format for 3D objects has been found suitable. It is the most basic mesh format, which is human readable, has a great interoperability with software from the entertainment sector and contains also texture information as a jpg-file. It can be loaded easily into Unity. Mesh colliders can be attached and the user can physically interact with the environment in VR.

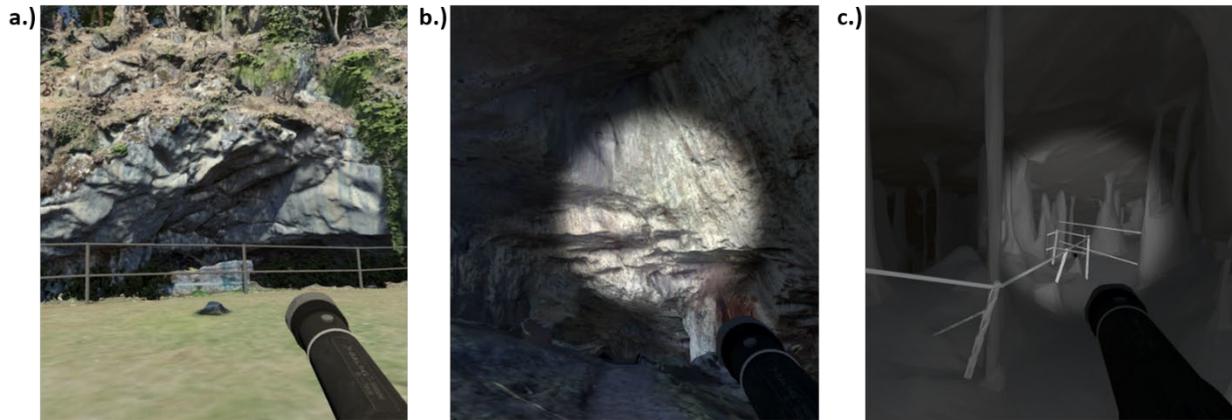


Fig. 7: a.) High resolution texture b.) Low resolution texture with virtual torch light c.) untextured part in the VR application

Based on the investigations of DANYLUK & WILLET (2019), to give the user a realistic cave experience in the application it was the aim to provide the possibility to move along the 3D model to explore and investigate every detail of the dataset. The HTC Vive Pro has an outside-in tracking system and provides all six degrees of freedom for user movement with an accuracy of several millimetres (BAUER et al. 2021). Therefore, the actual user movement is applied in 1:1 scale on the virtual counterpart and it is necessary to duck in narrow passages to get through. Furthermore, two handheld controllers with touchpads are used to interact with data sets and to apply user movement beyond the capabilities of the HTC Vive Pro tracking system.

Early versions of the simulation, especially by younger audience, were not received so well due to the missing of the texture, because the main focus was placed on presenting the mesh quality and dimensions of the cave. Different user groups have confirmed that introducing also parts with poor texture in the simulation is even better than homogeneously sparing out the texture at the entire mesh. Therefore, the different texture qualities have become an integral part of the story telling of the final VR application. The user starts at a highly textured and nearly photorealistic entrance area (derived from DJI drone imagery) to familiarize with the virtual environment and the controls, as seen in figure 8a. As the users progresses on the tourist path down the cave, there is a slow transition to lower resolution textures from the Istar camera or the RTC360 panoramas. For smoothing this transition, the lighting in the scene gets darker and the user has to rely more and more on a virtual torch (figure 8b). This ends up in nearly complete darkness (except the light spot from the torch) when the user reaches the untextured BLK meshes in the heart of the cave in figure

8c. This does not only cover up the variations in the quality, but also supports the feeling of venturing down the deep cave.

Along the user path additional information is provided as images and information panels, so the user can learn about the background of the Katerloch and the geodetic survey, as seen in figure 9a. 3D models of the used laser scanner are also placed in the scene to represent the scanner setup locations and to teach students about the optimal scanner placement and provide an immersive best practice example (figure 9b).

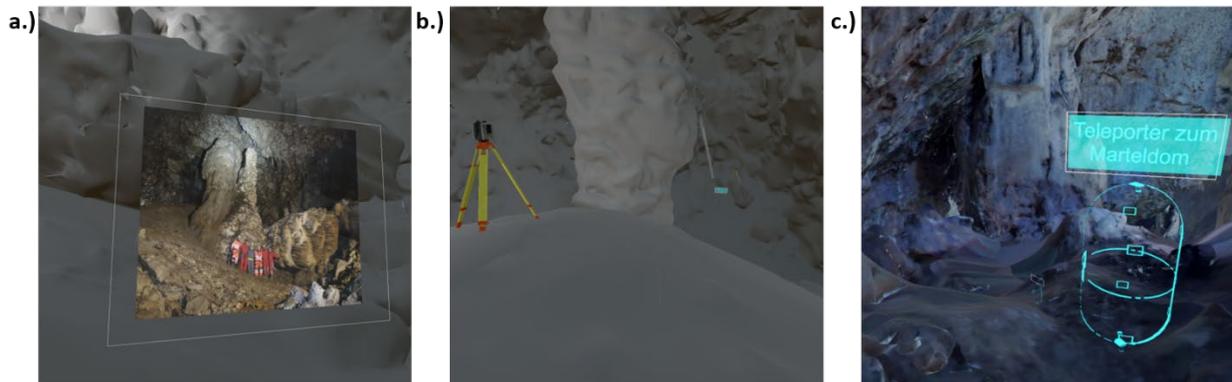


Fig. 8: a.) canvas with image b.) setup location of the RTC360 c.) teleporter for loading new scenes

Due to the mesh resolution and the amount of presented data, not all information can be loaded at once. In the real cave the visitor has to make use of ladders several times on the path. Not only is this hard to represent in VR applications, but also do these passages provide natural breakpoints in the visitor path. Therefore, the data set is separated in three levels, which are loaded sequentially and the user can change the scenes by accessing virtual teleporters, as seen in figure 9c.

## 7 Summary

Fast and mobile scanners solutions provide today the possibility of gathering a massive amount of data in a very short period of time. However, this often happens without an external reference only based on slam technology or cloud to cloud matching. This is prone for vast systematic deviations that cannot be revealed with relative quality inspection approaches. The campaigns in the Katerloch have demonstrated that several high-resolution scans with accurate registration through total station measurements provide a solid data foundation for more mobile solutions to capture challenging areas. Not only can these scans be co-registered into a global coordinate system, but the quality can be assessed by the investigation of the transformation parameters.

The meshing algorithms of point cloud data are making huge progresses, due to advances in the entertainment sector, who are also starting the use 3D surveying data for their movie set designs or for virtual worlds in video games. The geodetic software 3DReshaper provides here a straight forward automatic meshing approach, that relies strictly on the given data set. Therefore, the resulting mesh needs a lot of manual clean up to fill holes and merging parts. On the other hand, software solutions like RealityCaptor from Epic are able to produce a watertight mesh without much need of postprocessing. Within these software solutions, the algorithm takes many decisions

and automatically masks out lamps and other smaller objects. Although the resulting photorealistic mesh is good for presentations the detailed documentation of the scene is questionable up to a degree. This can be especially problematic when using such intelligent meshing approaches for sensitive documentations of crime scenes, because the resulting mesh is highly affected by many hypotheses.

The implementation of VR technology was a valid attempt for presenting complex 3D data to a diverse audience. The ego perspective of VR technologies takes over when conventional viewers reach their limits with overlapping geometries and multi temporal datasets. Nevertheless, the uncomfortable long-term use is still an issue with state-of-the-art devices. The VR application of the Katerloch is today a basic tool at public events to promote 3D scanning and the field of geodesy.

With the advances in software and hardware, especially in the combination of SLR images and scans is much potential for the creation of a photorealistic model of the entire cave, which will be the aim of future measurement campaigns.

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