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Edited by

Michal Filippi
Pavel Bosák

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Cover photos (some photos were adjusted/cropped)
Top left – A gallery along the "Rio de los Venezuelanos" in the Imawarì Yeuta Cave system in quartz sandstones, Auyan Tepui, Venezuela. Photo V. Crobu. For details see the paper by Sauro et al.
Top right – The 15th siphon of Ramo Nord in the Grotta del Bue Marino, Sardinia. Photo by R. Husák. For details see the paper by D. Hutňan.
Bottom left – Using an Xbox Kinect equipment to survey a cave. Photo by J. Gulley. For details see the paper by Covington et al.
Bottom right – Inclined workings of the Voskresenskyi Mine, Ural Mountains, Russia. Photo by A. Gunko. For details see the paper by A. Gunko.

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NEW ACQUISITION, 3D MODELLING, AND DATA USE METHODS: THE LASER SCANNING SURVEY OF RE TIBERIO CAVE

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Precise surveying in underground contexts with traditional systems is a challenge due to the complexity of natural forms, the extent of the caves, and the work conditions. Laser scanning is a solution that can be applied to many cave surveys to get a complete high-precision three-dimensional database, from which the end user can select the information on the basis of his technical and operational, or research objectives. Laser scanning is a multidisciplinary tool for knowledge and information management concerning the cave.

This paper illustrates the three-dimensional laser scanning survey, data processing, and representation of the so-called “Gothic Hall” of Re Tiberio Cave (Riolo Terme, Italy), carried out by Virtualgeo in September 2010. The three-dimensional digital model, which was obtained from processing the acquired laser data, allowed us to define in detail the shape of the surveyed object, which was represented in a series of graphic representations. Another advantage of laser scanning technology is the possibility to use the acquired data (and, in particular, the 3D model) for educational and dissemination purposes, with the same standards of precision and scientific rigor.

1. Introduction

The Re Tiberio karst system is located in Mount Tondo, in the right bank of the river Senio. The karst system, which is developed in the Messinian gypsum, is certainly the most important and most studied karst phenomenon of the Vena del Gesso Romagnola, at least in relation to some of its particular aspects (De Waele et al. 2011; Lucci and Rossi 2011). It’s the second longest epigenetic gypsum cave in Italy and among the top five in Europe for development and complexity (more than 6,000 m long with a depth of nearly 200 m). Today the Re Tiberio karst system is in the territory of Riolo Terme (Ravenna, Italy), is part of the Vena del Gesso Romagnola Regional Park (established in 2005), and was designated as a Site of Community Importance and Special Protection Area (code IT4070011). Nevertheless it continues to be partly demolished by a large, still active, gypsum quarry.

From the speleogenetic point of view, the morphologies present in the cave are basically due to joints and tectonic discontinuities (faults and diaclases). The former had a key role in the genesis of large galleries, which formed along them. The latter favoured gravitational morphologies such as pits and canyons, since such disjunctive lines were the preferential centers of the movement of groundwater that, gradually lowering, reached their current base level.

The general direction of the Re Tiberio Cave is NW-SE although there are many maze bodies and some galleries with SW-NW direction. The cave mostly develops horizontally, with five levels of superposed galleries connected by small vertical pits. However, many parts of the cave were partially destroyed by the quarry, thus their sedimentological and morphological characteristics are difficult to read.

From the hydrogeological point of view, the karst area of Mount Tondo remained totally unknown for a long time; only recently were targeted studies carried out (Ercolani et al. 2003). Today it’s a known fact that the area of Mount Tondo is divided into two distinct karst systems:

a) In the first one, the waters of the Abisso Mezzano reach the Re Tiberio Cave, as well as the waters from the Abisso dei Tre Anelli, Abisso Cinquanta and Inghiottitoio del Re Tiberio. Some of these underground rivers were intercepted by the quarry galleries.The spring of the system is just on the quarry plain, a few meters above the Senio riverbed.

b) The second karst system starts from the Buca Romagna and reaches the spring located N-W of Ca’ Boschetti, crossing the Grotta Grande dei Crivellari and the two caves of Ca’ Boschetti. Moreover, a tributary from the Enrica Cave directly flows into the main catchment of the Grande Grotta dei Crivellari.

Actively frequented from the Copper Age (probably as a burial area) until the 15th century (when it possibly was a clandestine mint), the cavity is famous for the archaeological finds, so that it has been the object of scientific excavations since the mid-nineteenth century (Pacciarelli 1996).

Finally the most recent speleological explorations discovered archaeological remains in other cavities of the Vena del Gesso, thus proving that the area of archaeological interest is much wider than the entrance of Re Tiberio Cave (Forti et al. 1997; Ercolani et al. 2003).

The three-dimensional laser scanning survey of caves and rocky habitats is widely discussed in the specialist literature. As in the case of the Re Tiberio, the caves often incorporate a set of values. They aren’t “only” unique geological archives, natural beauties and geological rarities, but they also have historical, archaeological, artistic, and ethno-anthropological value. Therefore, it’s necessary to apply a method that meets different needs:a method that, with a multidisciplinary approach, provides the key tool for exhaustive knowledge and complete management of all the information regarding the cave.

Concerning geology and engineering geology, the literature produced in recent years proves the potential of laser scanning techniques for geomorphic studies, for monitoring, and supervising (quantitative control) both in managing natural events (for routine and/or exceptional ones), and managing activities of territory "transformation" (geo-resource exploitation, infrastructure works, etc.) (Alba et al. 2005, 2009; Clerici et al. 2005, Francioni et al. 2010; Riccucci et al. 2010).

Interesting applications of laser scanning involve cases where geology and cultural values merge, such as in mines (Hanke et al. 2009; Tucci et al. 2009b).

Over the years, the use of laser scanning as a valid tool to survey hypogean contexts has increased (Beraldin et al. 2006; Baiocchi et al. 2011), particularly for works related to archeology and paleontology (Caprioli et al. 2003; Fryer et al. 2005; Chandelier and Roche, 2009; González-Aguilera et al. 2009; Pucci and Marambio, 2009; Tucci et al. 2009a).

The key tool is the three-dimensional qualitative high-precision database delivered by laser scanner. The laser scanning database integrates existing speleological surveys carried out with traditional topographic instruments. Moreover, it becomes a platform for merging and categorizing the data and documents from in-place sampling, analysis, and specialist research. That allows productive sharing between scholars, professionals, institutions, etc. fostering interdisciplinary exchanges. Such sharing can be extended to public enjoyment, without risks for safety of tourists and of the cave itself, especially for closed or not easily accessible sites.

2. Laser Scanning Survey in Caves

The survey of one of the most significant (from the archaeological point of view) natural caves of the Vena del Gesso Romagnola is the last of a series of important cave surveys (with three-dimensional digital data processing) performed by Virtualgeo in Italy and abroad. The company provides 3D laser scanning and reverse modelling services, and develops dedicated software technologies and work processes (Canevese et al. 2008, 2009, 2011).

Precision surveying in caves with traditional methods (total station or unsophisticated instruments used in underground topograpy) is a challenge due to the natural shape irregularity and complexity, cave extension, and (not negligible) work conditions. Laser scanning can be an alternative resource to apply to many cave surveys in order to obtain complete quantitative and qualitative high-precision databases.

Laser scanning survey instruments combine the functions of a distance measuring device and a theodolite, which measure respectively distances, and horizontal and vertical angles. Laser scanners systematically acquire x, y, z spatial coordinates of surveyed surfaces, as high density "point clouds", by analyzing the inbound signal of the emitted laser pulse. In addition to spatial coordinates, for each point the laser scanner acquires the intensity of the pulse reflected back, according to the material characteristics of the surfaces. Moreover, it allows linking of each surveyed point with a RGB colour value, thanks to an associated camera.

Terrestrial laser scanners available on the market have different functioning principles, inbound signal reception, processing systems (time-of-flight, phase shift, triangulation), range (maximum ranges vary from a few dozen centimetres up to some thousand meters), accuracy and precision. The choice of laser scanner has to be evaluated on the basis of the peculiarities of the object/area to be surveyed, and of its technical specifications: accuracy, field of view, range, measurement speed, wavelength of the pulse, material reflectivity, environmental factors (e.g., sunlight, humidity), portable format (weight, dimensions, toughness), power supply, user interface, data storage and transfer, peak operating temperature and humidity levels.

The fast rate measurement, amount and quality of acquired data (point clouds), non-contact with the surveyed surfaces, and adaptability of use allow laser scanning to perform precision surveys also for morphological complexity and large surfaces, keeping the work continuity in place. Moreover, thanks to process rapidity and automation, it assures high survey productivity even in difficult or dangerous working conditions (as it allows remote work in safe conditions), even with a single technician.

Laser scanning survey is independent of topographer's discretion and lets the various users (scientific, institutional, etc.) read and select the significant and useful data of the point clouds and/or 3D model obtained from point clouds, even after some time or while comparing scans acquired in separate time periods.

Once aligned in a single Cartesian coordinate system through known reference points by appropriate software, the point clouds reconstruct the three-dimensional shape of the surveyed object or area. The final result of the scans post-processing is a global point cloud, which is a metrically accurate three-dimensional point model of the surveyed object containing also chromatic information. The latter information, which can be grey scale reflectance data or RGB values, visually helps the final users to interpret the surveyed object and extract geometrical data from the point model.

Among their most important works in the underground, in the years 2006–08 Virtualgeo surveyed with laser scanner and 3D modeled: the Grave in the karst complex of Castellana, the mine caves of Naica, and the Santa Barbara karst system in Sardinia.

In the caves of Castellana, hosted in the Altamura limestone, Virtualgeo carried out the laser scanning survey of the Grave: the widest and most complex shaft of Apulia region (100 m long, more than 40 m wide, and about 60 m high), and among the most important of southern Italy (Canevese et al. 2009).

As a part of the multidisciplinary project, in Mexico the laser scanning work related to the survey of the Cueva de las Espadas and Cueva de los Cristales. They are extraordinary cavities, developed in the Albian age carbonate formations of the Sierra de Naica, hosting gigantic gypsum crystals (in Cueva de los Cristales they reach up to 12 m in length, and almost 2 m in diameter) (Canevese et al. 2008, 2009).

In Sardinia, near Iglesias, a part of the mine caves of Santa Barbara was surveyed. This system consists of two large subvertical cavities that are considered among the oldest limestone caves of the world. Moreover, the upper cavity (Santa Barbara 1) is one of the most famous mine caves worldwide for the beautiful euhedral baryte crystals covering its walls (Canevese et al. 2009, 2011).

In all those cases, the use of laser scanner allowed the fast acquisition of a large amount of data, required to describe the complexity of the cavities. It also allowed overcoming specific problems, such as the extreme climate in Naica (temperature of 48 °C and humidity around 100 % in the Cueva del los Cristales), and prevented interference with the flow of tourists in Castellana and Iglesias.

Figure 1. Survey with total station for the cartographic setting of the Re Tiberio cave (left), and laser scanning test with FARO LS PHOTON 20-120 model (right). The survey was carried out with laser scanner Leica HDS6100 (Table 1).

3. 3D Laser Scanning of the Re Tiberio Cave

In September 2010, the three-dimensional laser scanning survey was performed on the first 60 m of Re Tiberio Cave (from the cave entrance to the Gothic Hall, a circular hall with a diameter of about 15 m, and an ogive vault) (Figure 1). This includes the small portion of the Re Tiberio Cave (total length over 4 km) that everybody can easily walk along.

This paper focuses on the survey, data processing, and 3D modelling of the Gothic Hall, and of a portion of gallery giving access to it.

The purpose of the survey work was to accurately document the shape of the cavity, with a system that allows surveying and georeferencing the position and development of all significant morphological elements (including discontinuities, fractures, etc.), with the possibility to produce, in a flexible way, graphic representations to complement the existing maps.

A phase shift technology-based laser scanner, measuring the distance of an object by “comparing” the pulses of different wavelengths reflected back, was used to survey. It has a medium measurement range (suitable for limited distances), an almost spherical field of view (particularly suitable to survey inside closed spaces such as caves and galleries), and a high points-per-second measurement speed. Moreover, in comparison with other models, this laser scanner has a rather compact size and lower weight, and thus is more functional to carry and handle inside a cave (Table 1).

Table 1. Technical specifications of the Leica HDS6100 laser scanner used to survey the Gothic Hall in Re Tiberio Cave.

Range	up to 79 m
Measurement rate	up to 508,000 points/second
Accuracy	±1 mm at 25 m, ±2 mm at 50 m
Horizontal/vertical field of view	360/310°
Weight	14 kg
Dimensions	294 × 199 × 360 mm (W × L × H)
Operating conditions	from -10 °C to +45 °C, non-condensing, fully operational between bright sunlight and complete darkness
Camera model	Canon EOS 450 D – 12 MPixel

Before the laser scanner survey, an acquisition plan was prepared to locate the best positions (according to the development of the cave and the possibility to easily manage people and instrument mobility) for the scanner stations in order to reduce “shadows” in the scans, and to define the most appropriate scanning angles to obtain scans with a uniform resolution (by setting the average distance between scanner stations and surfaces to acquire, as well as the scanning point grid density) and a good overlapping area.

Before starting the cave laser scanning, 38 reference targets were placed (at significant visible points) and surveyed with total station to georeference and align the point clouds obtained from the various scans. The topographic works were executed to establish one open traverse (with 5 control points) to survey the reference targets, while 6 existing data points and a set of outside significant points were surveyed to establish the cartographic setting of the cave.

In about 8 working hours 2 technicians established the traverse, surveyed the targets and data points, and finally scanned the Re Tiberio Cave. The amount of acquired data is summarized in Table 2.

Table 2. Total data acquired by laser scanning and camera in Re Tiberio Cave and, in the right-hand column, the detail of data regarding the Gothic Hall.

	Re Tiberio Cave (total)	**Gothic Hall**
Acquired scans	14	6
Points	about 630,000,000	about 270,000,000
2D images	84	36
Laser data amount	7 GB	3.5 GB
2D images amount	378 MB	165 MB

The post-processing and representation of the data followed the laser scanning acquisition. These stages are crucial to optimize laser scanner characteristics; therefore the support of dedicated software is essential for the suitability of the acquired information, and for the production of an effective three-dimensional model that can satisfy the multidisciplinary purposes of the survey, and also unknown potential future objectives.

The post-processing of the acquired data started with alignment (to obtain a global point cloud from the various scans), cleaning, and filtering of the point clouds to remove "noise" and non-significant points with Leica Geosystems dedicated software.

The point cloud is a point model of the cave surface that documents exact dimensions, morphology, and, in particular, all the irregularities of the walls. Such information is by far better, in quantity and reliability, than the data obtained from traditional topographic surveys or on-site inspections. Point clouds allow visualization of the cave morphology (colours or grey scale make this reading phase easier), and extraction of dimensional data (linear and angular, slopes) (Figure 2).

Figure 2. Sectioned point model of the Gothic Hall: view from the south.

The three-dimensional modelling of point clouds to obtain a continuous surface 3D model was carried out with CloudCUBE, software on AutoCAD platform developed by Virtualgeo. The millions of points acquired were treated and arranged to produce a "smart" three-dimensional model of the cave: metrically exact (it sums the accuracy and precision of the laser scanner survey, topographical works and alignment of point clouds), corresponding to the surveyed morphometry, segmented, and innovative regarding the immediate and potential uses of the survey.

The cave was modelled with the most suitable among the techniques (2.5D and 3D triangular grid meshes, quadrangular "surfaces", "region" entities) for modelling its dimensions and complex uneven morphologies. The construction of 3D triangular meshes was carried out directly on point clouds by an automatic technique. In the process of point joining (triangulation) the 2.5D triangular mesh takes into account only the x, y coordinates (therefore, it's more suitable to model planar surfaces), while the 3D mesh considers all three x, y, z coordinates; thus it's more suitable to model complex three-dimensional surfaces.

The digital model of the Gothic Hall and entrance gallery, obtained by processing the point clouds, is a complete high precision three-dimensional database that allowed a detailed geometric definition. A series of graphic representations (plan with contour lines and elevation levels, significant sections with applied orthophotomaps) was elaborated from the model (Figure 3). They provided a clear graphic description of the cave (an example of the graphic representations is in Figure 4).

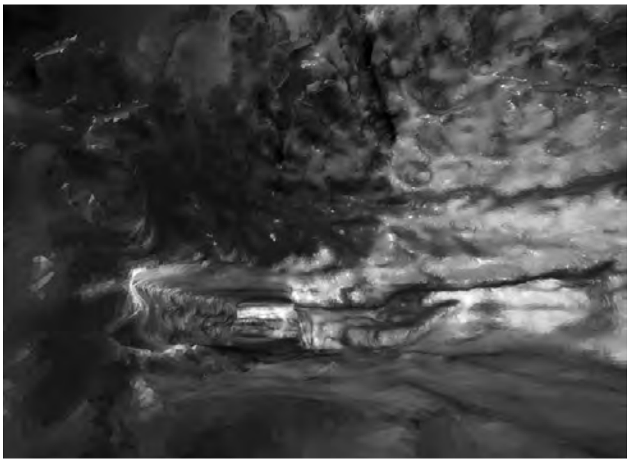

Figure 3. 3D model of the Gothic Hall: inside view from the west. On the lower side of the figure the 3D triangular grid mesh, obtained by triangulating the point cloud, is visible.

Anyway, it must be stressed that from the three-dimensional model it's possible to obtain unlimited representations of any type, with any scale, and plot plans at any elevation level and vertical sections along any section plan, without additional surveys on-site to acquire new data. That case would increase the costs and work time and, as in the case of Re Tiberio Cave, could conflict with access restrictions due to safety reasons.

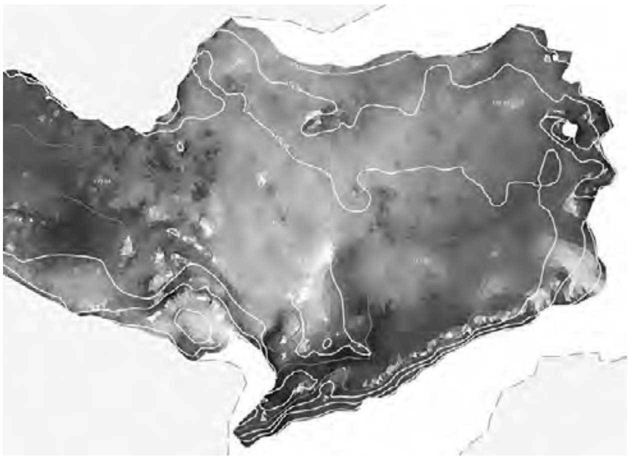

Figure 4. Plan with elevation levels and contour lines of the Gothic Hall.

Moreover, the model of Re Tiberio Cave can be "segmented", i.e. divided into parts associated with different layers (visually identified by different colors) according to specialized requirements and customized standards, e.g., geological units.

The segmented model is a particularly effective analytic tool (even for non-experts), thanks to the colors that makes the interpretation easier. It can be directly interrogated about dimension and information data.

The digital model, segmented or not, allows extracting any type of dimensional information (linear and angular, slopes) and computing contour lines, areas, and volumes. Moreover, it's possible to study and measure evolving phenomena (e.g., rock detachments, displacement, etc.) by "superimposing" digital models obtained in different monitoring surveys.

4. Conclusions

The speleological topographic survey and digital three-dimensional modelling systems presented here provide an accurate database that allows significant qualitative analyses and reliable computations for the morphological study of the current status, the analysis of rock mechanics and rock face stability, etc.

The possibility to use the survey data, and above all the 3D model, for multidisciplinary research in caves (without time and space restrictions) is a particularly interesting prospect.

The digital model and graphic representations can be used not only to study the current situation of the subject of interest, but also to verify a study hypotheses. For instance, in the geological field to retrospectively analyze collapses, or in a historical study to integrate the archaeological excavations carried out in the past, and materials exhibited in museums, etc.

Furthermore, the data acquired by laser scanning and, in particular, the 3D model can be used not only for technical-operative or research purposes, but even for educational and public dissemination purposes. In fact, from the acquired data (point clouds and pictures) and three-dimensional model it’s possible to obtain “products” for scientific dissemination (e.g., regarding geology and archaeology for Re Tiberio Cave), or accessing the cave virtually, such as traditional and 3D pictures and videos, 360° panoramic images, point cloud animations, 3D models to explore, scale models, etc.

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