Non contact shape and dimension measurements by LIDAR techniques of one of the biggest Italian caverns

F Radicioni¹, G Rossi¹², G Tosi¹ and R Marsili¹

¹ Department of Engineering - University of Perugia, Via G. Duranti, 06125 Perugia (Italy)
² Corresponding author

E-mail: gianluca.rossi@unipg.it

Abstract. Many measurements techniques have been proposed and used for the "digitalization of things": laser scanner, high resolution camera, depth cam, structured light 3D scanner, hyper-spectral sensor, multi-spectral cam, photo modelling, etc. In this work LIDAR measurement techniques has been applied for the digitalization of a cave room of about 180 x 120 m and a height recently discovered up to 250 m, named Abisso Ancona in the Frasassi caves, in the municipality of Genga, Ancona province, Italy.

1. History of Frasassi caves

The Frasassi caves are underground karst caves located in the municipality of Genga, Ancona province. In this area, the first underground explorations with modern techniques started in 1948 and the most important discovery dates back to 1971, the one of the Grotta Grande del Vento where the object of study of this work, the Abisso Ancona, is located.

The Grotta Grande del Vento, opened to the public through an artificial tunnel, is one of the most important hypogeous tourist centres and one of the most visited in Italy, counting about 250,000 visitors per year.

The complex is composed by a series of cavities, the oldest dated back to one million and four hundred thousand years ago, characterized by the presence of large and imposing gypsum deposits formed by the cooling of the sulphurous water by Sentino torrent. In the various rooms there are concretions of different form and sizes (stalactites, stalagmites, crystallized ponds) created thanks to the work done by the water.

The first cave of the karst complex to be discovered and the first that can be seen from the artificial entrance is the Abyss Ancona, a huge cave, one of the biggest in Europe and in the world, which has an extension of 180 x 120 m and a height, with new parts recently discovered in 2018, up to 250 m.

At the bottom of the cave there is a block of rocks, the result of destructive movements and collapses that occurred over millennia and that gave rise to the Ancona Abyss.

In this room there are crystallized ponds, flows of pure calcite of remarkable size and at the centre a majestic group of millenary stalagmites called "I giganti", whose diameter (2 mt - 5 mt) and height (1.50 mt - 20 mt), makes them part of the most important and ancient stalagmites of the cave.
2. Caves survey

More and more frequently in recent years, the laser scanning technique is catching on for high-resolution 3D models reconstruction of complex objects, in particular in cultural and environmental heritage field [1-2] [18-21]. This technique allows to acquire millions of points of the scanned object in a short time, creating an extremely realistic and detailed complete model and obtaining many different information regarding the detected object.

Some application of shape measurements techniques and comparison in order to get information on possible uncertainty levels has been performed recently by some of the authors of this work in artistic and nautical field also [3-4,16]

Terrestrial Laser Scanning techniques are increasingly used in underground geomorphological studies such as caves, where just a few years ago it was difficult to apply them due to the high cost of laser scanners and their characteristics (size, weight, fragility) that make difficult to transport them in rough spaces, and in particular for the complex geometry of cave structures, which requires an accurate scanning plan to obtain satisfying results.

The development of less expensive, more robust, lighter and easily transportable laser scanners now makes it possible to apply this technique to spaces that are difficult to access. Here are some examples of laser scanner applications for hypogeeum cavity survey.

In [5,15] the three-dimensional laser scanning of the so-called “Gothic Hall” of Re Tiberio Cave (Riolo Terme, Italy) has been performed by Virtualgeo in September 2010.

The three-dimensional digital model, which was obtained from processing the acquired laser data, allowed to define in detail the shape of the surveyed object, which was represented in a series of graphic representations. the 3D model was used also for educational and dissemination purposes.

In [6,14] the laser scanning of a natural cave, the Grotta gigante cave near Trieste in Italy is described. The 3D model obtained has been presented in many international conferences between 2011 and 2013. The model has been obtained using 3 laser scanning system in 10 days of work, 70 measurement stations giving 4.5 billion of measurement points with a density of 1000 p.ts/m2 and an accuracy of 5 mm.

In [7,13] a laser scanning survey was carried out in San Giovanni mine near Iglesias (Sardinia, Italy) particularly in Santa Barbara and Santa Barbara 2 natural caves. The model was obtained using two laser scanning system, 46 Scans, 8 billion of measurement points in 8 days of work of 4 technicians.

In [8] Virtualgeo company has surveyed many caves in September 2006 in Castellana Grotte (province of Bari, Italy), in May 2007 in Naica in northern Mexico and in December 2008 in Iglesias (Sardinia, Italy).

In the Apulian hypogeoal system of Castellana Grotte Virtualgeo performed the measurement using a time of flight laser scanner (RIEGL LMS-Z420i). In 10 scans 1.45 Gb of data was acquired. The Grave is the first of the caves of Castallana, the most wide and indented cavity of Apulia region and among the most important of southern Italy. It is particularly vast: 100 m long, more than 40 m wide and about 60 m high. The work took 2 technicians 8 hours (1 working day)

In the Cueva de los Cristales (Cave of the Crystals) some of them reach up to 12 m in length and almost 2 m in diameter. In the Cuevas de las Espadas and de los Cristales 4 scans were executed with a phase shift laser scanner and 40 pictures were taken with the camera associated with the instrument and the spatial coordinates and RGB colour values of more than 43 million points were gathered.

All the survey operations took a technician for 3 hours over 2 working days of which 20 minutes were needed for scanning. The chosen laser scanner here used (CAM2 LS 880) has a limited range suitable for the “forest of crystals” of Naica, a more compact size and lower weight than the laser scanner used in Castellana. Scanning has been performed in extreme ambient conditions (48°C temperature and humidity close to 100% in the Cueva del los Cristales).

The karst system of Santa Barbara consists of two large subvertical cavities (Santa Barbara 1 and Santa Barbara 2) developed in contact with a sulphides vein in the mine of San Giovanni, 5 km W from Iglesias in south-western Sardinia. Virtualgeo, in collaboration with Leica Geosystems S.p.A., surveyed with three-dimensional laser scanner part of the mine complex of San Giovanni. The survey required an acquisition plan due to the complexity of the whole and involved the exteriors at mine entrance level,
access and connection galleries, caves Santa Barbara 1 and Santa Barbara 2, magazine of explosives and extraction areas. Using two scanner (RIEGL LMS-Z420i, LEICA HDS6100) 46 scans has been performed and 15 Gb of data was acquired.

3. Geomatic techniques used for the Abisso Ancona survey

The aim of this work is to experiment laser scanner technique in a difficult environmental context from logistics and accessibility point of view such as Frasassi Caves, and to create a geo-morphological model of the Abisso Ancona hall, one of the biggest in Italy, in order to define its dimensions and shape, assess the survey accuracy and create video and virtual models of the cave, aimed at tourism promotion and in particular for visitors unable to access directly.

Among the various techniques available, we choose to use laser scanning as it allows to obtain a metrically correct model characterized by a high density of points and a centimetric precision.

For the survey it was used the CAM2 FARO FOCUS 3D X 130 laser scanner (figure 1), small-size, very light and extremely fast phase-measurement scanner (about 1 million points per second), equipped with an integrated 70 megapixel camera with automatic color overlap to the point cloud. It is characterized by a high accuracy (a few millimeters) and a range of about 100 meters.

![Figure 1. Faro Focus 3D X 130 used for the cave survey.](image)

Angles and distances are measured thanks to a laser beam emission that performs a 360 ° scan of the detected surfaces (actually 360 ° horizontally, 300 ° vertically). The result is a 3D point cloud, composed of millions of points, each with its XYZ coordinates associated to the reflectivity of the material.

Thanks to the internal camera, RGB color is added to each points from digital frame taken contemporarily to the scan and automatically oriented in the same reference system of the instrument (figure 2).
In a single working day, 24 scans were performed from different measurement stations in order to cover the all cave as much as possible. From the survey we obtained a cloud composed of about 1 billion points, with an average density between points of 7 mm at 10 meters distance and an acquisition time for each scan of about 6 minutes and 30 seconds.

For the acquisition of the single scans and for relative orientation between contiguous scans, planimetric targets consisting of square cards with a pattern of four black and white alternating squares and a set of 6 calibrated spheres were used. The 6 spheres are positioned in the surrounding area so that they must be simultaneously visible in the same scan. For the next scans, only 3 spheres are moved while the other 3 are left in position, so that there are always 3 spheres common to two contiguous scans, which allow relative orientation and merge of the scans.

The advantage of the spheres is that the scanner software automatically detects them and accurately determines the coordinates of their centre from each scanner position, obtaining the maximum scanning efficiency from different directions and reducing the error in relative alignment of the point clouds.

The software used for processing and aligning the single scans is SCENE: by performing the spatial rototranslation of the single point clouds with respect to a reference one, it can be obtained a single point cloud oriented in a local reference system coinciding with the instrumental one.

To perform the registration, artificial planar targets and three-dimensional spheres were used as common points. The result of the registration between clouds is expressed by the “normalized tension” parameter: due to the complex geometry of the cave, it was decided to consider admissible a maximum normalized tension of 5 mm.

After cleaning the cloud from noise and unwanted points, it is possible to create vectorial drawings of the model, obtaining plans and sections, by setting up appropriate cutting planes that intersect the three-dimensional point cloud parallel to the various fronts to be represented (figure 3, figure 4). This operation was made with Cyclone software (Leica Geosystems). In this way extremely representative images are obtained which allow to do geometric evaluations (dimensions, surface evaluation, altimetric analysis, etc.).
Thanks to the integrated 70 mega pixel internal camera that acquire 85 frame for each scan, it is possible to associate the RGB colours to the point cloud obtaining a realistic visualization of the scan (figure 5).

From the three-dimensional model obtained, it was possible later to create images and virtual video. The 3D digital model show exactly what visitors can see directly inside the cave: stalactites, stalagmites, rock walls.

This virtual tour allows, even to those who are unable to enter, to experience the thrill of a virtual tour of the Cave through the paths that cross it, seeing the most interesting details that identify itself.

### 4. Evaluation of the survey accuracy

The survey and processing of the data was followed by a test to analyze and estimate the uncertainty on the angles (azimuthal and zenith) and distance measurement.

The accuracy, meaning as the agreement degree between the measurement of a quantity and its conventional "true value", can be considered as the best indicator of the quality of a data item or information[9-10].
Called X, Y and Z the coordinates of a generic point of the cloud measured from a specific station point (figure 6), these coordinates can be expressed with the following relations:

\[
\begin{align*}
X &= d \cdot \sin \xi \cdot \cos \theta \\
Y &= d \cdot \sin \xi \cdot \sin \theta \\
Z &= d \cdot \cos \xi
\end{align*}
\]

Figure 6. Schematic representation of laser scanning measurement.

in which d is the inclined distance between the station point and the measured point:

\[
d = \left[ (x_s - x_i)^2 + (y_s - y_i)^2 + (z_s - z_i)^2 \right]^{\frac{1}{2}}
\]

\(\theta\) is the anomaly equal to:

\[
\theta = \arctg \left( \frac{x_i - x_s}{y_i - y_s} \right) \pm k\pi
\]

while \(\xi\) is the zenith angle:

\[
\xi = \pi - \cos^{-1} \frac{\Delta z}{d}
\]

Called \(x_i, y_i, z_i\) the coordinates of the measured point, \(x_s, y_s, z_s\) the coordinates of the station point and \(\Delta z\) the difference in height between the measured point and the station point, the uncertainties on the three coordinates of the points was calculated using this relations [11] assuming an accidental errors distribution:

\[
\sigma_x = \left[ (\sin \xi \cdot \cos \theta)^2 \cdot \sigma_d^2 + (d \cdot \cos \xi \cdot \cos \theta)^2 \cdot \sigma_\xi^2 + (d \cdot \sin \xi \cdot \sin \theta)^2 \cdot \sigma_\theta^2 \right]^{\frac{1}{2}}
\]

\[
\sigma_y = \left[ (\sin \xi \cdot \sin \theta)^2 \cdot \sigma_d^2 + (d \cdot \cos \xi \cdot \sin \theta)^2 \cdot \sigma_\xi^2 + (d \cdot \sin \xi \cdot \cos \theta)^2 \cdot \sigma_\theta^2 \right]^{\frac{1}{2}}
\]

\[
\sigma_z = \left[ \cos \xi^2 \cdot \sigma_d^2 + (d \cdot \sin \xi)^2 \cdot \sigma_\xi^2 \right]^{\frac{1}{2}}
\]

The total uncertainty on the position of the point was obtained as the square root of the sum of the squares of \(\sigma_x, \sigma_y, \sigma_z\):

\[
\sigma_p = \left( \sigma_x^2 + \sigma_y^2 + \sigma_z^2 \right)^{\frac{1}{2}}
\]
For the uncertainties on distance and on zenith and azimuth angles, the values chosen for the FARO FOCUS 3D X 130 laser [12] are:

\[
\sigma_d = 1.9 \text{ mm}; \quad \sigma_\xi = 1.71 \times 10^{-4} \text{ rad}; \quad \sigma_\theta = 1.51 \times 10^{-4} \text{ rad}
\]

The first analysis consisted in evaluating the trend of the single uncertainties \(\sigma_x, \sigma_y, \sigma_z\) and the total one \(\sigma_P\) by varying the distance \(d\) and keeping the zenith and azimuth angles constant. By varying the distance from 0 to 50 m and considering the angles equal to 45°, it can be seen from the figures below that the uncertainties vary quadratically, with a parabolic trend, as a function of the distance; the \(\sigma_x\) and \(\sigma_y\) uncertainties are identical and vary from a minimum value of around 0.95 mm to a maximum of around 5.8 mm (figure 7, figure 8); the uncertainty \(\sigma_z\) varies from a minimum of around 1.3 mm to a maximum of approximately 6.2 mm (figure 9). The total uncertainty \(\sigma_P\) varies from a minimum of around 2 mm to a maximum of 10 mm (figure 10).

The second analysis allowed us to evaluate the trend of the uncertainties on \(x\), \(y\) and \(z\) varying zenith and azimuth angles, considering a fixed distance of 50 m. It was decided to evaluate separately the influence of each angle on the uncertainties variation, keeping one fixed at 45° and changing the other one according to the instrument characteristics (300° on zenith angle, 360° on azimuth angle).

Varying the zenith angle from -60° to 90°, it has been obtained that the uncertainties have a sinusoidal trend; in particular the \(\sigma_x\) and \(\sigma_y\) are the same, presenting a maximum value of approximately 6 mm for
a zenith angle of 0° and a minimum of about 5.5 mm for \( \xi \) equal to 90° (figure 11, figure 12). The \( \sigma_z \) uncertainty presents instead a minimum value of about 1.9 mm for a zenith angle of 0° and a maximum value of about 8.5 mm for \( \xi \) equal to 90° (figure 13).

![Figure 11. The \( \sigma_x \) uncertainty related to \( \xi \) angle.](image)

![Figure 12. The \( \sigma_y \) uncertainty related to \( \xi \) angle.](image)

![Figure 13. The \( \sigma_z \) uncertainty related to \( \xi \) angle.](image)

By varying the azimuth angle instead (from 0° to 360°), it has been obtained that only the \( \sigma_x \) and \( \sigma_y \) uncertainties have a sinusoidal trend, while the \( \sigma_z \) uncertainty has a constant value of about 6.2 mm depending only on the zenith angle; in particular \( \sigma_x \) has a maximum value of approximately 6.2 mm for an azimuth angle of 0° and a minimum of about 5.3 mm for \( \theta \) equal to 90°. The \( \sigma_y \) uncertainty has a specular trend to \( \sigma_x \) one, presenting the minimum value of about 5.3 mm for an azimuth angle of 0° and a maximum value of around 6.2 mm for \( \theta \) equal to 90° (figure 14, figure 15).

![Figure 14. The \( \sigma_x \) uncertainty related to \( \theta \) angle.](image)

![Figure 15. The \( \sigma_y \) uncertainty related to \( \theta \) angle.](image)
5. Conclusions

The processing of the collected data has allowed to know for the first time with high accuracy the effective shape of the cave room Abisso Ancona in its different parts, obtaining sections and plans and to position it correctly in the three dimensions inside the mountain. The survey of hypogean caves with laser scanner technology represents an exceptionally valid and innovative tool to analyse and spread, at all levels, the research and the environmental monitoring of this complex as well as promote tourism and the virtual use of these sites by creating virtual tours, with which the tourist can move inside the cave and visit all the parts, even those inaccessible, through the new smart technology (smartphone, tablet, computer).

From the data analysis, it can be seen that the greatest influence on the shape measurement uncertainties is given by the distance measurements, for which the uncertainty value quintuplicates at the greater distance.

According to angles, it can be seen that the zenith angle has a greater influence on the $\sigma_z$ uncertainty with a range of variation of about 7 mm, while the influence on the x and y coordinates can be considered approximately zero, being lower than one millimeter. Regarding the azimuth angle, its influence is almost nothing in all directions.

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