Innovative laser device for capturing cross sections in dry and underwater caves

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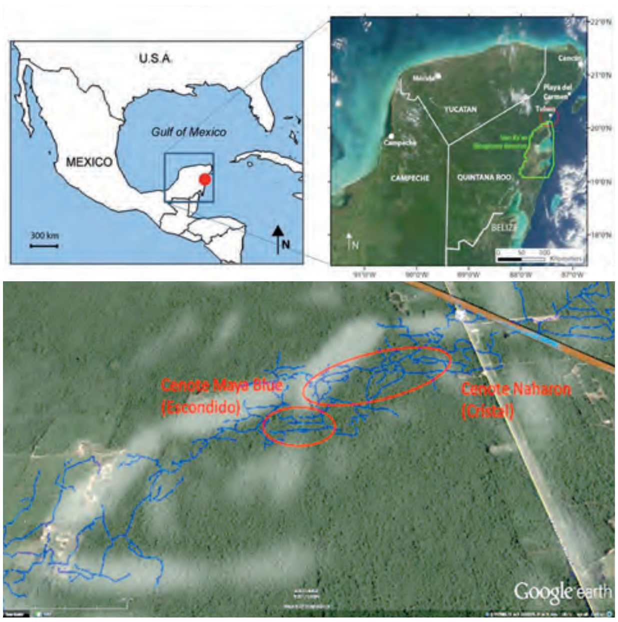
Introduction

The Ox Bel Ha Karst conduit system is located at the south-east coast of the Yucatán peninsula in the region of Tulum, México (Text-Fig. 1). In the subsurface, and below the city, the whole area is nerved by a wide and complex network of underwater caves and conduits developed in nearly horizontal layered limestone. The uppermost layer of the karst aquifer represents practically the only fresh water resource of the region. Below the freshwater layer there is saltwater intruding from the sea and reaching deep regions. The freshwater is endangered by rapid urban development and partially inappropriate wastewater management. Within this context, sustainable water management as well as protection of the reef and the nearby Sian Ka'an biosphere reserve require better understanding of the water re-source and its potential (Gondwe, 2010). To achieve this, collaborations of local NGOs, exploration divers, different universities and the Geological Survey of Austria are in progress since 2006 with the objective to acquire crucial input data for hydrologic modelling by means of standard and innovative measurement methods (Vuilleumier, 2011; Schiller et al., 2012). The method presented herein addresses a new time-saving acquisition method for geometric data of karst conduits.

Text-Fig. 1.
Testing site. Top Left, right: Location of study area. Bottom: Part of Ox Bel Ha cave system with cenotes Cristal, Maya Blue and Jailhouse.

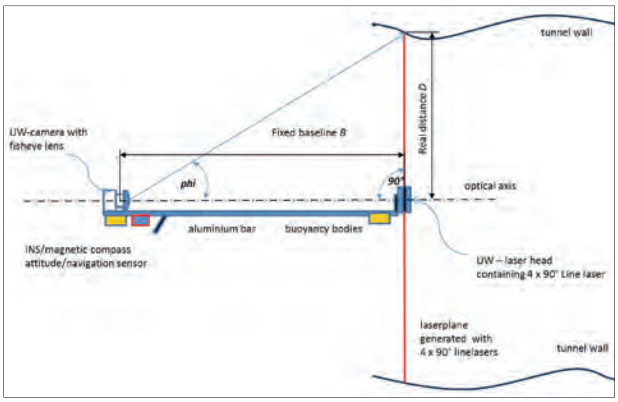


Basic Principle

The technique is derived from similar laser scanning methods as applied for measuring tasks in industrial processes (e.g. Kannala et al., 2008; Matsui et al., 2009), and adapted to the special measurement conditions in underwater caves. The device (Text-Figs. 2, 6) consists in principle of a) a camera and b) a laser head projecting a laser line over the whole perimeter of a tunnel. Both main components of the device are connected through a rigid bar (made of aluminium) preserving a defined geometry of the system. The projected laser line can be interpreted as consisting of a large number of laser points. Corresponding laser rays are gathered in a plane, designated here as laser plane.

The system consisting of *camera, optical axis of imaging system, laser ray, point of the projected laser line on the tunnel wall* forms a rectangular triangle with 90° between the optical axis and a

Text-Fig. 2.
Basic principle of the scanning method.



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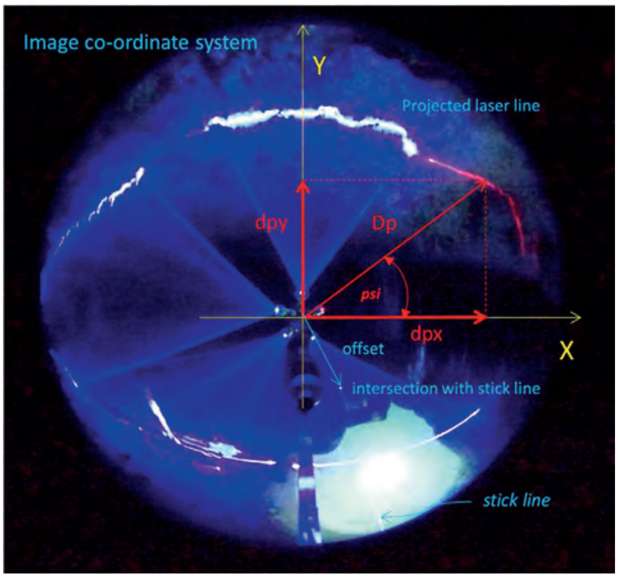
laser ray as shown in Text-Figure 2. The separation between camera and laser plane is fixed by design and represents the base line ***B***. The crossing point of the optical axis through the laser plain is here defined as the centre of the laser plane coordinate system with ***z*** upwards and ***x*** pointing to the right (Text-Fig. 3). ***Phi*** is the angle between the optical axis and the line of sight to the specific point of the laser line on the tunnel wall as seen from the position of the camera. The length ***B*** of the base line is defined by design. With this it is possible to calculate the distance ***D*** of the specific point of the line on the wall from the centre of the laser plane. ***Phi*** is measured by means of the camera since every angle in the real world system maps to a certain pixel distance in the image. Since the optical distortion of the imaging system is axial-symmetric referred to the optical axis, the mapping function is axial-symmetric as well. That means that the basic parameter for obtaining the real distance ***D*** of the laser point from the laser plane centre is the pixel distance ***p***.

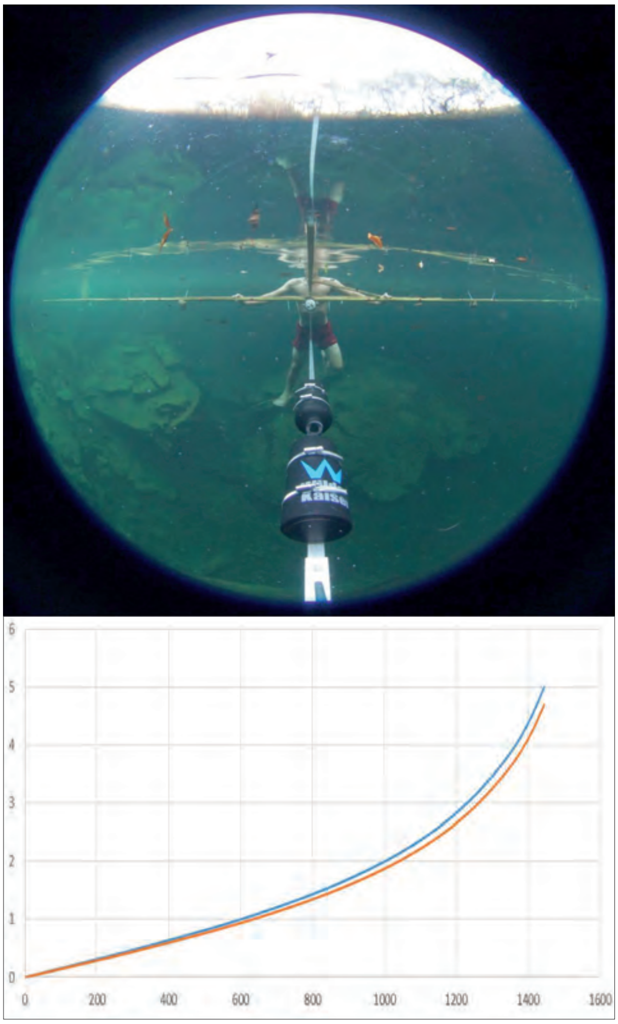
This calculation can be done for every point along the imaged laser line. The real distance can then be split into ***z*** and ***x*** components in the laser plane system taking into account the angle ***psi*** between ***z*** axis and laser ray from the centre of the laser plane to a specific point of the laser line (Text-Fig. 3). This angle is mapped directly to the image without distortion if axial symmetry of the optical system is maintained. Herewith the problem is comfortably solved in the ideal case.

Text-Fig. 3.
Coordinate system definitions in laser plane.



Calibration

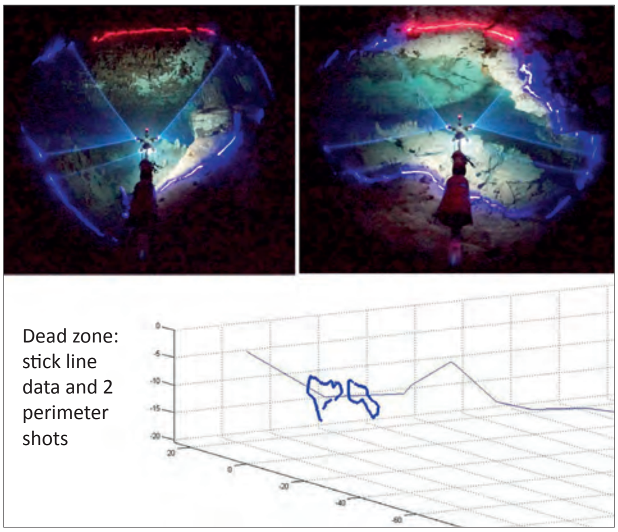
The real case emerges more complex: Geometric errors in the instruments design introduce non-axial- symmetric behaviour of the mapping function. The effective length of the base line depends on the lens system. The angular distortion is additionally affected by light refraction at the water/dome/air- interfaces when light passes from the water into the waterproof casing. All these combined effects can be addressed by a simple calibration procedure in which a scale bar or scale tape is placed into the laser plane (lasers off) and imaged. The image of this scale under measurement conditions gives directly the over-all mapping function by relating the pixel distance to distance-marks on the imaged scale (Text-Fig. 4). The computational realisation of this mapping is a simple and fast look-up table operation.



Text-Fig. 4.
Principle of calibration procedure. Top: Scale in Cenote.
Bottom: derived mapping functions (for two geometries).

Positioning

In the test survey the cross sections positions are related to the ‚stick line'. The stick line represents a tunnel's geometry as a series of connected straight lines, similar to sticks (Text-Fig. 5). In reality it is a cord, attached by exploration divers in the cave onto rocks and other suitable features at the tunnel wall. The stick line is then measured with compass, depth meter and scale tape in dead reckoning technique. The normal offset of a laser scanned cross section to the stick line is visually well defined by the intersection of the laser plane with the cord as indicated by a bright dot where the line laser hits the cord. After mapping, this gives the in-plane offset of the laser planes coordinate system relative to the stick line. The position along the line is defined by equally spaced intervals of one to three metres. The diver is instructed to keep the spacing constant.



Text-Fig. 5. (up)
Top: Two cross section shots. Bottom: mapped cross sections connected to stick line data.

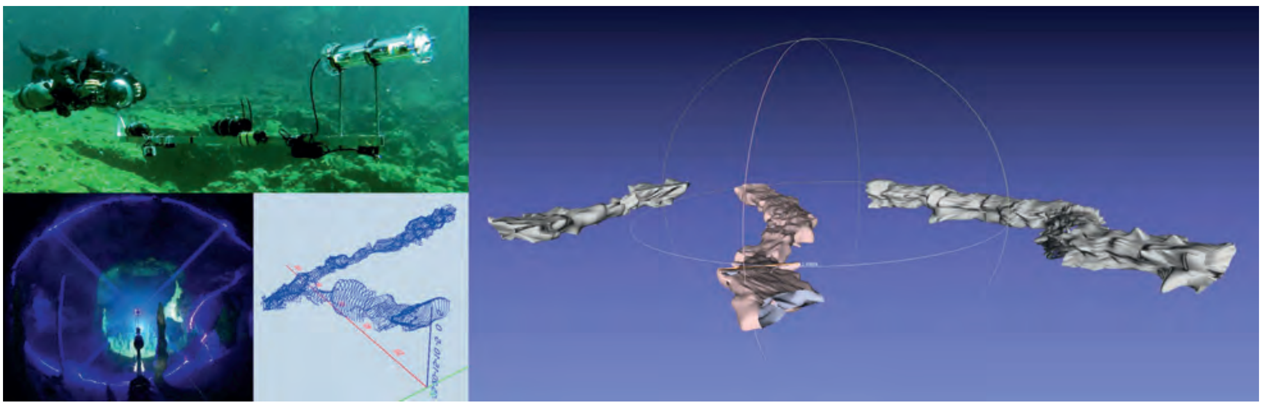
Processing

First processing step is digitising the imaged laser line of each cross section shot. This can be accomplished automatically by standard image processing techniques (Fisher & Naidu, 1991). However, manual editing gives the opportunity of interpreting gaps in the laser line (shadows obstacles or side tunnels or light absorbed due to large distances (Text-Figs. 5, 6). Second step is transforming the data from pixel coordinates to real world coordinates. In principle, this is done with a look-up table as soon as the mapping function is known from calibration. Third processing step is the compilation of successive cross sections to any 3D representation of a scanned tunnel by incorporating attitude and position information as acquired by an attitude sensor (Text-Fig. 6).

Field tests

A first prototype was designed and prepared for a field test in Tulum in March 2013. Since then the instrument was advanced till latest operation in April 2017 in Tulum. The tunnels scanned are located in the Ox Bel Ha system and accessible through Cenotes (Maya Blue, Cristal, Tercier Cielo, Jailhouse). Line lasers are installed with batteries into an underwater casing. The imaging system consists of a DSLR camera with 4.5 mm circular fisheye lens. At each shot the device was levelled horizontally with the help of inclination indicators in the camera display and adjusted parallel to the stick line deployed by divers. The position along the line was defined by approximately equal separation along a straight leg of the line, marked with clothe pins. In course of the tests and surveys

Text-Fig. 6.
Left top: 2015 device. Bottom: cross section in in jailhouse tunnel. Bottom right: 3D-model of dead zone/ Cenote Maya Blue. Right: size comparison of 3D-models of Cenotes Jailhouse, Cristal and Tercier Cielo.



approximately 800 cross sections have been captured in six tunnels. With an average separation of two meters in mean this gives about 1,600 meters of scanned tunnels producing six 3D-models of karst conduits.

Results and Discussion

The tests showed that the device is light and easily operable underwater. An additional front light is of advantage for the orientation of the diver as well as for interpretation purposes during subsequent image processing (e.g. distinguishing between laser line gaps caused by side tunnels or rock shadows). The red laser was quickly absorbed in the freshwater layer while the blue laser showed good penetration and covered well in the diameter range up to 20 metres. The touchpoint of the laser plane with the stick line for offset correction is usually clearly visible. After digitising and mapping the data was visualised in cross sections combined with stick line data as shown in Text-Figure 5. In-plane accuracy is in cm-range depending on sensitivity of mapping function, stick line accuracy is in centimetre to meter range depending on the length of the stick line survey.

With this device important geometric parameters can be quickly captured in underwater as well as in dry caves. The method gives several thousand perimeter points with one shot, i.e. in 0.2 seconds – so acquisition speed, resolution and information density is presently superior to other methods underwater. Processing is fast, straight forward and well behaving in case of 360° concave structures, whereas stereometric methods face problems. In case of further funding full automatic processing can be achieved on basis of developed algorithms. The data enables high-resolution analysis for quantities such as cross section area, shape and roughness parameters, which represent important data for further statistical analysis, simulation and modelling of karst groundwater systems.

Acknowledgements

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