Available online at scholarcommons.usf.edu/ijis

International Journal of Speleology

Official Journal of Union Internationale de Spéléologie

A decade of modern cave surveying with terrestrial laser scanning: A review of sensors, method and application development

Mohammed Oludare Idrees and Biswajeet Pradhan*

Department of Civil Engineering, Geospatial Information Science Research Center (GISRC), Faculty of Engineering, University Putra Malaysia, 43400 UPM, Serdang, Selangor Darul Ehsan, Malaysia

Abstract: During the last decade, the need to survey and model caves or caverns in their correct three-dimensional geometry has increased due to two major competing motivations. One is the emergence of medium and long range terrestrial laser scanning (TLS) technology that can collect high point density with unprecedented accuracy and speed, and two, the expanding sphere of multidisciplinary research in understanding the origin and development of cave, called speleogenesis. Accurate surveying of caves has always been fundamental to understanding their origin and processes that lead to their current state and as well provide tools and information to predict future. Several laser scanning surveys have been carried out in many sophisticated cave sites around the world over the last decade for diverse applications; however, no comprehensive assessment of this development has been published to date. This paper reviews the state-of-the-art three-dimensional (3D) scanning in caves during the last decade. It examines a bibliography of almost fifty high quality works published in various international journals related to mapping caves in their true 3D geometry with focus on sensor design, methodology and data processing, and application development. The study shows that a universal standard method for 3D scanning has been established. The method provides flexible procedures that make it adaptable to suit different geometric conditions in caves. Significant progress has also been recorded in terms of physical design and technical capabilities. Over time, TLS devices have seen a reduction in size, and become more compact and lighter, with almost full panoramic coverage. Again, the speed, resolution, and measurement accuracy of scanners have improved tremendously, providing a wealth of information for the expanding sphere of emerging applications. Comparatively, point cloud processing packages are not left out of the development. They are more efficient in terms of handling large data volume and reduced processing time with advanced and more powerful functionalities to visualize and generate different products.

Keywords: 3D scanning, LiDAR, cave modeling, speleology, geomatics, geomorphology

Received 7 May 2015; Revised 3 January 2016; Accepted 3 January 2016

Citation: Oludare Idrees M. and Pradhan B., 2016. A decade of modern cave surveying with terrestrial laser scanning: A review of sensors, method and application development. International Journal of Speleology, 45 (1), 71-88. Tampa, FL (USA) ISSN 0392-6672
<http://dx.doi.org/10.5038/1827-806X.45.1.1923>

INTRODUCTION

Caves are underground space formed by the process of natural weathering in carbonate rocks. The mystery of the origin of cave formations has a long history with different theories postulated during the early 19th century. Practical exploration to document this subterranean environment, in order to advance knowledge, took its modern form by the turn of 20th century. This was the time when Edouard-Alfred Martel (1859–1938) and his contemporary speleologists believed that a combination of both

vadose solution and erosion provided the complete explanation for speleogenesis (Shaw, 2004a). Martel, referred to as the father of speleology (Shaw, 2004b), was active in advancing a method of cave surveying that eventually metamorphosed to a distinct field of science called speleology.

The use of caves has been a behavioral trait of human and animals alike, whose activities span several hundred thousand years until present. Prehistoric residents lived in caves on a short or long term basis as necessitated by the circumstances of the activities carried out. Even after Industrial Revolution

*biswajeet24@gmail.com

(during World War II), Bedeilhac Cave, in the French Pyrenees, was reported to be used as aircraft factory (Tolan-Smite, 2004). Also, recent investigations in the French Bronze Age cave, Les Fraux, uncovered ceramic and metal deposits that suggest it was used as “industrial” workshop by ancient bronze workers (Grussenmeyer et al., 2012; Burens et al., 2013). Apart from the “industrial” use mentioned above, caves have also served as sources of raw material for economic production [e.g., Buchroithner & Gaisecker, 2009 (water); Canevese et al., 2009 (chemical); and Kingston, 2010 (mineral)]. Other valuable resources have been extracted that include the Chinese delicacy, swiftlet nests (Kingston, 2010; McFarlane et al., 2015), which have been harvested along with bat guano as fertilizer for centuries in many parts of the South-east Asia, especially Gomantong caves in Sabah and Niah Great Cave in Sarawak, Borneo Island (Kingston, 2010; Buchroithner et al., 2012). Human use of caves for ritual/religious functions is also indicated from findings in the Aboriginal rock arts cave (El-Hakim et al., 2004), votive deposit (Bullock, 1965), and human bones and coffins used for burial (Chasen, 1931; Tolan-Smite, 2004). Interestingly, some of these caves still retain their spiritual functions today, with hundreds of thousand devotees paying homage to their deities. A typical example is the well-known Batu Cave in Kuala Lumpur.

Ever since the foundation of speleology as a scientific discipline was established, various methods to map caves have evolved in line with advances in survey instrumentation. Early speleologists used freehand drawings as a simple way to depict and document their experience (Fryer et al., 2005). Succeeding the freehand drawing is the use of simple traditional surveying instruments like compasses, tapes and clinometers (Tsakiri et al., 2007), that was later rendered obsolete with the advent of total stations, which allows single 3D coordinate points to be determined. The use of total station was a major improvement in underground surveying in terms of methodology and accuracy, but these methods are not efficient for capturing irregular geometry such as caves (Haddad, 2011). Photogrammetry is another proven technique with potential similar to terrestrial laser scanning (TLS). The perpetual darkness in many caves renders the technique a rather arduous task (Fryer et al., 2005). In recent years, high resolution TLS technology has revolutionized cave surveying, resulting to significant shifts in the prospect for 3D cave research.

The idea of using TLS survey in cave environments was initiated by the realization of its potentials for 3D digital documentation, visualization and analysis of a spatial context. Caprioli et al. (2003), El-Hakim et al. (2004) and others pioneered today's cultural heritage documentation technique in caves, which combines 3D scanning and images taken with high resolution imaging camera to create a photorealistic models. Since then, a number of significant scientific applications have benefited from this methodology (see section 5). In another development, modern hydrogeologists have realized that 3D information

from TLS is a fundamental base data to the study of karst and its geomorphological structure. According to Buchroithner and Gaisecker (2009), calcareous mountains are known for hosting large amount of ground water, so connection between hydrology and climate over time can be analyzed from TLS data (Silvestre et al., 2015). Moreover, having data depicting the shape and volume cavity of a cave will allow projecting water storage capacity. Also, a combination of elusive surface geological structure with precise observation in the cave will enable modeling scenarios such as seepage/percolation (Yumin et al., 2013) and water run-off (Silvestre et al., 2013).

From the foregoing, it is evident that there has been growing interest in three-dimensional cave mapping for different applications long before laser scanning was invented. The development and incorporation of laser technology in surveying instruments have witnessed successive improvement over the past few decades with expanding applications beyond industrial and engineering surveying. The emergence of laser scanning systems do not come as a surprise to the geomatics community, but rather an evidence of consistent stride for making available state-of-the-art surveying hardware (and software) for the geospatial professionals. TLS offers unparalleled possibilities in accuracy, speed and point density for small and medium scale topographical mapping of open and closed environments (El-Hakim et al., 2004). These factors therefore made it an acceptable and mature tool for accurate 3D cave surveying and mapping. This study intends to present a review of scanning in world's great caves for different purposes through the exploration of high quality works published in various international journals. The paper examines cave surveying with TLS, specifically for 3D cave modeling and as base data to reference other cave information. The study attempts to clarify progress made in standardizing the method for 3D scanning particularly in cave, hardware/software design, and applications development during the last decade.

EVOLUTION OF 3D CAVE SURVEYING WITH TLS

Literature search reveals that protracted efforts to map cave in true 3D geometry has a long history, however, the introduction of short and medium range terrestrial laser scanners is a phenomenon. The first attempt to replicate Altamira cave, located in northern Spain, using a triangulation-based Minolta VI-700 scanner was carried out between 1988 and 2001. The project took a very long time to complete due to scanner range limitation (0.7-1.1m), excessive modeling/CAD packages and manual handling (Blais, 2004). Almost 10 years after the Altamira project, a team of researchers experimented with 3D mapping in the Upper Palaeolithic cave of Cap Blanc, southwest France in March 1999 (Robson et al., 2001). They used Surveyor Autoscanning Laser System (Surveyor ALS) to produce accurate 3D model of the cave. Two major drawbacks of these early studies are, one, the method adopted is not empirically rigorous and, two,

the instrument has limited storage capacity. Despite that, both projects, indeed, signposts the evolution of a new era in modern cave surveying.

Cyrax 2400 and Riegl LMS-Z210 are the first set of products that came to the market in 1998. Almost immediately, Cyrax 2400 was put to test in May, 1999 through a pilot project jointly initiated by Cyrax Technology and National Park Service to comprehensively explore the documentation of the complex tourist Chapel's cave in the southwestern Oregon, USA, and also to assess its viability for 3D cave mapping (Perperidoy et al., 2010). Accurate 3D model of the cave was built from which precise horizontal and vertical sections were obtained. Cyrax 2400 was equally tested by Kanaya et al. (2001) to scan and reconstruct a prominent Japanese prehistoric Shofukuji Tomb. Another pilot study was conducted in Castellane Grotte cave, Bari, Italy by Caprioli et al. (2003). The team tested two 3D techniques; scanning with Mensi-GS100 scanner and independent photogrammetric method. A limited number of scans were taken and merged. The surface model was not reconstructed but the mesh produced depicts the structure of the stalagmite with the horizontal section. These pilot studies, obviously, proved TLS as viable and reasonable alternative method to execute 3D cave mapping. Nonetheless, the success recorded ignites renewed perspective in cave research around the world's famous caves as several other projects follows with a chain of improvement in all ramifications.

Previous case studies

In this section we discuss previous caves around the world where TLS had been used for 3D cave surveying and mapping. For the purpose of comprehension, the topics are treated on regional basis.

Australia - El-Hakim et al. (2004) pioneered research effort in developing methodology to record the shape and appearance in the cave. In Baiame rock art cave, New South Wales, Australia, the researchers combined data obtained with Riegl LMS-Z210i and images acquired with cheap digital camera using bundle adjustment to create photorealistic 3D model. A significant achievement was made to automatically register image and 3D geometry without the need for corresponding points. The authors concluded that the geometry of cave cannot be satisfactorily represented using image-based method alone. Fryer et al. (2005) revisited the cave using different approach. They generated DEM and orthophotographs using automated image correlation software from survey control points and digital photogrammetry images. The product and accuracy was compared with the work of El-Hakim et al. (2004) and the author claimed both techniques exhibit similar capability.

Austria - The first sketch of Dachstein South Face Cave was produced in 1913, since then consistent visits have been made to the cave in order to accurately describe the intricate nature on map. Buchroithner and Gaisecker (2009) successfully scanned with Riegl LMS-Z420i and created a 3D model of the cave chamber from where approximate height and volume were obtained. The authors established that laser scanning

has the potential to elicit richer information that can be useful for geologists to explore the structural and hydrogeological characteristics of rocks in the cave. Marchenhohle cave, Northern calcareous Alps, Styria, is another site where the efficiency of laser scanning for 3D modeling for geomorphological applications was established with Z+F Imager 5006i (Roncat et al., 2011). High precision data collected using scanner permitted the researchers to identify, analyze and describe the internal formation of the cave surface.

Eisriesenwelt, Werfen, is the world's largest ice-filled rock cave that has attracted intense investigations on different research issues because of its prominent touristic and commercial values. With FARO Photon 20/120, Buchroithner et al. (2011) built 3D model of the cave and accurately computed the ice surface. Similarly, Petters et al. (2011) analyzed the cave morphology and identified areas prone to hazard within the cave system using the 3D model. Milius and Petters (2012) focused on providing methodical solutions to generating realistic 3D model. According to the researchers, the data will serve as the baseline for change detection and monitoring.

The Americas - The United States of America is one of the early places where the idea of 3D cave scanning was conceived with Chapel's cave as pilot project (Perperidoy et al., 2010). The successful scanning of a section of the historic world longest cave, the mammoth cave in central Kentucky, running to about 4km in length, further strengthened the conviction that TLS is, undeniably, a mature technique for cave surveying (Addison, 2011). The project produced about 18 million points, which was decimated to 500,000 points in order to generate 3D model and digital animation. Again similar expedition was carried out in Coronado cave with Leica ScanStation C10 to produce 3D model and analyze passage stability for risk and hazard management (Lyons-Baral, 2012).

Another cave on record is the Preacher's Cave, Eleuthera, Bahamas, where high definition scanning was carried out by a group of researchers from the University of South Florida's Alliance for Integrated Spatial Technologies, GeoArch Division, in February 2006 with Leica HDS 3000 for 3D modeling and archaeological documentation (Doering et al., 2006). In Mexico, the endangered Naica Cave, Chihuahua, equally played a host to researchers of different speleological orientations to provide comprehensive understanding and knowledge of the origin and development of the famous massive gypsum crystals (Canevese et al., 2009). The geomatic research group from Canevese Surveying Company undertook the scanning task with FARO laser scanner for digital documentation of 3D data for research and educational purposes.

In a similar development, a number of European world-class caves have delivered impressive applications that rely on high resolution 3D data. In Italy, a foundational test to promote 3D scanning was inaugurated in the Italian Grotta dei Cervi, Porto Badisco in 2004 (Beraldin et al., 2006) following similar pilot project in Castellane Grotte in southern Italy (Caprioli et al., 2003). The cave was scanned

with a prototyped laser scanning system 'Big scan' capable of mapping at different resolutions to produce 3D model. The Santa Barbara karst system (Sardinia), and the surrounding topography was scanned with Leica HDS6100 and Riegl LMS-Z210i to advance understanding of the morphological relationship of the two environments (Canevese et al., 2011). Furthermore, Canevese and Tedeschi (2013) used Leica HDS6100 to document Re Tiberio Cave in Mount Tondo. The cave is rich in historical and archaeological relics but faces the threat of extinction. Arma Pollera Cave (Cosso et al., 2014) and Santa Croce Cave (Marsico et al., 2015) are also among the Italian cave that have been accurately surveyed with TLS for archaeological and geomorphological applications.

France – The yearnings of paleontologist to enrich analysis of their investigations in Tautavel Cave, southern Corbieres, called for 3D scanning with Trimble GS200 equipment. The work produced cave database that facilitates visualization and examination of cave finds in relation to the geometry interactively in a single system (Chandelier & Roche, 2009). The archaeological Bronze Age cave "Les Fraux", Dordogne, France, is probably one of the most studied caves in Europe with the largest number of researchers with different background (Grussenmeyer et al., 2012). The cave consists of a network of constricted horizontal corridor adorned with a range of historical artifacts such as ceramic, metal deposits, fireplace and parietal engravings meticulously emplaced across a length of more than 1000 m. The documentation work kicked off in 2007 and lasted for six years (Burens et al., 2013). Three novel 3D technologies; FARO photon 80, FARO Focus3D and Trimble Spatial Station, and close range photogrammetry were used to produce the geometric and virtual 3D model of the cave (Grussenmeyer et al., 2010; Grussenmeyer & Guillemain, 2011). As part of the objectives to deliver a system that will be handy for the use of the multidisciplinary team, Grussenmeyer and his team (2012) proposed an adaptable recording processing workflow to integrate information collected at different scales with the 3D model of the entire cave. In a recent paper, Burens et al. (2013) further demonstrated the possibility to combine data by merging topographic, archaeological and magnetic information in the same depiction system.

Spain – is one of the European nations that have actively engaged in 3D scanning in caves for various applications. González-Aguilera et al. (2009) scanned "Las Caldas" and "Pena de Candamo" with Trimble GS200 to create 3D model of the caves at global point resolution of 20 mm. From the high-resolution model metric measurements, sections and plan were derived. In order to produce photo-realistic model of the caves, the author proposed an automatic co-registration technique to merge high resolution images acquired with digital camera with the model in a two-steps processing chain (González-Aguilera et al., 2009). In another move to consolidate strategy to facilitate recording rock arts, advance processing procedure for 3D reconstruction allowed to capture different information related to a cave to be combined in a common spatial information system. This was

the case with Paleolithic rock art caves, la Loja and Buxu, which were scanned with Trimble GX scanner to provide data for efficient management and cartographic shrewdness (González-Aguilera et al., 2011). Unfortunately, the efficiency of the method is hampered with technical limitation of handling large volume of data.

Olerdola Cave is another test site in Spain where laser scanning data was combined with GIS data of the environment to allow archaeologists to reconstruct and interactively view the cave system in 3D environment. Pucci and Marambio (2009) used Riegl LMS-Z420 to generate the 3D model, which was introduced to a mobile visualization environment, ALICE, together with other GIS data for position tracking and stereo viewing. La Cova del Parpalló Cave located in Iberian Peninsula was also scanned with FARO LS 880HE to produce 3D model for geomorphological analysis. Lerma et al. (2010) combined the model with close range photogrammetric images to create the 3D model and virtual navigation in 3D. The subject of research in Pena Castil Ice Cave is to quantify temperature differences within the cave surface in relation to the geometry. Hence, thermographies and 3D model built from data collected using Leica ScanStation C10 were merged to quantitatively analyze interrelated phenomena such as ice morphologies, climate evolution, air and heat flow dynamic and other measurements (Berenguer-Sempere et al., 2014). Last but not the least, the Ardales Cave and its environment was scanned with TLS to generate accurate 3D model (Hoffmeister et al., 2014).

Other isolated cases in Europe are recorded in Greece, Portugal, and Croatia. Kefala Cave in the Greek Island of Kalymnos was surveyed with iQsun 880HE80 for rendering of 3D model of the cave structure. The researcher discovered that the accompanied processing software package could not define the center of the targets, which affects the registration process and as a result caused holes in the model (Tsakiri et al., 2007). Perperidoy et al. (2010) later used Leica Cyclone processing package to register point clouds and produced a better 3D model. Additionally, the accuracy of the model was evaluated. Another Greek site, Skoteino Cave located in Crete was scanned with Riegl LMS-Z420i laser scanner to generate 3D model as basis to understand what function the prehistory generation used the cave for (Tyree et al., 2014).

In Portugal, 3D model of the karst cave, Algar do Penico (Algarve) was produced from point clouds collected with Leica ScanStation C10 to describe the morphological characteristics of the cave on the web for visualization (Silvestre et al., 2013). The researchers further their work focusing on 3D analysis by developing algorithm to extract speleothem and delivering the model on web (Silvestre et al., 2015). Similar to the French Les Fraux, the Croatian fortified cave of Kuca, is another location in Europe with abundant remnant of human presence that enlists it one of the European "Karst Underground Protection" project (Kordic et al., 2012). The cave was scanned with FARO Photon 120 to create the 3D model for digital documentation and visualization as basis

upon which targeted research findings in the fields of geodetic, geology, archaeology and anthropology can be built.

Malaysia – is among the countries in South-eastern Asia with the most revered historic caves (McFarlane et al., 2013). The presence of dozens of species of swiftlet birds and bats in large quantities vis-à-vis the symbiotic relationship with their environment, and the fallout of uncontrolled bird's nest harvesting causing sharp reduction in species population has been a subject of investigations of late. The Niah Great Cave, Borneo (Buchroithner et al., 2012), Gua Kelawar Cave, Langkawi (Azmy et al., 2012), and Gomantong Cave, Sabah (McFarlane et al., 2015) have been scanned with FARO scanner products to produce 3D model, estimate species population, describe roosting pattern, and analyze cave morphology. Also in China, Yumin et al. (2013) documented 3D models of Grottoes and carving produced from TLS data.

Two African countries, South Africa and Egypt, are the only countries on the continent where TLS have been used in cave. Wonderwerk Cave in South Africa was fully scanned with Leica HDS3000 to build 3D model as part of the African Cultural Heritage Sites documentation project (Rüther et al., 2009). The output provides realistic model for visualization and permits deriving other metric measurements. In the North African country of Egypt, the 3D model of Sodmein Cave derived from point clouds collected with Riegl LMS-Z420i was used to evaluate morphological features (Hoffmeister et al., 2014).

A general overview of these case studies shows that the rest of the world is not as active in cave research as the European nations. Does it mean that Europe have more caves than others? It is doubtful. This probably may be related to factors such as perceived importance of cultural heritage, impact of educational institutions, economy, and even access to instrument as it can be observed that most of the producers of TLS are based in Europe. It is hoped that this trend will change with the level of awareness scientific publications are rolling out.

TERRESTRIAL LASER SCANNING TECHNOLOGY

Light detection and ranging (LiDAR) systems are contact-free ranging instruments that measure and record geometric (and at times texture) information of surface targets using pulse of laser lights to create three-dimensional representations. Since late 1990s, TLS has been seen as a promising and reliable alternative to land-based survey and close-range photogrammetry for different applications (Tamás, 2010). According to findings, Riegl (Austria) and Cyrax (USA) are the first producers to break a new ground in 1998 with Riegl LMS-Z210 and Cyrax 2400 scanners respectively (see Table 1). Since then, TLS technological development has witnessed unimaginable scale of production that floods the market with different types and model of scanners available to the user community (Lerma et al., 2010). To avail users the opportunity to identify suitable scanner for specific application,

scanners are generally categorized on the basis of measuring principles (pulse-based i.e. time-of-flight and phase measurement, and triangulation); scan angle (panoramic, hybrid, and camera scanners); and distances at which ranging can be achieved – (short, medium, and long range) (Canevese et al., 2011).

Classification of TLS according to range is based on some defined maximum distance limits at which laser light can collect data. For scanners that can acquire data below 150m, they are classified as short-range scanners, while scanners with maximum range between 150m and 350m are said to be in the medium-range. TLS with effective range of up to 1000m and beyond belong to the long-range class (Petrie and Toth, 2008). Before the recent introduction of FARO Focus3D x330, the short range TLSs comprises of instruments that employ phase measurements. TOF (Time-of-flight) scanners have range measurement advantage over phase-based instruments, however, the gain in range is accompanied by reduction in the accuracy of measured distances. On the other hand, limitation in range measurement with phase instruments is offset by very high distance accuracy and faster data rate. The last category, the triangulation-based scanners, is designed to measure distances less than 5 m. They are portable and sometimes handheld devices restricted to applications such as industrial inspection and high-resolution 3D detailed documentation of archaeological artifacts such as petroglyphs and pictographs (Fryer et al., 2005; Beraldin et al., 2006; Grussenmeyer et al., 2010). Short and medium range scanners are commonly used for indoor or enclosed space like cave, tunnel, industrial plants, whereas, long-range scanners are most suitable for topographic applications. Detailed information on classification of scanners can be found in the books edited by Shan and Toth (2008) and Vosselman and Maas (2010).

In principle, scanners operate by emitting pulse of laser light to the target and receive the inbound signal which carries along with it range, elevation differences, angle and horizontal directions (González-Aguilera et al., 2009). These observables are translated into scanner Cartesian coordinates and internally processed as a set of 3D xyz points, called point cloud. In addition to the xyz coordinates, the reflectance of the surface at scanned points is simultaneously recorded as gray scale or RGB intensity image. And most recently, full-waveform laser data are increasingly available. These products and their derivatives have been widely used by geomorphologists in their research (discussed in section 4). Fig. 1 shows the gray scale intensity image of the first cave chamber in Simud Hitam, Gomantong cave.

TLS in caves

The market today is inundated with varieties of TLS with varying design, operational principles, range, accuracy and resolution. Market evaluation reveals that the number of producers and the types/models of scanners currently available are enormous, beyond what can be discussed in application-specific paper like this. We therefore limit the discussion to scanner producers and model of scanners used exclusively for 3D cave surveying.

Fig. 1. Gray scale intensity image of entrance section of Simud Hitam (Gomantong Cave) in north Borneo, Malaysia.

FARO - based in North America, had been in business since 1981 developing varieties of advanced handy computer-based technologies such as laser trackers, gauge and measuring arms for 3D medical diagnosis and industrial plants metrology (www.faro.com). In 2005, FARO acquired IQvolution, a German based company that specializes in manufacturing terrestrial laser scanner and its IQsun phase shift product. FARO rebranded the IQsun 880 introduced to the market in 2004 to LS 880 after it took possession (Shan & Toth, 2008). Since then other products such as LS420, LS840, FARO photon 80 and 120, FARO Focus3D have been introduced. The introduction of light-weight FARO Focused3D in 2010 is an exceptional technological advancement that makes it easy to scan complex environments like cave.

The latest series of FARO products, Focus3D x330 and x130 launched in October 2013 and March 2014 respectively are lightest and smallest high-speed scanners designed for outdoor and indoor applications available in the market. Small weight and size, touch-screen, SD-card, and a battery life of 4.5 hours make the Focus3D X 330 supreme and easy to use. Furthermore, the capability to scan objects up to 330m away up to 330m takes the normally considered middle range Phase-shift scanning technology into the realm of the long-range. In addition to this, both scanners are multi-sensor with integrated GPS receiver, compass, height sensor and Dual Axis Compensator capabilities permit correlating individual scans. This has significantly reduced the efforts required during data collection and in post-processing.

The native software, FARO SCENE, is now optimized to automatically recognize objects that provides tool for automated target-less scan positioning with high-quality colorized scans. SCENE is efficient for 3D visualization, meshing, and exporting into various point cloud and CAD formats of third-party software for different applications. Another achievement is the ability to publish scan project on web server using the SCENE WebShare Cloud. In short, scanning is increasingly going mobile with remote scanning and virtually unlimited scan data sharing through this platform.

Leica Geosystems – founded in 1997 in Heerbrugg, Switzerland is a company with a mark of distinction

in the manufacturing of state-of-the-art surveying instruments. Leica herald its interest in terrestrial laser scanner by first investing in Cyra Technology in 2000 and took over ownership of the company a year later. Cyra Technology, an American company incorporated in 1993, produced its first terrestrial laser scanner Cyrax 2400 in 1998 and a later model Cyrax 2500. The company initially kept its identity as a unit of Leica Geosystem, but was officially renamed Leica Geosystems HDS Inc. in 2004 (Shan & Toth, 2008). To this effect, Cyrax 2500 was changed to HDS 2500. Subsequent model with enhanced functionality called HDS3000 have emerged in 2004. Ever since, several other models such as the ultra-high speed HDS 6100 scanner and the later long range HDS8810, HDS8400 and Leica ScanStation P and C series have been put into market (www.hds.leica-geosystems.com).

In April 2, 2015, Leica Geosystems rolled out the eight generation of its high performance laser scanners, ScanStation P40, P30, and P16. This products advance into entirely new dimension in terms of range, very high speed and high-quality 3D data and HDR digital imaging that offers complete scanning solutions for varieties of applications, even under severe environmental conditions. P40 and P30 improve survey capabilities with longer range (120 m for P30 and up to 270 m for P40) while P16 operates at short-range.

Beside the advances in hardware, Leica Geosystems have improved the proprietary Cyclone software to support automatic target finding, fitting and matching to complement automated registration capability. Furthermore, a suit of other specialized packages, such as Leica CloudWorx, TruView, and JetStream, has been developed. CloudWorx is a pug-in for CAD and virtual reality applications whereas TruView provides access to view and measure scans via internet browser on any mobile devices and computer with no additional pug-in or App installed. Like the FARO Cloudshare, Leica JetStream facilitates sharing Cyclone data over data streaming server for third party users. Overall, Leica range of software packages offer the essential tools to manage, process, and distribute point cloud and other scanning products efficiently.

Riegl Laser Measurement Systems (LMS) – founded by Dr. Johannes Riegl in 1978, Riegl is the pioneer company that advances the development of 3D laser

technology into airborne, land-based and industrial measurement tools. Riegl put its first medium-range terrestrial laser scanner, LMS-Z210, into market in 1998, and subsequently long-range scanners LMS-Z420i and LMS-Z210i in 2003 and 2004, respectively. In 2008, LMS-Z620 was added to the Z-series (Cheves, 2013). The Z-series have similar design features but vary in range. Concurrently in 2008, the VZ family was introduced starting with VZ-400. Subsequent very long range (a classification common to scanners with range distance above 1000 m) models VZ-1000, VZ-4000, and VZ-6000 followed, where numbers that suffix model indicate measurement range (www.riegl.com). All Riegl terrestrial scanners employ the time of flight measurement principle and have GPS-Sync option available for time stamp. RiSCAN Pro and Ri Profile are the two data manipulation software dedicated to Riegl scanners. The software equally supports automated registration, point cloud filtering using hue, saturation and brightness.

Trimble – established in 1978 as Trimble Navigation Limited, has placed itself as a company with outstanding reputation in providing high-tech navigation and positioning solutions. Although Trimble specializes in GPS and allied software packages to improve positioning solutions, it has successfully combined it with inertial and laser technologies to expand its market and operational sphere (www.trimble.com). Trimble entered into the terrestrial laser scanner production front in 2003 through the purchase of the Mensi Company. Mensi is a French-based company that has been established since 1986 producing short-range laser scanners utilizing triangulation measurement mode for industrial purpose. In 2001, Mensi made their first terrestrial laser scanner, GS100, that use TOF. This was followed with GS200 in 2003 with longer range and higher precision (Shan & Toth, 2008). Trimble introduced its GX 3D model in 2005, and Trimble VX Spatial station, which integrates precision total station, imaging and 3D scanning in 2007.

The latest series include advanced models Trimble TX8 with maximum range of 340m and Trimble TX5 (a repackaged FARO Focus3D model with Trimble branding and software). This was possible after FARO and Trimble signed original equipment manufacturer (OEM) and distribution agreement for 3D laser scanners in August 2012 to expand market network (Trimble, 2012). Trimble RealWorks is the proprietary point cloud processing and analysis software to efficiently register, analyze, model and create deliverables. It supports automated scan registration using both target-based and target-less workflow and can handle large volume of data. Other advance features of the latest version of RealWorks include powerful fitting tools and SketchUp Pro interoperability for accurate modeling to the point cloud.

Zoller + Frohlich GmbH – founded in 1963 by Hans Zoller and Hans Frohlich, the company stepped into laser scanning market in 2002 with its first compact standalone scanner IMAGER 5003 and later IMAGER 5006 in 2006. Advanced models 5006i and 5006h with

superior precision, longer range and point density of the order of million points per seconds came out in 2008 and in 2010 respectively (Zoller+Frohlich, 2013). Similarly in 2010, IMAGER 2010 with integrated control panel and high-resolution color display was added (www.zf-laser.com) followed by IMAGER5010C in November, 2012 designed with touchscreen interface that make it easy to operate.

The most recent 3D scanner in the line of succession, Z+F IMAGER 5010X released in April 1 during the SPAR International 2015, is a revolution in 3D scanning technology. The device is the first-industry maneuvering for indoor navigation and movements tracking between scan positions. The navigation system will estimate the scanner position and orientation that enable automatic registration of scans immediately in the field, without the use of external targets. In fact, the integration of GPS, compass, bar, IMU, and HDR i-Cam camera brings IMAGER 5010X to the multi-sensor category, providing complete survey solution with remote scanner control. Likewise, improved WiFi speeds permits easy communication and fast scan data streaming to other portable devices for other users. Z+F scanners come along with in-house developed data processing software Z+F LaserControl Professional PLUS. The new Z+F LaserControl Scout is designed to automatically register scans on site and as well verify data quality in the field.

The list above is not exhaustive; other producers of terrestrial laser scanners are Callidus, Topcon, Optech, I-SITE, etc. whose products are equally up to the task for the same purpose. Table 1 specifically discusses TLS products and models reported in referenced academic publications for three dimensional cave surveying.

3D CAVE SCANNING METHODOLOGICAL DEVELOPMENT

Laser scanning workflow

Surveying with TLS in the cave environment has a workflow that is somewhat comparable with that of above ground. Generally, caves are characterized with complex and naturally constrained shape and size, harsh environmental conditions, and darkness (Addison, 2011). Total darkness in caves and issue of targeting in such confined spaces are the most significant factors that differentiate the two environments, which are more of logistical concerns than scanning workflow. Although absence of light is not a barrier to collection of point data, it limits the ability to capture color data and photograph. This may not be an issue for applications such as 3D modeling and geomorphological analysis, but for applications such as photo realistic modeling and documentation of cave arts (pictographs and petroglyph), external lighting is required. In view of this, it is fundamental to apply systematic and efficient strategy that guarantees data collection and processing steps to adequately capture cave cavities in their correct three dimensional orientations and geometry, and where necessary, make provision for adequate lighting for photo capture.

Table 1. TLS systems discussed and their basic properties with respect to cave surveys.

Manufacturer	Product	Year	FOV	Range (m)	Points/Sec	Accuracy	Weight (kg)	Wave-length (nm)	Meas. mode
FARO	iQsun 880HE80	2004	360H 320V	30	120,000	±3 mm @ 30 m	14.5	-	TOF
	FARO LS 880HE		360H 320V	76	120,000	±3 mm @ 10 m	14.5	785	PS
	FARO photon 80	2008	360H 320V	76	120,000	≤2 mm @ 25 m	14.5	785	PS
	FARO Photon 120	2009	360H 320V	120	120,000 - 976,000	±2 mm @ 25 m	14.5	785	PS
	FARO Focus 3D 120	2010	360H 305V	120	12,200 - 976,000	± 2 mm	5.0	905	PS
Leica Geosystems	Cyrax 2400	1998	40H 40V	50	800	±6 mm	20.5	532	TOF
	Leica HDS 3000	2004	360H 270V	100	1,800 - 4,000	±4 mm @ 50 m	17	532	TOF
	Leica HDS6100	2009	360H 310V	79	500,000	±1 mm @ 25 m ±2.4 mm @ 50 m	14	650 - 690	PS
	Leica ScanStation C10	2011	360H 270V	300	50,000	±4 mm	13	532	TOF
Riegl	Riegl LMS-Z210	1998	330H 80V	150	12,000	±25 mm	13	900	TOF
	Riegl LMS-Z210i	2004	360H 80V	400	12,000	5 mm (±25 mm single shot)	13	900	TOF
	Riegl LMS-Z420i	2003	360H 80V	350 - 1,000	8,000	±10 mm	16	NIR 905-1,550	TOF
Trimble	Mensi GS100	2001	360H 60V	100	5,000	±5 mm	13.6	532	TOF
	Trimble GS200	2003	360H 60V	200	5,000	±2 mm	12.8	532	TOF
	Trimble GX 3D	2005	360H 60V	200 - 350	5,000	±3 mm @ 100	12.2	532	TOF
Zoller + Frohlich GmbH	Z+F Imager 5006i	2008	360H 310V	79	500,000	±6.5 mm @ 25 m	14	Visible	PS
	Z+F Imager 5010	2010	360H 320V	187	1,016,027	≤1 mm	9.8	1,500	PS

TOF, PS are time-of-flight and phase shift

Today we dare to say that in theory and practice, the methodical approach to cave surveying and 3D modeling using terrestrial laser scanners has attained full maturity with undisputable acceptance within and outside the geomatics discipline. Discussion on the standard method adopted for field procedure and data processing exercise involved in cave surveying and 3D model are classified into two stages: fieldwork and data processing (Lerma et al., 2010; Perperidoy et al., 2010; Diego Gonzalez-Aguilera et al., 2011).

Fieldwork: Planning and data collection

A standard practice in surveying that comes first before data collection is reconnaissance. In cave surveying however, this exercise is even much more critical because the cave environment is confronted with several challenges such as high temperature and humidity, movement restriction and darkness (Canevise et al., 2013; Berenguer-Sempere et al., 2014). So cave surveying needs proper planning to ensure that appropriate methods are determined and efficient processing scheme is designed ahead of fieldwork. This will reduce the length of time spent in the cave, allowing maneuvering geometric complexity and environmental unfriendliness on one hand.

On the other hand, proper planning will secure the quality of data collected and invariably the 3D model (González-Aguilera et al., 2009).

The first assignment at the planning stage is to define the project objectives and to ensure that the purpose of the task and user needs is clearly understood. Next is a visit to site to identify technical and environmental constraints that need to be resolved prior to data collection. According to Lerma et al. (2010) and González-Aguilera et al. (2011), the planning stage should take into account the intricacies of the cave shape, coverage, and other physical characteristic such as illumination, temperature and mobility of the equipment and crew members before mobilizing to the cave site. In most cases, the physiological arrangement of the cave may render single point clouds insufficient to cover the entire area of interest. So, scanner positions must be painstakingly selected in a way that successive scans have sufficient overlap that will make it easy to combine point clouds from different scans. With that, issues related to instrument, number of scans, their positions and resolution, and reference coordinate system are clarified (González-Aguilera et al., 2009; Milius & Petters, 2012). It must be noted that the decision to use a particular scanner has to be

weighed relative to the technical specifications and its adaptability to the conditions in the cave (Canevese et al., 2011).

Fig. 2. Left: FARO Focus3D set up in October 2012 by Drs. Buchroithner and Pradhan (standing) and the two scanner operators in the Niah Cave, Borneo. Right: Scanning with Riegl LMS Z420i at a rock pulpit in the Ramsau Dome, Dachstein South-Face Cave, Austria; numbers 1-4 indicate the component parts: scanner, tripod, backup power pack, and laptop (Source: Buchroithner et al., 2009, p. 333).

The underlining factor in 3D cave scanning is to provide accurate three dimensional data that can provide detail and high-quality morphometric data layer as a bedrock upon which other cave information can be integrated and analyzed spatially. This, however, requires some level of expertise and technical know-how on the part of the operator. Buchroithner and Gaisecker (2009) described two possible ways to set up terrestrial laser scanners for data collection. The first procedure is analogous to using total station where the instrument is leveled over ground control point whose coordinates are known and 'backsight' to another visible control point to compute the correct bearing and angle. Nevertheless, structural irregularity and perpetual darkness inside cave make this orientation-based setup impracticable. Because of this, an alternative instrument setup particularly was adopted for cave surveying. The approach allows scanner to be mounted at any location that guarantees optimal scan coverage. Fig. 2 demonstrates the later setup option with artificial targets placed around the scanner's field of view. The targets are made of reflective surface materials for easy identification; nevertheless the accuracy of automatic registration improves with increase in scan resolution (Roncat et al., 2011). A common practice is usually to strategically place targets inside the cave before the actual survey such that at least three (preferably more) targets are at any time visible on two adjacent scans and their global positions measured accurately using theodolite (González-Aguilera et al., 2009; Rüther et al., 2009), total station (Perperidoy et al., 2010; Canevese et al., 2011), or combination of GPS and total station (Tsakiri et al., 2007; Chandelier & Roche, 2009). The availability of alternative scan registration procedures such as cloud-to-cloud and automated registration in target-less mode is gradually phasing out the use of artificial targets.

As mentioned earlier, the output of laser shots is a dense xyz point clouds computed from the signal that bounces off from the surface and stored in scanners' local coordinate system (see Fig. 3) for 3D point cloud of the entrance of Simud Hitam). The time taken on a station to complete a scan differs from one scanner to another, depending on the scanner's coverage (field of view) and operating scanning resolution. Scan density defines the interval between adjacent point in the horizontal and vertical plane usually in millimeters. An unavoidable choice in selecting point spacing is that compromise has to be made between scan time, coverage and scan density (Rüther et al., 2009). Meanwhile, most of the authors advocate high point density scanning which can be decimated in the course of data processing to meet specific applications.

Scanning cave in most cases will require multiple setups to cover area of interest, so overlap must be well planned for before data acquisition.

A general rule of thumb is that about 25 percent overlap between two contiguous scans will yield high quality registration. Points scanned from different stations are in different local coordinate system. Therefore, registration is needed to align these individual point clouds into a single Cartesian reference frame. Moreover, in order to accurately georeference cave data and aggregate cave information, it must be tied to global coordinate system. This is usually accomplished by using surveying techniques (GPS and Total Station or Theodolite). Since GPS is ineffective inside the cave, a usual practice is to drop control points on the ground at the cave entrance and use total station to translate the coordinates underground through a network of survey points. Point clouds processing packages are designed to automatically extract target point coordinates used during registration to stitch point clouds acquired from different scans together and again to transform scanner's Cartesian coordinate system to local or global reference framework. The data is further processed to generate 3D model and other derivatives subject to the application requirement.

Fig. 3. 3D point cloud of the entrance of Simud Hitam (Black Cave) in Gomantong Hill, north-eastern Borneo, Malaysia (Source: McFarlane et al., 2013, p. 317).

Data processing

The huge volume of data acquired with laser scanner need to be processed before it can be of value to users. Point clouds processing is a time demanding task that has to be endured (Rüther et al., 2009; Milius & Petters, 2012). To stress how time intensive it could be, González-Aguilera et al. (2011) approximated as much as three times the duration taken to complete the fieldwork. All scanners come along with proprietary software packages developed by the manufacturers to efficiently manage scans and process point clouds. Data processing stage goes through these three steps in their order of sequence: filtering and registration, 3D meshing and post processing.

Filtering and Registration – comprises of all corrections made to point clouds to eliminate erroneous points before generating mesh surface. Editing functions usually carried out at this level are scan registration, filtering, and noise reduction (Fabio et al., 2003). The process of combining scans obtained from several positions using artificial target points is called scan registration. As mentioned earlier, scanners come with software packages that facilitate this. Iterative closest points (ICP) developed by Besl and McKay (1992) remains so far the most effective and widely used algorithm for scan alignment (Kanaya et al., 2001; Tsakiri et al., 2007; Buchroithner & Gaisecker, 2009). The algorithm employs a minimum of three points common to successive adjacent scans to automatically compute accurate transformation parameters (translation, rotation and scale factors) to glue set of scans and bring them to single point clouds (González-Aguilera et al., 2009, 2011). Occasionally the cave structure may hinder the likelihood to have adequate overlap or to identify sufficient target points, in that case homologous points appearing on adjacent scans are visually identified and interactively selected as data input into the registration process (Gonzalez-Aguilera et al., 2009; Cosso et al., 2014). All point clouds processing software provide the flexibility of using the automatic and manual point correspondence to create high quality registered point clouds.

Once scans are aligned the next step is to reduce noise in the data and get rid of unnecessary points. Cleaning point clouds of unwanted data eliminates invalid data caused by instruments, lessen data redundancy, and maximizes data processing speed and efficiency (Pucci & Marambio, 2009; Cosso et al., 2014). Filtering and allocation of point clouds to feature class usually involve automatic and manual procedure. points outside the cave walls are discarded statistically using predetermined distance range or surface curvature threshold (Gonzalez-Aguilera et al., 2009; Rusu & Cousins, 2011), while those not required or belonging to object groups not related to the surface are deleted manually (Petters et al., 2011). The success of this process is highly dependent on the technical skill and familiarity of the operator with the environment (cave). No matter how carefully executed, it is very rare to attain absolute point clouds coverage without gaps. The possible ways to fill the holes is either to manually add points or fill the void

automatically using cluster of points in the immediate surroundings (Tsakiri et al., 2007).

3D Meshing – triangulated irregular network (TIN), created from a set of x, y, and z coordinates values, is the most widely used topological data structure to depict 3D surfaces. A Triangulation first divide input surface into regular polygonal model that encloses the sampled points. Then the polygons are further partitioned into triangles by connecting the each point to boundary points with straight lines that do not intersect. Two basic rules are critical in defining best triangles that accurately model the surface; one that the triangles are as equilateral as possible, and two that the circumference passing through the three vertexes of a triangle does not contain any other point. According to Pucci and Marambio (2009), triangulation performs three key functions: transform point clouds to a more visually perceptive facsimile, reduce data size, and permit interactivity within and across platforms.

Converting point clouds to polygonal model is more complicated in true three dimensional space than digital terrain model because it involves correct modeling of closed or freeform shapes like caves and overhang that contain multiple elevation values at the same x, y positions (Besl & McKay, 1992; Fabio et al., 2003). Two classes of surface reconstruction algorithms are particularly used for closed surfaces; they are volume oriented Delaunay triangulation (DT) and the parametric function-based B-spline curve (Fabio et al., 2003; Temizer et al., 2013). Delaunay triangulation is an optimal triangulation algorithm that satisfies all the rules for proximal surface reconstruction. The method partitions point clouds into assemblage of adjoining tetrahedrons that meet only at shared edges, summits and sides (Temizer et al., 2013). DT is efficient for storing surface representation while the model thus generated offers an advantage for quantitative analysis of volume of cavity, slope, aspect, elevation, and other geometric elements. The parametric Non Uniform Rational B-Spline (NURBS) curves produce a close-to-surface reconstruction using a set of parameters. The method describe continuous surface using polynomial equation that model as patches of curves (Buchroithner & Gaisecker, 2009). Fig. 4 is a 3D model of a section of Gomantong cave in North Borneo island.

Post-Processing – this is the final processing stage where a number of actions are taken to manually correct surface defects. Filling of holes, correcting edge defects and modification of polygons are the key-editing task done to refine three-dimensional model (Fabio et al., 2003). Triangles can be split up into two; moved to other location, completely removed or even new triangle added to fill void or fix edge problem while still respecting the integrity of the surface. Similar modification can be done to polygons by adding points, adjusting edge or vertexes in order to repair, perfect and preserve shapes. For the purpose of dissemination, visualization or manual interaction and analysis, mesh may be also compressed to reduce data to manageable size and yet preserving the geometric quality.

Fig. 4. 3D model of the Gomantong Cave, Sabah, Malaysia taken from the animated video (Producer: Lundberg & McFarlane, 2012).

Point clouds processing software packages

Point clouds are basically the primary output of laser scanning which are by themselves not useful without software packages to process them. Though not at equal pace with hardware development, point cloud processing packages have received tremendous attention during the last years on three different fronts. Table 2 presents the different modeling and visualization software for 3D reconstruction of the cave geometry.

The first source is from scanner manufacturers who usually accompany their products with dedicated point clouds processing packages. This category includes FARO Scene, Leica Cyclone, RiSCAN Pro and Ri Profile, Trimble RealWorks, and Z+F LaserControl. This group of software is dedicated to TLS hardware and designed to manage scan projects and to process point clouds. Current versions have improved data storage capability and can perform both target-based and automatic scan registration. Also, they are equipped with powerful tools for point cloud editing, visualization and measurement, efficient 3D meshing, and sharing scan projects almost instantaneously via internet streaming thereby enriching point cloud mobility. Applications of these software has expended beyond the traditional point cloud processing and 3D model to other specialized purposes such as infrastructure management, forensic, multimedia, and modeling complex scenarios.

The second front, commonly referred to as third party software, comes from independent point clouds processing software developers with similar capabilities with the scanner companion packages. This group of packages accepts point clouds acquired with any scanner in the standard ASCII 3D coordinate xyz file format as input for processing and analysis. Third party software provides standalone workflow for efficient point cloud processing, editing, manipulation, animation, visualization, and analysis. In this class are PolyWorks, Geomagic, MeshLab, CloudCompare, 3DReshaper, and Bentley 3D imaging and point cloud

tools (Pointools, Descartes, Map Enterprise) offering industry standard applications in infrastructure, GIS and mapping, engineering design, arts and entertainment, and manufacturing industries for prototyping, product design and inspection.

The third source is point clouds processing plug-in packages that run on AutoCAD platform. Usually professional CAD software does not offer tools to import point clouds, edit, visualize and manipulate them. So, one common way to allow editing and 3D polygonal modeling is the development of auxiliary CAD/CAM add-ons like Cloudworx (Intergraph), RapidForm (Donelan, 2002), CloudCUBE (Canevese et al., 2013), PointSense Heritage and pointCloud for AutoCAD (Milius & Petters, 2012), and Autodesk 3D Studio Max (Petters et al., 2011; Milius & Petters, 2012). CAD-enabled point clouds processing software are reverse engineering packages oriented towards providing engineering and industrial solution for automatic solid shape reconstruction. They offer powerful edge detection capability to define boundaries of surfaces and extract geometric standard shapes like pipe, steel structural elements, bridge, etc. (Rüther et al., 2009; Lundberg & McFarlane, 2012; Milius & Petters, 2012) from point clouds, and also to compute volume based on user define lines or planes.

High-resolution laser scanners with powerful point cloud processing software are resourceful tools for many applications. Powerful all-in-one survey production packages such as PointSense Heritage that combines laser scanning and photogrammetry within AutoCAD environment is gradually bringing together different surveying and engineering production workflows under a single platform.

Most of the software packages have capability for basic editing functions like point cloud cleaning and visualization, registration, meshing, quantitative measurement and support for different 3D export file formats like LiDAR Exchange Format (LAS), Virtual reality Modeling Language (VRML), XYZ, X3D, etc. (Boehler et al., 2002; Silvestre et al., 2013).

Table 2. Point clouds processing software packages.

Package	Developer	Availability	Basic Point Cloud Management Capability	3D Modeling	Visualization	Other products
FARO Scene	FARO Technologies	Commercial	Automated (target & target-less) registration. powerful processing & editing capability, colour coded 3D point cloud view. Map external photo to point cloud, data sharing via internet with SCENE WebShare	3D meshing & editing	3D visualization, Texturing, flythrough, and orbits of point clouds	Horizontal and vertical section, volume calculations
Leica Cyclone	Leica Geosystems	Commercial	Automated (target & target-less) registration. Efficient processing & editing. Full 3D point clouds visualization, map external photo to point cloud. Web-based data sharing with Cyclone-PUBLISHER. Direct point cloud importing from other products. Supports distributed parallel computing with Cyclone-SERVER.	3D meshing and 3D CAD geometry/meshes from point clouds as for engineering applications	fly-through animations of point cloud and model	Cross-sections, profiles, contours, Volumes & areas,
RiSCAN PRO & Ri Profile	Riegl LMS	Commercial	Automated (target & target-less) registration, supports hue, saturation and brightness filtering, colour mapping 3D view.	3D meshing & editing, 3D CAD geometry model of pipe from point cloud	3D navigation, Animation with camera focus, texture mapping	Mesh texturing, orthophoto, create geometric objects (Point, line, cylinder, section & plane)
RealWorks	Trimble	Commercial	Automated (target & target-less) registration, 3D point cloud visualization, Advanced-Tank edition. Data sharing with publisher.	3D meshing & editing, 3D CAD geometry model of pipe from point cloud	Mesh coloured with inspection colours. Photo-realistic model	Profile/cross-sections, volume & Surface calculation, contour, video output.
Z+F LaserControl	Zoller + Frohlich GmbH	Commercial	Automated (target & target-less) registration. Map external photo to point cloud for visualization in 3D. data sharing via internet streaming.	3D meshing & editing	Automatic texture mapping & 3D movie/fly-through	Geometric measurements, field of view simulation
PolyWorks	InnovMetric Software inc	Commercial	Target-based registration, powerful point cloud editing. View point shaded by intensity or colour.	Real-time quality 3D meshing & editing	Rendering & 3D view, walkthrough and animation	Volume calculation, profile/cross-section, pipe and planar steelworks modeling and measurement in 3D
Geomagic	Geomagic Inc. (3D Systems)	Commercial	Scan registration and editing. Point cloud visualization	3D meshing & polygonal editing	Animation	3D virtual and actual realities
MeshLab	ISTI-CNR, Italy	Open Source	Scan registration and editing	3D meshing & polygon editing	Interactive mess painting & colour	Supports linear measurement
CloudCompare	Cloud Compare Project	Open Source	Scan registration and edit point cloud. 3D colour view	Mesging & polygon editing	Orthophoto, orthographic and perspective 3D view	Cross-section, volume & surface measurement, local statistics
3DReshaper	Hexagon Metrology	Commercial	Scan registration and edit, extract geometric shapes, Planar & cross-sections. Light model of building from point cloud.	3D meshing & editing,	3D presentation, animation, & photo-realistic rendering	Volume calculation, inspection & 3D comparison, reverse engineering
*Cloudworx	Leica Geosystem	Commercial	Runs on Cyclone and CAD packages; allows interactive point cloud visualization	3D CAD geometry model of Pipe & other planar surface	Intensity & photo-quality true color mapping, TruSpace panoramic viewing	3D coordinate extraction Engineering design & reverse engineering
RapidForm	3D Systems	Commercial	Manages scanc	3D mesh & polygonal editing		Rapid prototyping, product design
*CloudCUBE	VirtualGeo	Commercial	Manage, edit, and visualize point cloud and 3D model on AutoCAD. Direct modeling from point cloud	3D model		Vertical and horizontal sections, linear, angular, slope
PointCloud for AutoCAD	Kubit International	Commercial	Add-on to AutoCAD tool to view and work directly with Point cloud. Speed up 2D drawing, detail image mosaicing.	As-built piping model and other 3D construction		Create geometric model from point cloud semi automatically. Geometric measurements
PointSense Heritage	FARO	Commercial	Combine laser scanning and photogrammetry within AutoCAD. Visualization of point cloud	3D model	Photo-realistic rendering	2D and 3D Plans, detail and sectional drawings
3D Studio Max	AutoDesk	Commercial	3D animation, and rendering	3D modeling	3D graphic animation with camera focus in flight & rendering	
Pointtools	Bentley	Commercial	Point cloud visualization, manipulation, editing, and animation in standalone workflow		Virtual fly-through with camera path and videos	Scaled true ortho-images, plans, facades and sections

Whereas others have extended capabilities such as cloud-to-cloud registration, fusion with other data, rendering, animation, fly-through, and other

sophisticated visualization resources (see Fig. 5 for an advance visualization using RiScan Pro and Pointools View).

Fig. 5. Color point cloud image of Skoteino Cave looking from the back toward the entrance; advance visualization allows stratigraphy within the limestone bedrock to be clearly denoted in the cave walls (Source: Tyree et al., 2014, p. 187).

APPLICATIONS THAT HAVE BENEFITED FROM 3D CAVE SCANNING

Archaeology - Preserving cave environment through the process of recovery, documentation, analysis and archiving of things left behind is one of the key applications that promote the use of TLS in caves (El-Hakim et al., 2004; Beraldin et al., 2006; González-Aguilera et al., 2011; Grussenmeyer et al., 2012). Due to human presence for a long time in the past, caves has become a symbolic community identity venerated by generations as remain of their lineage and cultural attraction. Prehistoric human populations used cave environments for different purposes: shelter, protection, cultural, and spiritual functions. Archaeologists exploit information obtained from such materials, artifacts, and inscriptions of classical antiquities using various devices to understand the evolution of human history and culture. Documentation of cave arts requires a number of integrated hardware such as camera to capture photograph, handheld scanners like FARO Arms for high resolution scan. Integrating these information with cave scan is a complicated and time consuming task that older hard/software cannot process. This is expected to change in the near future with the evolution of more powerful hardware and efficient and high performance software.

Geomorphology - The study of geomorphological processes and characterization of the structure of cave is another scientific application that proves the relevance of 3D scanning. TLS point cloud has been efficiently utilized for 3D visualization of caves with animated fly-through and 3D colored point cloud. 3D mesh derived from point clouds accurately represents the geometry of cave topography which is very useful for geomorphometry, geomorphological mapping, landform process modeling, and, also, 3D visualization (Höfle & Rutzinger, 2011). TLS provides very detail DEM as important resources for quantitative analysis and visualization. Morphometric information such as

volume of cavity, area, plan, sections, slope, elevation, etc. (Lerma et al., 2010; Canevese et al., 2011) have been accurately computed from 3D scanning. In addition to this, third level derivatives such as shaded relief maps can assist in both manual and semi-automatic feature detection and interpretation. The high vertical accuracy of TLS data makes it possible to detect geomorphological features that are difficult to access or rarely perceptible in the field. Laser intensity is another product that has been used to complement other data for geomorphological analysis in cave. Intensity image enhances geometric description, surface classification (Milius & Petters, 2012), and object detection (Azmy et al., 2012; McFarlane et al., 2015). With repetitive scanning, deformation measurement and change in cave structure and form can be detected. High-resolution 3D data is a promising offer for future comparison and analysis of changes at millimeter level that will advance understanding of the dynamic transformation within cave system.

Ice surface morphology change - Closely related to geomorphology is the scientific problem of measuring ice surface morphology and changes. 3D data is a potential basis for change detection and monitoring in the near future. Practical application of TLS has been demonstrated in Buchroithner et al. (2011) and Berenguer-Sempere et al. (2014). 3D model provides opportunities to accurately measure ice surface area and volume. Future scanning will improve understanding of ice surface morphology and dynamics and will equally benefit from glacier mass/area balance estimation.

Ecology - Caves have been a natural habitat for prehistoric human generation; and till this present time a home to varieties of animals and organisms. Ecologists have recognized the importance of 3D data in the study and analysis of inter and intra-species interaction with cave environment as they compete for food and space. For example, Burens et al. (2013) studies the interaction of Bronze Age residents of

Les Fraux Cave through integration of magnetic field measurement with 3D scanning. In his study, he could locate position of fireplaces by analyzing thermal impact on sediment causes local distortion of magnetic field relative to the cave geometry. Biospeleology dominates studies in Malaysian caves where species population counting, roosting pattern and biogenetic modifications are analyzed from TLS intensity data (Azmy et al., 2012; McFarlane et al., 2013).

Palaeoclimatology and Paleontology - The scientific study of past climate and fossil is another field of research with interest in 3D cave scanning. Scientists exploit physical characteristics of data previously preserved within earth such as rocks, sediments, ice sheet, et cetera to reconstruct past earth climatic condition. Chandelier and Roche (2009) provide extensive analysis of paleontological information relative to Tautavel cave geometry. Ice surface morphology plays a key role in ecosystem and climate change. According to Berenguer-Sempere et al. (2014), ice melting contributes to changes in wind temperature condition in and around the cave, the process, which can be better comprehended when viewed and represented in 3D. So, he merged thermal observations with cave model to analyze temperature variation within the cave surface in relation to the geometry. In addition to that, it was possible to extract climatic variables to model the evolution and the behavior of air and heat flow (Petters et al., 2011).

Passage stability/Hazard - As more and more caves are opened to tourists, proactive measures must be taken to ensure safety of their lives at all time. Geologist and geotechnical engineers have proven the capability of TLS data for soil/rock stability analysis (Beraldin et al., 2006). There had been growing concern to identify areas in the cave that are prone to the risk of collapse and rock fall. The works of Lyons-Baral (2012) and Petters et al. (2011) identified vulnerable locations within cave system through the measurement of surface displacement from high-resolution 3D model. Beside passage stability assessment, engineers use 3D data for facility development plan (Rüther et al., 2009; Addison, 2011).

Visualization and education applications - High-level 3D models provide the basic means of viewing the structure of cave. Meshed surface on its own brings home the feel of the shape and form of caves, in addition to being able to make accurate and precise measurements. Another engaging channel of visualization combines photographic imagery with 3D scanning to create virtual cave model (Pucci & Marambio, 2009; Tyree et al., 2014). Currently digital animation and virtual fly-through are the means to convey adequately the picture of the shape of caves (Buchroithner & Gaisecker, 2009). At advanced level however, researchers are exploiting building immersive virtual reality that will give tourists a taste of physical visit to caves - virtual tourism (Cosso et al., 2014), and as well provide special opportunity to engage students, scientists, and marketers in education and outreach while still preserving history for the future generations. The GIS community has

also inject geovisualization into cave research for data exploration, transmission and decision making process by combining cave information with other geospatial data for knowledge construction using different medium such as 3D color coded point cloud, 3D PDF, and 3D web-based visualization (Pucci & Marambio, 2009; Canevese et al., 2011) and web visualization (Silvestre et al., 2013).

DISCUSSION

TLS has become a pivotal tool that brings people of different research orientation together to open new lines of thoughts and inquiries. In general an overview of the duration under consideration can be described in three stages: proof of concept, method standardization and application development. 3D scanning in cave, which began as a “prove of concept” has been accepted today as a scientific tool of enquiry in cave. Starting from 1999 to 2003, scanners were deployed to caves just to assess its capability and thus developed new method of data collection. Then, by establishing universal procedure for scanning in cave was not given a priority, but rather how to generate models that can accurately depict the form and shape of cave and as well facilitates visualization in 3D. When it became certain that TLS provide unparalleled potential, research focus gradually shifted to “method standardization”.

Starting with the work of El-Hakim and his team in the Aboriginal rock arts cave in Baiame, Australia (El-Hakim et al., 2004; Fryer et al., 2005), the method discussed in section 4 have emerged following series of refinement between 2004 and 2012; that was the period when validation of 3D scanning in cave went through the process of maturation as a technique. Then there were concerns about the best possible way to define the level of accuracy needed to achieve optimum visual and geometric fidelity, how to maneuver with different 3D modeling packages with minimum loss in quality of data and products, in addition to coping with large volume of data and excessive processing time (El-Hakim et al., 2004; Grussenmeyer et al., 2010; Lyons-Baral, 2012). Testing with applications outside 3D reconstruction, geomorphology and archaeological documentation, particularly between 2009 and 2012, provides opportunity to scale these issues. The current state of 3D scanning sees application specific researches taking over, a situation that is influenced by technological advances in sensor (Terrestrial scanners for data collection) and improved efficiency of computer system and software solutions.

Advances in sensor technology have been evolving with such rapidity that is well ahead of software solutions. Ever since the first generations of scanners appeared, the design of TLS devices has become more and more reduced in size and weight. For example, it was observed that FARO Focus3D weighs 65 percent less than the first generation FARO LS 880HE model. In the same way, Leica HDS6100 is about 32 percent less than the weight of Cyrax 2400 (see Table 1). This makes the new generation scanners much more mobile and suitable to survey constricted and longer

caves (Lyons-Baral, 2012). The reduction in size of these scanners has made it possible to get into confined spaces that were not possible to scan before.

Beside reduction in weight, design of compact standalone scanners like Leica HDS6100, Focus3D, Imager5006i, Imager5010, etc. with soft touch screen to manage and view scanning in the field is becoming common. In fact the use of external laptop and other peripherals attached to scanners is seemingly an outdated technology. Also, an overall market trend in the newer scanners unveils an evolution of multi-sensor scanning hardware. The integration of other hardware sensors (i.e., GPS receivers, inclinometers, IMU, compass, powerful imaging cameras, and height compensator) with scanners like Focus3D x330, x130 and Z+F Imager 5010X, which have increased the capabilities, brings in sight a new era of total survey solution in the possible near future. Other physical improvement includes enhanced field of view to obtain full panoramic system i.e. 360° by 360°. This can be noticed in Riegl LMS-Z420i, which has a default 80° vertical coverage but now customized to achieve 360° via stepwise tuning at an angle of 5° (Canevese et al., 2011).

Aside the physical characteristics discussed above, technical specifications have also steadily improved during the last decade. Initially, absence of scanners that can provide the needed 3D data for high resolution visualization was a problem (Beraldin et al., 2006), in contrast today, dealing with large volume of points acquired with high resolution scanners turn out to be a subject of concern, though still an advantage. Scanners like Focus3D, Imager5010 and the later scanner models are capable of collecting million and above points per second at relatively short time and higher precision (Burens et al., 2013; Cosso et al., 2014).

Speed and measurement accuracy that use to distinguish CW from TOF is gradually becoming neutralized as both methods now compete favorably in both aspects. Compare FARO photon 120 with Focus3D and Trimble GX with Imager5006i in Table 1. Similarly, the assertion that TOF scanners have range superiority over phase-based scanners is shifting, depending on the application. This can be observed in FARO Focus3D x33 and Z+F Imager 5010x which are PS scanner stepping into the long-range category with exceptional performance in penetration, noise reduction and measurement accuracy. As much as the aforementioned advances in hardware progresses, it cannot, in isolation, deliver without software to complement it.

There has been rapid shifting from 32-bit to 64-bit processors to increased computational performance and the speed at which tasks can be completed in modern computing. This advances in processors, coupled with cores level grading (i.e., 64-bit Core i3, i7, etc.), allow for an increased number of calculations per second that can be performed. This development has increased the processing power and makes computers run faster and more efficiently for processing large volume of point cloud which require many calculations to run smoothly. Apart from performance, the amount of memory (RAM) supported by a computer system depends on the type

of processor. 32-bit computers have maximum of 3-4 GB memory it can accommodate whereas 64-bit computers support over 4 GB memory space. Another progress made in computer processing is in graphic components, which enhance the way pictures, video, animation, and 3D data are displayed on computer screen. Advancements in graphic card technology have augmented the efficiency of translating binary data from the CPU and turn it into a picture on the screen. Also worth mentioning is the growing use of distributed computing using internet infrastructure as a link to share data. This often happens between scanning hardware and other remote devices (computer and mobile platforms) that allow remote user access and process the data.

A major advance in software development is handling data volume (Silvestre et al., 2015). Most of the regular point clouds programs have been optimized to counter excessive processing time and accommodate large volume of data at reasonable processing time. Developers provide enhanced super-highway interface capabilities that make interoperability between different software possible through different data formats that allow exchange from one platform to another with minimal loss of data quality as alternative (Zoller+Fröhlich, 2013). An important achievement in this direction is the growing adoption of E57 compliant data (ASTM E57 File Format for 3D Imaging Data Exchange), which have been accepted as industry standard 3D format by most scanner producers, including all those discussed in this paper. ASTM E57 File Format provides a single common format that reduces the need to convert from one file format to another. Other advantages of the format include efficient storage and data compression (Huber, 2011). This will allow easy transfer of 3D data and other products across different processing platforms (Fabio et al., 2003), which used to be difficult with the binary format of the older versions of point cloud processing programs (Petters et al., 2011; Kordic et al., 2012).

Another development is the increasing convergence of point cloud software developers and laser scanner manufacturers. In February 2013, Geomagic Inc. was taken over by 3D Systems to emphasize CAD applications within 3D scanning. There are numerous examples of smaller software and applications companies being purchased and repackaged through scanning companies like FARO, Leica, and Trimble. These market shifts, purchases and application streamlining will continue to have a major impact on the industry and will likely increase user options and accessible use of tools that work together, rather than separate and hard to work with packages for each specific deliverable. The outcome of this takeover is expected to bolster more powerful and robust platforms that can offer complete solution for reverse engineering, 3D imaging and inspection, and virtual rendering.

Future outlook

The future holds an excellent outlook for incredible innovations in sensor technology, software for

data processing and visualization, and amazing applications. In the near future, the likelihood that miniaturized terrestrial laser scanners capable of collecting data at micro and macro resolution is envisaged. The recent novel laser scanning device used by Schiller and Pfeiler (2015) in underwater cave hints on this. Furthermore, powerful multipurpose system capable of delivering simultaneous 3D scanning, optical positioning, high resolution imaging and video technology, and at the same time communicate with external remote platform for real/near-real time data processing – with appellation such as “RoboScan” (robotic scanner) may soon be a reality.

As hardware becomes more and more sophisticated, so also there will be a pressing need for software packages to handle those huge amounts of scanned data. The problems faced with processing large data and merging images with 3D scan still persists, although less critical (Silvestre et al., 2015). Current virtual reality rendering engines are yet to reach optimal satisfaction in handling mesh structure (Silvestre et al., 2013). Progress is expected in future in response to rising number of immersive intelligence applications such as gaming and immersive virtual realities. Developing operative geovisualization packages is expected to be on the rise due to increasing need to integrate data collected by different interest groups. This decade could see the growth of solution targeted applications and packages such as Split-x (Lyons-Baral, 2012) in the fields like hydrology, structural hydrogeology, volcanology, geodetic and geodynamic, change detection, and so on.

CONCLUDING REMARKS

In this study, the paper presents a comprehensive account of scanning in cave during the last ten years with emphasis on 3D modeling from different perspectives, sensor (hardware), software, and applications through exploration of case studies around the world. It is clear that a lot have been achieved in all the components examined and more is still expected looking through the periscope of current developments and future direction. On sensors, great progress have been made in terms of physical features like size, weight, compactness with new innovations like touch screen, increased memory capacity, battery life time, powerful imaging and video cameras that will counter the current limitations imposed by darkness in the cave. On the technical side too, scan resolution and accuracy, coverage and range have significantly improved. Point cloud processing packages have also advanced with more functionalities, enhanced efficiency and user friendliness. It is expected that future studies will explore further the potential applications of LiDAR intensity either as a product or in combination with 3D scan, in particular to further understand the relationship between the terrestrial topography and the hypogean environment and their contributions to micro and macro climate modification. In conclusion, the current state of cave research is interesting; however the future awaits more innovative products and scientific discoveries.

ACKNOWLEDGEMENTS

This research is supported by Ministry of Higher Education, Malaysia research grant (FRGS/1-2014-STWN06/UPM//02/1) with vote number 5524502 and University Putra Malaysia research grant (GP-1/2014/943200).

REFERENCES

- Addison A., 2011 - LiDAR at Mammoth Cave. Civil Engineering Surveyor, April 2011: 22–25.
- Azmy S.N., Sah S.A.M., Shafie N.J., Ariffin A., Majid Z., Ismail M.N.A. & Shamsir M.S., 2012 - *Counting in the dark: Non-intrusive laser scanning for population counting and identifying roosting bats*. Scientific Reports, **2**: 1–9. <http://dx.doi.org/10.1038/srep00524>
- Beraldin J.A., Blais F., Cournoyer L., Picard M., Gamache D., Valzano V., Bandiera, A. & Gorgoglione M., 2006 - *Multi-resolution digital 3D imaging system applied to the recording of grotto sites : the case of the Grotta dei Cervi*. In The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST: Cyprus, October 30 - November 4, 2006, p. 1–10.
- Berenguer-Sempere F., Gómez-Lende M., Serrano E. & de Sanjosé-Blasco J.J., 2014 - *Orthothermographies and 3D modeling as potential tools in ice caves studies: The Peña Castil Ice Cave (Picos de Europa, Northern Spain)*. International Journal of Speleology, **43** (1): 35–43. <http://dx.doi.org/10.5038/1827-806X.43.1.4>
- Besl P. & McKay N., 1992 - *A method for registration of 3-D shapes*. IEEE Transactions on Pattern Analysis and Machine Intelligence, **14** (2): 239–256. <http://dx.doi.org/10.1109/34.121791>
- Blais F., 2004 - *Review of 20 years of range sensor development*. Journal of Electronic Imaging, **13** (1): 231–240. <http://dx.doi.org/10.1117/1.1631921>
- Boehler W., Heinz G., Marbs A. & Albertz J., 2002 - *The potential of non-contact close range laser scanners for cultural heritage recording*. Cipa 2001 International Symposium on Surveying and documentation of historic buildings, monument and sites. Traditional and modern methods, Postdam, September 18–21, 2001, **1**: 430–436.
- Buchroithner M.F. & Gaisecker T., 2009 - *Terrestrial laser scanning for the visualization of a complex dome in an extreme alpine cave system*. Photogrammetrie - Fernerkundung - Geoinformation, **4**: 329–339. <http://dx.doi.org/10.1127/1432-8364/2009/0025>
- Buchroithner M.F., Milius J. & Petters C., 2011 - *3D surveying and visualization of the biggest ice cave on earth*. In: Proceedings of 25th International Cartographic Conference. Paris, France, 3–8 July 2011.
- Buchroithner M.F., Petters C. & Pradhan B., 2012 - *Three-dimensional visualisation of the world-class prehistoric site of the Nial Great Cave, Borneo, Malaysia*. In: Kremers H. (Ed.), Interdisciplinary Conference on Digital Cultural Heritage. Saint-Die-des-Vosges, 2–4 July, 2012.
- Bullock J.A., 1965 - *Malaysian caves*. Malayan Nature Journal, **19** (1): 1–3.
- Burens A., Grussenmeyer P., Guillemin S., Carozza L., Lévêque F. & Mathé V., 2013 - *Methodological developments in 3D scanning and modelling of archaeological French heritage site: the Bronze Age painted cave of “Les Fraux”, Dordogne (France)*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, **XL-5/W2**: 131–135. <http://dx.doi.org/10.5194/isprsarchives-XL-5-W2-131-2013>

- Canevese E.P., Tedeschi R. & Forti P., 2009 - *The caves of Naica – laser scanning in extreme underground environments*. The American Surveyor, **6**: 3–10.
- Canevese E.P., Forti P. & Tedeschi R., 2013 - *New acquisition, 3D modeling, and data used methods: The laser scanning survey of Retiberio Cave*. In: Filippi M. & Bosák P. (Eds.), 16th International Congress of Speleology, Brno, **2**: 340–345.
- Canevese E.P., Forti P., Naseddu A., Ottelli L. & Tedeschi R., 2011 - *Laser scanning technology for the hypogean survey: the case of Santa Barbara karst system (Sardinia, Italy)*. Acta Carsologica, **40** (1): 65–77.
- Caprioli M., Minchilli M., Scognamiglio A. & Strisciuglio G., 2003 - *Architectural and natural heritage: virtual reality with photogrammetry and laser scanning*. In: Proceedings of XIXth International Symposium CIPA, Antalya, Turkey, p. 1–5.
- Chandelier L. & Roche F., 2009 - *Terrestrial laser scanning for paleontologists: the Tautavel Cave*. In: XXII CIPA Symposium: Digital Documentation, Interpretation & Presentation of Cultural Heritage, Kyoto, Japan, 11–15 October, 2009, p. 1–5.
- Chasen F.N., 1931 - *Report on the Birds' Nest Cave and industry of British north Borneo with special reference to the Gomantong caves*. Jesselton, p. 1–24. <http://dx.doi.org/10.5962/bhl.title.101600>
- Cheves M., 2013 - *LIDAR*. LIDAR Magazine, **3** (5): 2–4.
- Cosso T., Ferrando I. & Orlando A., 2014 - *Surveying and mapping a cave using 3D laser scanner: the open challenge with free and open source software*. ISPRS Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, **XL-5**: 181–186. <http://dx.doi.org/10.5194/isprsarchives-XL-5-181-2014>
- Doering T., Collins L. & Branas C., 2006 - *Preacher's Cave high definition survey and 3D laser scanning project, Eleuthera, Bahamas*. Scanning. <http://aist.usf.edu/data/preacher-report.pdf>
- Donelan J., 2002 - *Making prehistory: Researchers digitize a cave-art gallery*. Computer Graphics World, **25** (3). <http://www.cgw.com/Publications/CGW/2002/Volume-25-Issue-3-March-2002-/Making-Prehistory.aspx>
- El-Hakim S.F., Fryer J. & Picard M., 2004 - *Modeling and visualization of aboriginal rock art in the Baiame Cave*. In: Proceedings of the XXth Congress of the International Society for Photogrammetry and Remote Sensing: 12–23 July 2004, Istanbul, Turkey. Commission V, Working Group V/2, p. 990–995.
- Fabio R., 2003 - *From point cloud to surface: the modeling and visualization problem*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, **XXXIV-5/W10**, 11 p.
- Fryer J.G., Chandler J.H. & El-hakim S.F., 2005 - *Recording and modelling an aboriginal cave painting: with or without laser scanning?* International Society for Photogrammetry and Remote Sensing, **2**: 1–8.
- González-Aguilera D., Muñoz A.L., Lahoz, J.G., Herrero J.S., Corchón M.S. & García E., 2009 - *Recording and modeling paleolithic caves through laser scanning*. In: Proceedings of the International Conference on Advanced Geographic Information Systems and Web Services, GEOWS 2009, **2**: 19–26. <http://dx.doi.org/10.1109/GEOWS.2009.7>
- González-Aguilera D., Muñoz-Nieto A., Gómez-Lahoz J., Herrero-Pascual J. & Gutierrez-Alonso G., 2009 - *3D digital surveying and modelling of cave geometry: Application to paleolithic rock art*. Sensors, **9** (1): 1108–1127. <http://dx.doi.org/10.3390/s90201108>
- González-Aguilera D., Rodríguez-Gonzálvez P., Mancera-Taboada J., Muñoz-Nieto A., Herrero-Pascual J. & Gómez-Lahoz J., 2011 - *Application of non-destructive techniques to the recording and modelling of palaeolithic rock art*. In: Wang C.-C. (Ed.), Laser scanning, theory and applications. InTech, p. 305–326. <http://dx.doi.org/10.5772/14567>
- Grussenmeyer P., Burens A., Moisan E., Guillemin S., Carozza L., Bourrillon R. & Petrognani S., 2012 - *3D multi-scale scanning of the archaeological cave les Fraux in Dordogne (France)*. In: Ioannides et al. (Eds.), 4th International Conference, EuroMed 2012: Progress in Cultural Heritage Preservation, **7616**: 388–395. http://dx.doi.org/10.1007/978-3-642-34234-9_39
- Grussenmeyer P. & Guillemin S., 2011 - *Photogrammetry and laser scanning in cultural heritage documentation: an overview of projects from INSA Strasbourg*. In: GTC 2011: Geomatics Technologies in The City **1937**: 1–8. <http://geomaticsksa.com/GTC2011/S4/PDF/21.pdf>
- Grussenmeyer P., Landes T., Alby E., & Carozza L., 2010 - *High resolution 3D recording and modelling of the Bronze Age cave "Les Fraux" in Périgord (France)*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVIII: 262–267.
- Haddad N.A., 2011 - *From ground surveying to 3D laser scanner: A review of techniques used for spatial documentation of historic sites*. Journal of King Saud University of Engineering Sciences, **23** (2): 109–118. <http://dx.doi.org/10.1016/j.jksues.2011.03.001>
- Hoffmeister D., Zellmann S., Kindermann K., Pastoors A., Lang U., Bubenzer O. & Bareth G., 2014 - *Geoarchaeological Site Documentation and Analysis of 3D Data Derived By Terrestrial Laser Scanning*. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, II-5: 173–179. <http://dx.doi.org/10.5194/isprsannals-II-5-173-2014>
- Höfle B. & Rutzinger M., 2011 - *Topographic airborne LiDAR in geomorphology: A technological perspective*. Zeitschrift Für Geomorphologie, Supplementary Issues, **55** (2): 1–29. <http://dx.doi.org/10.1127/0372-8854/2011/0055S2-0043>
- Huber D., 2011 - *The ASTM E57 file format for 3D imaging data exchange*. In: Proceedings of the SPIE, Electronics Imaging Science and Technology Conference (IS&T), 3D Imaging Metrology, **7864A**, 9 p. https://www.ri.cmu.edu/pub_files/2011/1/2011-huber-e57-v3.pdf
- Kanaya I., Kadobayashi R. & Chihara K., 2001 - *Three-dimensional modelling of Shofukuji burial chamber*. In: 7th International Conference on Virtual Systems and Multimedia, Berkeley, 25–27 October 2001, p. 113–120. <http://dx.doi.org/10.1109/VSM.2001.969662>
- Kingston T., 2010 - *Research priorities for bat conservation in Southeast Asia: A consensus approach*. Biodiversity and Conservation, **19** (2): 471–484. <http://dx.doi.org/10.1007/s10531-008-9458-5>
- Kordic B., Dapo A. & Pribicevic B., 2012 - *Application of terrestrial laser scanning in the preservation of fortified caves*. In: FIG Working Week 2012 - Knowing to manage the territory, protect the environment, evaluate the cultural heritage, Rome, Italy, 6–10 May 2012, 7 p.
- Lerma J.L., Navarro S., Cabrelles M. & Villaverde V., 2010 - *Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic cave of Parpalló as a case study*. Journal of Archaeological Science, **37**: 499–507. <http://dx.doi.org/10.1016/j.jas.2009.10.011>

- Lundberg J. & McFarlane D.A., 2012 - *Post-speleogenetic biogenic modification of Gomantong Caves, Sabah, Borneo*. *Geomorphology*, **157-158**: 153-168.
<http://dx.doi.org/10.1016/j.geomorph.2011.04.043>
- Lyons-Baral J., 2012 - *Using terrestrial LiDAR to map and evaluate hazards of Coronado Cave, Coronado National Memorial, Cochise County, AZ*. Retrieved February 14, 2015, from <http://azgeology.azgs.az.gov/article/earth-science/2012/08/using-terrestrial-lidar-map-and-evaluate-hazards-coronado-cave>
- Marsico A., Infante M., Iurilli V. & Capolongo D., 2015 - *Terrestrial laser scanning for 3d cave reconstruction: support for geomorphological analyses and geoheritage enjoyment and use*. In: Andreo B., Carrasco F., Durán J.J., Jiménez P. & LaMoreaux J.W. (Eds.), *Hydrogeological and environmental investigations in karst systems*. Springer-Verlag Berlin, p. 543-550.
<http://dx.doi.org/10.1007/978-3-642-17435-3>
- McFarlane D.A., Buchroithner M., Lundberg J., Petters C., Roberts W. & Rentergen G.V., 2013 - *Integrated three-dimensional laser scanning and autonomous drone surface-photogrammetry at Gomantong Caves, Sabah, Malaysia*. In: Proceedings of the 16th International Congress of Speleology, Brno, **1**: 317-319.
- McFarlane D., Roberts W., Buchroithner M., Rentergem G.V., Lundberg J. & Hautz S., 2015 - *Terrestrial LiDAR-based automated counting of swiftlet nests in the caves of Gomantong, Sabah, Borneo*. *International Journal of Speleology*, **44 (2)**: 191-195. <http://dx.doi.org/10.5038/1827-806X.44.2.8>
- Milius J. & Petters C., 2012 - *Eisriesenwelt – From laser scanning to photo-realistic 3D model of the biggest ice cave on Earth*. In: Jekel T., Car A., Strobl J. & Griesebner G. (Eds.), *GI-Forum 2012: Geovisualization, Society and Learning*. Wichmann Verlag, Berlin: 513-523.
- Perperidou D.G., Tzortzioti E. & Sigizis K., 2010 - *A new methodology for surveying and exploring complex environments using 3D scanning*. In: FIG Congress 2010 - Facing the Challenges - Building the Capacity, Sydney, 11-16 April 2010, p. 1-14.
- Petters C., Milius J. & Buchroithner M.F., 2011 - *Eisriesenwelt: Terrestrial laser scanning and 3d visualization of the largest ice cave on Earth*. In: Proceedings European LiDAR Mapping Forum, Salzburg, Austria, 8 p.
- Pucci B. & Maramba A., 2009 - *Olerdola's Cave, Catalonia, past and present: A virtual reality reconstruction from terrestrial laser scanner and GIS data*. In: 3D ARCH'2009. 3D Virtual Reconstruction and Visualization of Complex Architectures, 25-28 February 2009, Trento, Italy, p. 1-6.
- Robson-Brown, K.A., Chalmers A., Saigol T., Green C. & D'Errico F., 2001 - *An automated laser scan survey of the Upper Palaeolithic rock shelter of Cap Blanc*. *Journal of Archaeological Science*, **28**: 283-289.
<http://dx.doi.org/10.1006/jasc.2000.0574>
- Roncat A., Dublyansky Y., Spötl C. & Dorninger P., 2011 - *Full-3D surveying of caves: a case study of Märchenhöhle (Austria)*. In: Marschallinger R. & Zobl G. (Eds.), *IAMG 2011 Proceedings: Mathematical geosciences at the crossroads of theory and practice*, Salzburg, Austria, p. 1393-1403. <http://dx.doi.org/10.5242/iamg.2011.0074>
- Rusu R.B. & Cousins S., 2011 - *3D is here: point cloud library*. IEEE International Conference on Robotics and Automation, p. 1-4. Retrieved from <http://pointclouds.org/>
- Rüther H., Chazan M., Schroeder R., Neeser R., Held C., Walker S.J. & Horwitz L.K., 2009 - *Laser scanning for conservation and research of African cultural heritage sites: the case study of Wonderwerk Cave, South Africa*. *Journal of Archaeological Science*, **36**: 1847-1856.
<http://dx.doi.org/10.1016/j.jas.2009.04.012>
- Schiller A. & Pfeiler S., 2015 - *A laser technique for capturing cross section in dry and underwater caves*. In: Andreo B., Carrasco F., Durán J.J., Jiménez P. & LaMoreaux J.W. (Eds.), *Hydrogeological and environmental investigations in karst systems*. Springer, Berlin, p. 551-558.
<http://dx.doi.org/10.1007/978-3-642-17435-3>
- Shan J. & Toth C.K., 2008 - *Topographic laser ranging and scanning principles and processing*. CRC Press, Boca Raton, 616 p.
<http://dx.doi.org/10.1201/9781420051438>
- Shaw T., 2004a - *Speleogenesis theories: early*. In: Gunn J. (Ed.), *Encyclopedia of caves and karst science*, Fitzroy Dearborn, New York, p. 669-670.
- Shaw T., 2004b - *Speleologist*. In: Gunn J. (Ed.), *Encyclopedia of caves and karst science*. Fitzroy Dearborn, New York, p. 686-689.
- Silvestre I., Figueiredo M. & Veiga-Pires C., 2015 - *High-resolution digital 3D models of Algar do Penico Chamber: limitations, challenges, and potential*. *International Journal of Speleology*, **44**: 25-35.
<http://dx.doi.org/10.5038/1827-806X.44.1.3>
- Silvestre I., Rodrigues J.I., Figueiredo M.J.G. & Veiga-Pires C., 2013 - *Cave chamber data modeling and 3D web visualization*. In: Proceedings of the International Conference on Information Visualisation, p. 468-473.
<http://dx.doi.org/10.1109/IV.2013.103>
- Tamás L., 2010 - *Data acquisition and integration 4. Laser scanning*. Retrieved March 26, 2015, from http://www.tankonyvtar.hu/en/tartalom/tamop425/0027_DAI4/ch01.html
- Temizer T., Nemli G., Ekizce E., Ekizce A., Demir S., & Yilmaz H.F., 2013 - *3D documentation of a historical monument using terrestrial laser scanning case study: Byzantine Water Cistern, Istanbul*. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **XL-5/W2**: 623-628.
- Tolan-Smite C., 2004 - *Human occupation of caves*. In: Gunn J. (Ed.), *Encyclopedia of caves and karst science*. Fitzroy Dearborn, New York, p. 919-924.
- Tsakiri M., Sigizis K., Billiris H. & Dogouris S., 2007 - *3D laser scanning for the documentation of cave environments*. In: 11th ACUUS Conference: Underground Space, Expanding the Frontiers, 10-13 September 2007, Athens, p. 403-408.
- Tyree L., McCoy F., Frey J. & Stamos A., 2014 - *3D imaging of Skoteino Cave, Crete, Greece: Successes and difficulties*. *Journal of Field Archaeology*, **39 (2)**: 180-192.
<http://dx.doi.org/10.1179/0093469014Z.00000000081>
- Vosselman G. & Maas H.-G. (Eds.), 2010 - *Airborne and terrestrial laser scanning*. CRC Press/Whittles Publishing, Boca Raton, 318 p.
- Yumin L., Rong Z. & Yu Z., 2013 - *The application of 3D laser scanning in the protection of grottoes*. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, **XL**: 705-709.
<http://dx.doi.org/10.5194/isprsarchives-XL-5-W2-705-2013>
- Zoller+Fröhlich, 2013 - *How we build reality: Zoller + Fröhlich in 50 years*. Wangen im Allgäu, Germany. Retrieved from www.zf-laser.com