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Performance of Affordable 2D Cave Scanning Technique from LiDAR for Constructing 3D Cave Models

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Abstract

This research presents a new approach to the cave 3D model construction by a combination of a cave two-dimensional profile scanning using a low-cost modified 2D LiDAR, and data processing via a computer-aided design (CAD) software. The proposed technique has been tested to create 3D models of three Permian limestone caves in northern Thailand, namely Chiang-Dao, Muang-On, and San-Han. The entire method takes 27-30 hours to achieve, covering approximately 614.59 meters of the total survey distance and generating an overall cave volume of 41,310.0 m^3. The resulting 3D models ultimately resemble the shape, orientation, and dimension of the caves, exhibiting burrow-like, irregular-shaped, and some deformation-induced features. The proposed LiDAR scanning method appears to be relatively cheap and fast compared to other scanning methods as it has the working speed of 63.5 meters per hour costing less than $200 USD. These findings distinctly indicate that the developed data processing of cave scanning profiles using 2D LiDAR is affordable and meets the need for cave 3D modeling. However, there are minor limitations, including missing data among the scanned profiles and overlaps of cave features formed in the sidewalls. The cave models produced here can be used as reference sources for geoscientific research, geotourism, georesource management, and other research activities in caves. Further hardware and software development is strongly recommended to improve the existing methods.

1. Introduction

Over the past decade, interest in natural and show cave surveys has been growing, probably due to a rising number of natural phenomena and/or accidents. A couple of notable instances include (i) the life rescue of unintentional entrapment of thirteen boys in a large well-known show cave located in Chiang Rai Province, northern Thailand, in 2018 (Irwin, 2022), and (ii) one of the causes of the global COVID-19 emergence has been presumed that is affected by the animals living in natural caves (Wacharapluesadee et al., 2021). Recently, thousands of show caves worldwide have been discovered attracting over 70 million visitors annually (Chiarini et al., 2022). These emphasize the need for advanced cave environmental research and management. Numerous publications derived in the past twenty years have highlighted the significance of cave studies and suggested proper ways for cave management (Cigna and Burri, 2000; Whitten, 2009; Bocic et al., 2006). However, there is a lack of modern implementation research, especially in Thailand, as it is difficult to put a confined space exploration strategy into practice (Auler and Piló, 2011; Morgan and Walker, 2011; Bolger and Ellis, 2015). In addition, lack of support from the government and economic challenges appear to obstruct the research-related activities of the cave surveys (Dusan, 1994; National Cave and Karst Research Institute, 2013).

The cave mapping method plays a crucial role in the exploration and management of caves worldwide (Kambesis, 2007). The method involves the creation of two-dimensional (2D) and/or three-dimensional (3D) maps displaying the layout and description of the cave system. The maps also serve as practical tools for general public users to grasp specific characteristics of the caves and visualize their surrounding landscapes before entering, especially in the show caves (Alt and Moura,

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2013; Zieliński et al., 2022; Haryono et al., 2022). A cave 2D map is a representation of cave features on a two-dimensional surface with a scale. It includes the orientation and size of passages, e.g. length and width, and the reference locations of the cave. A cave 3D model, on the other hand, represents a user-interactive object drawn on a three-dimensional view in the x, y, and z axis with a scale. It is an effective tool for cave geotourism and geoscientific research. The model likely exhibits a real-world shape of the cave that can be used to comprehend the geomorphological characteristics formed in the cave, and thus the cave-forming process.

According to numerous previous works, three-dimensional scanning Light Detection and Ranging (3D LiDAR) technology, also known as Terrestrial Laser Scanning (TLS), is a significant tool for creating three-dimensional models of caves (Fabbri et al., 2017; Oludare and Pradhan, 2016; Walters and Hajna, 2020). Unsurprisingly, this technology comes with a likely high cost for commercial uses, ranging from $4,000 USD to $100,000 USD (Bi et al., 2021). Despite a lack of cave details, the 2D cave mapping survey becomes more workable and cost-acceptable than the 3D survey.

A two-dimensional scanning LiDAR, known as a 2D LiDAR, has a majority of useful applications for autonomous driving vehicles, unmanned aerial vehicles (UAV), object-based detection of robotic systems, etc. The tool provides a wide range of data quality associated with a relatively low price, starting from $76 USD, compared to those of the 3D LiDAR (Bi et al., 2021, Sun et al., 2023; Ho et al., 2021; Mihálik et al., 2022). However, working with the data obtained by this tool comes up with a major challenge.

This article presents a comprehensive technique of cave 3D modeling from data acquiring and processing practices using a low-cost modified 2D LiDAR. This technique was initially trialed in three cave surveys, namely Muang-On, Chiang-Dao, and San-Han caves, which are located in the northern part of Thailand. This study additionally aims to evaluate the effectiveness of the proposed method according to its overall expenses, total working hours, data accuracy, and data resolution, as well as the occurrence of limitations.

2. Equipment and Software

The equipment used involves (i) a modified two-dimensional vertical-scanning LiDAR instrument, (ii) a portable digital laser distance measuring device, and (iii) a geological compass. More details are provided in the following.

The Slamtec model A1M8 of 2D LiDAR provides the operating process of laser triangulation and object distance measurement. The tool emits an infrared laser hitting the surface object horizontally. The laser is then reflected off and received by the detector of the tool resulting in data points on the coordinating axis that can be related to the shape of the chamber or area (Fig. 1). To collect a cave 2D profile data set, the original horizontal-scanning LiDAR has been modified by 90° clockwise rotation of the basal axis as shown in Figure 2. The modified version also comes with a tripod and a working function for data storage via a laptop presented in Figure 3.

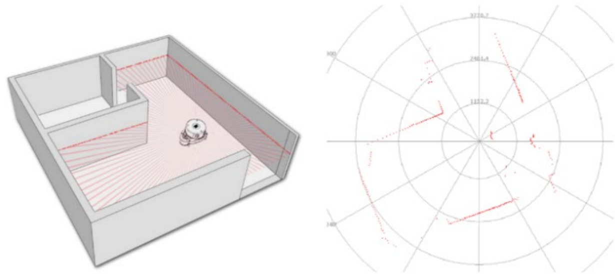

Figure 1. A traditional two-dimensional LiDAR model of Slamtec (2020) exhibits a clockwise full-circle rotating pattern that allows to detect and measure the distance and azimuth of the surrounding objects in horizontal direction.

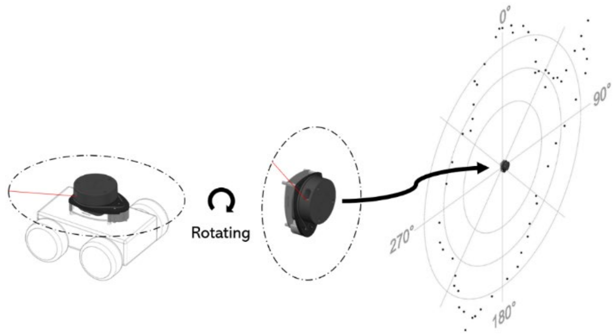

Figure 2. A modification of the traditional 2D LiDAR by 90° clockwise reorienting of the original basal plane. This allows the LiDAR to detect the surrounding objects in a vertical direction. This can help to obtain a numerical data set of each cave profile.

Figure 3. Cave profile scanning in the Muang-On show cave, Chiang Mai, Thailand. The equipment used exhibits the modified 2D LiDAR carefully attached to a camera tripod connected to a laptop. The LiDAR sensor rotates vertically to measure the distance between cave walls, floors, and roofs to create a single cave profile.

The use of the Bosch laser distance measurer and the Brunton geological compass are managed to obtain the scanning intervals, profile orientations, and walking direction (Fig. 4). These measured parameters are keys to construct a survey line, which is subsequently integrated with the set of cave 2D profiles, in order to create a cave model. Other tool brands can be applied as long as they work efficiently and precisely.

This study has ultimately employed computer-aided design (CAD) software to process all field-collected data and generate a three-dimensional model of the cave. The CAD software facilitates data virtualization, data visualization, and allows for the modification of coordinates through computer graphics (Swamidass, 2000).

Figure 4. A portable laser distance measurer and geologic compass were used for the entire study method.

3. Method

3.1. Cave Scanning and Survey

A dataset of two-dimensional cave profiles is obtained by LiDAR scanning along a survey line drawn in a cave passage. The collected data of each profile are originally plotted in a Polar Coordinate System format, determined by the distance from a reference point and an azimuth of 0°–360°. The data is then transformed into a Cartesian Coordinate System, which, on the other hand, exhibits a set of data points related to three coordinate axes, including x, y, and z, allowing for work in three-dimensional space. To perform the conversion from Polar Coordinates into Cartesian Coordinates, we have used an equation proposed by Lippman and Rasmussen (2017) (Eq.1).

$$y = r\cos(\theta) \text{ and } z = r\sin(\theta) \qquad (1)$$

where y = distance from a reference along the y-axis
z = distance from a reference along the z-axis
r = distance from a reference of the Polar Coordinates
θ = an azimuth or angle from a reference position

All converted coordinate data is plotted against the x, y, and z axes of the Cartesian System as presented in Figure 5. These processes are carefully applied to the scanned profiles of all three studied caves.

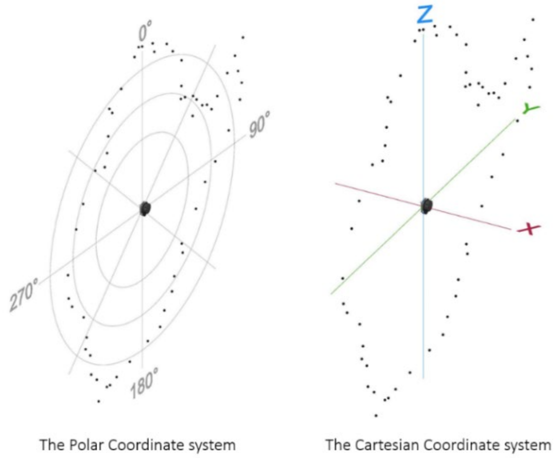

Figure 5. Original data of a single cave profile obtained by 2D LiDAR scanning methods presented in the Polar Coordinate System (left) and the converted version of the data shown in the Cartesian Coordinate system (right).

3.2. Three-Dimensional Modeling

The point data of each cave profile is connected by polylines, exhibiting a polygon with an orientation. The cave profiles can potentially indicate the size of the passages, while the survey line indicates cave length and shape. A number of polygon cave profiles are subsequently rearranged and combined into the cave survey line via CAD software. The resulting process is presented in Figure 6.

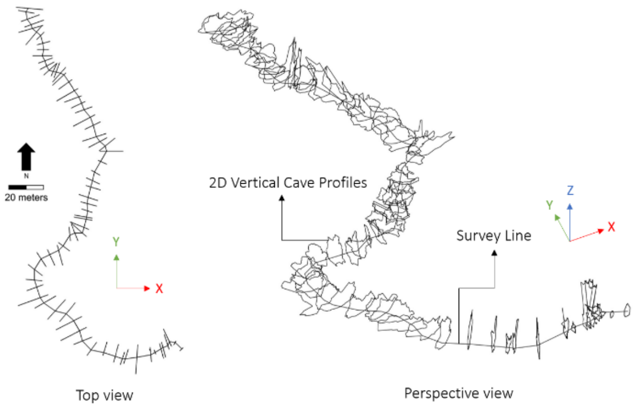

Figure 6. Arrangement of numerous 2D cave profiles, exhibiting various-sized polygons along the cave survey line, shown in both top view and perspective view with a scale.

These polygons, or cave profiles, are then merged in order to generate a three-dimensional sketch. The process is performed using one of the CAD functions called Ruled Surfaces or Loft Surfaces (Fig. 7). According to Farin (2001), this function is a geometric system used to generate a smooth surface between sketch profiles by moving a straight line along a trajectory, which is also called a generator curve. The function of Loft Surfaces is widely used in mathematics and engineering to simulate various 3D model objects, such as aircraft wings, car roofs, and ship hulls. Applying the Loft Surfaces function to the cave profiles ultimately results in a three-dimensional model of a cave showing a particular shape, for example, an irregular tube-like, burrow-like, or orthogonal pattern depending on geological background of the areas. The resulting model of Chiang-Dao cave is shown in Figure 8. The identical methods are applied to the other two caves (Fig. 9).

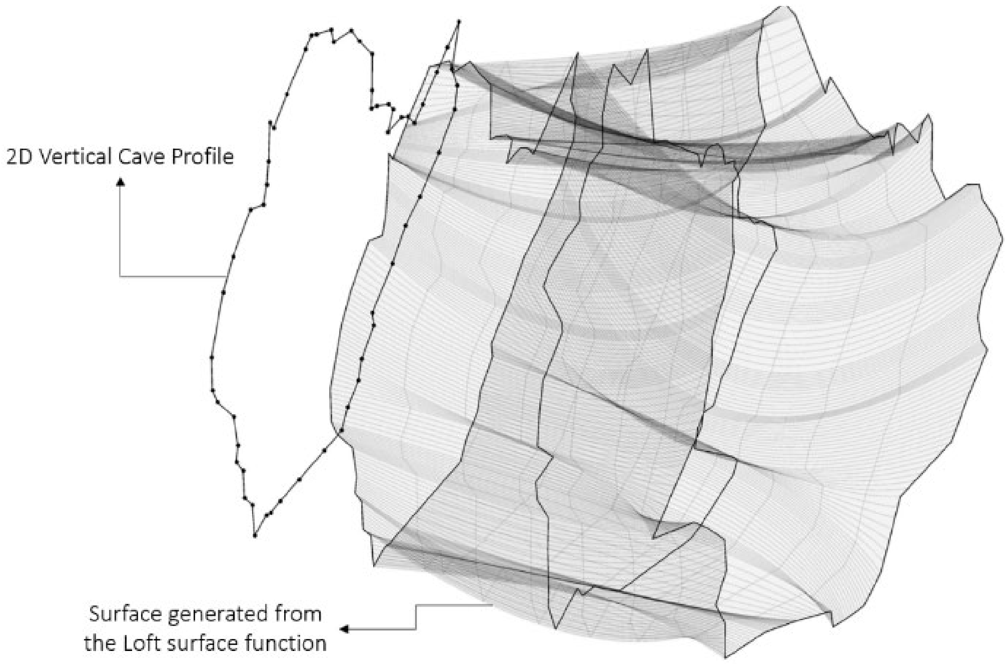

Figure 7. Each profile is merged using a Loft Surfaces function through CAD software. This command creates a smooth surface, showing a light grey color in the transition between cave profiles.

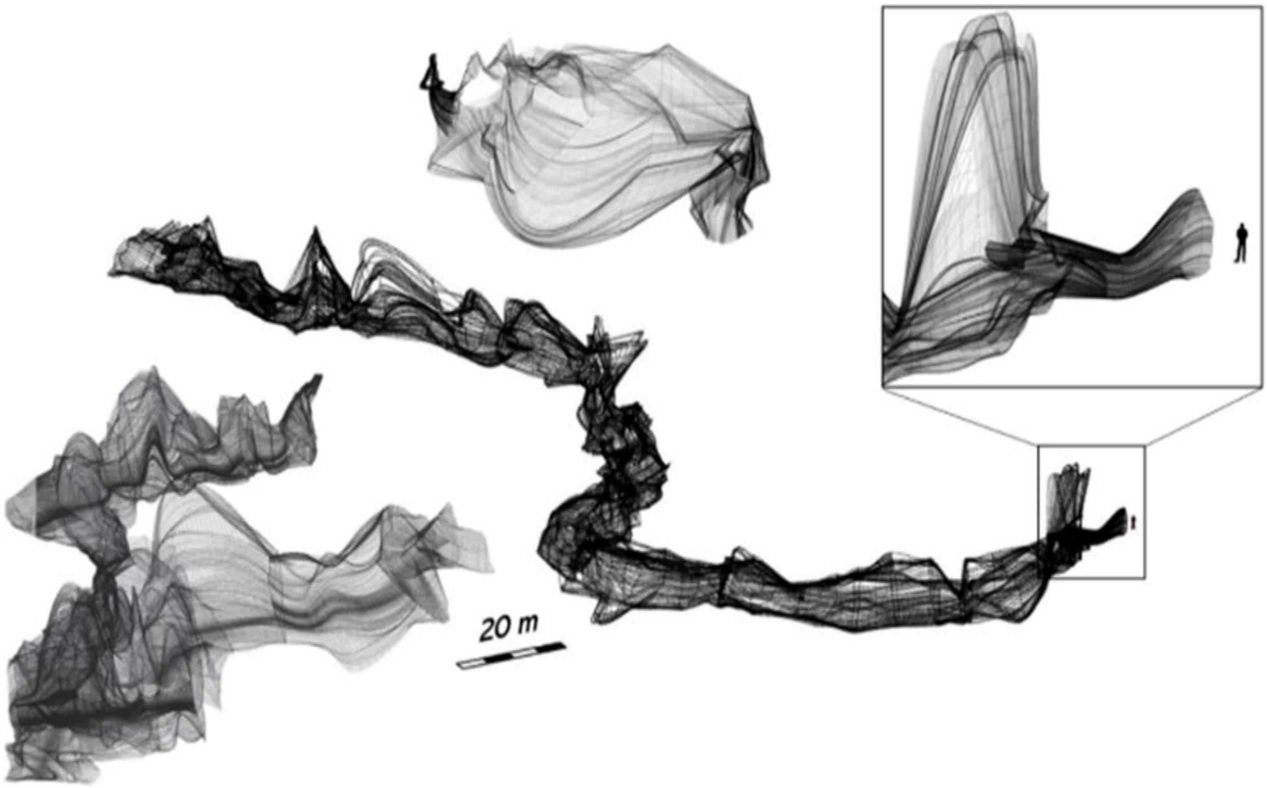

Figure 9. 3D models of the three show caves resulted from the proposed techniques. The caves include Muang-On (lowermost), Chiang-Dao (middle), and San-Han (uppermost). An additional scale is presented as a human with a height of 1.7 m showing in the extended square area. The user-interactive version of the Muang-On and Chiang-Dao cave 3D models are published via Sketchfab.

Figure 8. The resulting three-dimensional model of Chiang-Dao cave generated from the proposed methods, is displayed with scale and direction. The cave entrance is located to the south.

4. Results

Three caves in Thailand have been trailed by the proposed methods. Two of them are located in Chiang Mai Province namely Chiang-Dao Cave (*19.39411°N, 98.92786°E*), and Muang-On Cave (*18.78657°N, 99.23843°E*). The third cave, San-Han Cave (*17.99047°N, 100.71601°E*), is in Uttaradit Province. The total length of the survey lines for these three caves is approximately 614.59 meters, comprising 309.57 meters for Chiang-Dao, 217.15 meters for Muang-On, and 87.87 meters for San-Han. The resulting three-dimensional models of the studied caves distinctly provide information on their length, orientation, structure, and volume.

Chiang-Dao Cave likely formed in the north-south and northeast-southwest direction with a cave volume of 9,124.0 m^3. Muang-On Cave exhibits two passages showing the structure driven by the fracture system formed in the Permian limestone formation, with a cave volume of approximately 23,676.0 m^3. San-Han Cave, with a volume of 8,510.0 m^3, shows a relatively large passage compared to the other two caves. The shape possibly indicates one of the fractures formed in limestone.

The entire process apparently takes ten hours of working time per cave. This time can be divided into two periods: (i) field working hours and (ii) office working hours. The fieldwork activities consist of a two-or-three-hour cave scan, excluding travel time. The remaining seven-to-eight hours are spent on data processing and cave modeling in the office. However, it is necessary to note that the working time is highly depended on cave dimensions, the number of scanned profiles, safety rules, and the social and legal status of the areas.

Consideration of the performance speed of cave modeling methods are based on working time and cave dimensions. The results suggest that the cave 2D LiDAR scan for one hour can likely cover at least 100 meters. According to cave 3D modeling, this method achieves a speed of 27 meters per hour. The working performance is also considered in terms of cave volume, with the results indicating that the entire cave 2D scanning and 3D modeling methods are accomplished at a speed of 1,642 m^3 per hour.

5. Discussions

The outcomes of this study have significantly provided new insights into cave modeling techniques using a simple 2D LiDAR. The equipment and software used were discussed in terms of financial aspects and efficiency. The overall working period of this technique was also compared to that of other modeling instruments. Tool limitations and further suggestions were also provided in the following.

5.1. Cost and Timing Operation

The hardware involved in this study was certainly purchased from any available store at a total price of less than $300 USD. The LiDAR tool adapted in this study, manufactured by Slamtec with the A1M8 series model, individually costs $76 USD. The distance measurer and the Brunton geologic compass were purchased at prices of $35 USD and $20 USD, respectively. According to information from an online retailer and web service provider, the prices of portable distance measuring devices can range from $30 USD to $150 USD (Amazon, 2023). The geologic compasses of other brands exhibit a wide range of prices starting from $20 USD to $250 USD (Amazon, 2023a). This study strongly supports the idea that the judicious use of the tools at reasonable prices is key to performing a three-dimensional cave modeling.

Another crucial cost is software licensing. It is well-known that there are a variety of popular CAD software such as (i) AutoCAD developed by Autodesk and (ii) Rhino developed by Robert McNeel & Associates. These software options potentially cost $150 USD monthly for an annual rental option. To obtain a perpetual license for this software, it costs $995 USD that is clearly equal to $83 USD monthly paid only in the first year. However, software development companies also offer academic versions of CAD software at a relatively low price, as low as $30 USD annually (Robert McNeel & Associates, 2023), or even free of charge (Autodesk, 2023). Moreover, there are several free open-source software available, such as FreeCAD (Riegel et al., 2023) and Blender (Blender Foundation, 2023) that can sufficiently provide necessary features for working on cave three-dimensional modeling tasks.

Previous work of Gallay (2015) investigated that a cave 3D scanning using a (TLS) method certainly takes an average speed of 15 meters per hour. The method is apparently six times slower than the 2D scanning using LiDAR and four times slower than the entire cave 3D modeling methods proposed by this work. However, it is essential to consider their working performance and price as the TLS offers three-dimensional imaging data, providing more detail and higher accuracy. These abilities come with relatively high costs, starting from $4,000 USD. Proper machine maintenance is strongly required in association with a scanner technician position. Future studies are recommended to deeply compare other factors, such as the overall costs, the total number of workers or technicians required for single operation, and the complexity and quality of the data.

5.2. Accuracy and Resolution

Since this study has not tested detailed resolution of the 2D LiDAR, the tool potential has been referred to the standard information of the 2D LiDAR model A1M8 provided by the manufacturer.

According to Slamtec (2020), the 2D LiDAR model A1M8 has a scanning range of 0.15-12 meters with a distance resolution output of <1% of the distance. The angular working range of the tool covers 0-360° with an angular resolution of ≤1°. The scan rate is approximately 5.5 Hz. The tool tolerates temperatures of 20-40 °C. The data accuracy is likely decreased with increasing distances, for instance, 99% at distances of below 3 meters, 98% at distances of 3-5 meters, and 97.5% at distances of 5-25 meters. This tool model has been extensively applied in a variety of usages, in which require high data resolution with acceptable accuracy, and be able to adapt to a vast condition of environments, for example, autonomous navigation (Ariante et al., 2022; Aslam et al., 2020; Jiang et al., 2018). This study has totally agreed that the 2D LiDAR model A1M8 is sufficient for working on cave scanning methods.

5.3. Limitations

Besides the specification and limitation of the equipment itself, the proposed technique obviously comes with a couple of constraints including, (i) missing data or missing gap among the scanned profiles and (ii) overlaps of objects on the same profile. The details have been provided as follows.

Since the spacing interval among the scanned profiles have been previously set at 1-3 meters depended on the cave morphology, this causes an unintended missing of profile data along the survey line and leads to a misinterpretation of a cave model. Increasing the number of scanned profiles by reducing the interval space to less than 1 meter seems to prevent the problems. However, the solution certainly requires longer working time.

The presence of cave geologic formations that include stalactites, stalagmites, pillars, or columns, poses a major challenge in the cave two-dimensional scans. These features are overlapped, irregular-shaped, and formed on the sidewall, roof, and floor leading to misinterpretation of the exact size and shape of cave profiles. Additional survey lines with a different set of orientations and directions should probably be considered to cover this doubt. This method must unsurprisingly handle a majority and complexity of data resulting in the need for longer working time.

5.4. Applications

The technique of using a two-dimensional scanning modified device coupled with self-development CAD software for the cave three-dimensional modeling proposed here effectively provides numerous potential applications in geoscientific research, geotourism, and georesource management.

The 3D models of natural or show caves have served as a reference to structural characteristics on a regional scale and some karst features on a local scale. The models resemble the shape, orientation, and dimension of the caves that can augment the understanding of the cave genesis and geological deformation. The cave 3D models also appear to be practical in many other research activities conducted in caves, for example, cave-influencing cultures, geohazards, troglophiles, architectures, and historical evidence of ancient civilization found in the caves.

The cave 3D products have distinctly encouraged the use of a traditional two-dimensional cave mapping as shown in Figure 10. The models can also provide more detailed features than those of 2D maps allowing the updates on the cave characteristics and structures to be obviously recognized. These cost-effective and less time-consuming methods for generating cave 3D models seem to fit for georesource management procedures run by the national organizations and private individuals.

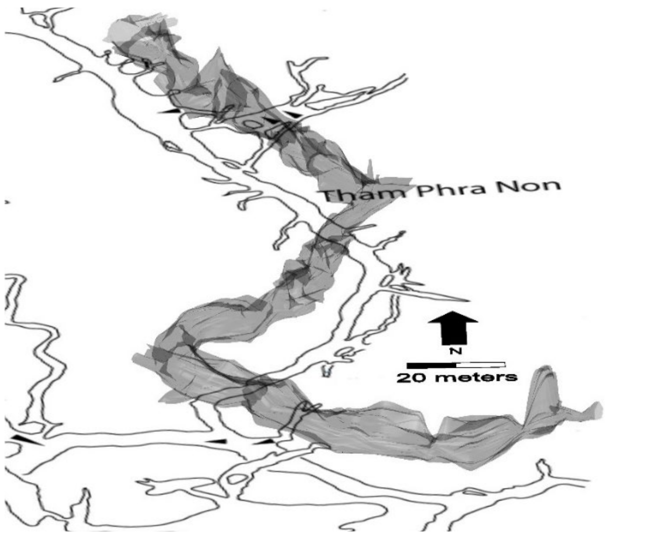

Figure 10. A traditional 2D map of Chiang-Dao Cave presented with the 3D model of this work exhibiting its main passage in a grey-colored zone (modified from Ellis, 2022).

6. Conclusion

Although there are many modern methods and equipment used in cave 3D modeling for vast purposes, the proposed technique meets the need for 3D modeling, in terms of data quality, time, and cost. It is also a straightforward method that includes (i) 2D LiDAR profile scanning and survey, which were conducted in fields, coupled up with (ii) 3D modeling through CAD software. The resulting cave models of the three studied caves distinctly exhibit burrow-like, irregular-shaped, and some deformation-induced features. Relative prices, working speeds, and specification of the tools indicate that the cave 3D models created by processing of cave 2D scanning profiles using a modified 2D LiDAR are affordable with minor limitations. The cave models can be used as reference sources for geoscientific research, geotourism, georesource management, and other activities in the caves. Further research and innovation relating to hardware and software development is strongly required to improve the existing methods.

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Author contributions

Khomchan Promneewat; Methodology, Fieldwork, and manuscript editing.
Tadsuda Taksavasu; Fieldwork and original manuscript writing.

Conflicts of interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

Research and publication ethics were complied with in the study.

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