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MARIA GIMENA CHAVES FITZGERALD

3D RECONSTRUCTION OF CAVES:
An analysis of existing low-cost reconstruction alternatives and their application process

Recife
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An analysis of existing low-cost reconstruction alternatives and their application process

Dissertation submitted in partial fulfillment of the requirements for the award of the degree of Master of Science in Computer Science with a concentration in Artificial Intelligence, as stated in the defense record.

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Maria Gimena Chaves Fitzgerald

“3D Reconstruction of Caves: An analysis of existing low-cost reconstruction alternatives and their application process”

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ABSTRACT

Caves are complex environments from a spatial point of view and modeling and graphically representing them is not a trivial task. 3D models are often needed to research, record, and represent these environments. Recently, with the use of laser scanning systems, it has become possible to obtain reliable 3D representations of caves. However, the high costs and difficult acquisition of the equipment needed limit the possibilities of its use in Brazil. Considering the speleological potential of the country, being able to carry out low-cost 3D reconstructions of natural underground cavities would allow the expansion of the documentation of caves in the Brazilian territory, adding new possibilities such as precise calculations of volume and area. The three-dimensional products would also serve multiple purposes, such as environmental licensing and ecotourism, among others. This dissertation presents an analysis of three existing affordable reconstruction alternatives using the iPhone 13 Pro Max and the Intel RealSense L515 camera. The reconstructions obtained with each alternative and the application process for data capturing, processing, visualization, and area and volume estimations are presented. The three low-cost reconstruction techniques demonstrated potential for reconstructing small-scale caves and specific objects/features inside them, being the iPhone 13 Pro Max's built-in LiDAR scanner approach the most time efficient and simple to use. However, the limited capture range of all the sensors tested does not allow capturing very distant objects, so the reconstruction of big-size caves may not be possible with the presented approaches. Considering the results of this dissertation, new research opportunities arise, like testing the proposed step-by-step pipelines in different caves, amongst others.

Keywords: 3D modeling; caves; LiDAR; photogrammetry; low-cost reconstruction; 3D reconstruction pipeline.

RESUMO

As cavernas são ambientes complexos sob o ponto de vista especial, e modelar e representá-las graficamente não é uma tarefa trivial. Não obstante, modelos 3D são frequentemente necessários para a pesquisa, registro e representação destes ambientes. Recentemente, com o uso de sistemas de escaneamento a laser, tornou-se possível obter representações 3D fidedignas de cavernas. Porém, os elevados custos e a difícil aquisição dos equipamentos usados para este fim limitam as possibilidades de sua utilização no Brasil. Considerando o potencial espeleológico do país, poder realizar reconstruções 3D de baixo custo das cavidades naturais subterrâneas permitiria ampliar as documentações das cavernas no território brasileiro, adicionando novas possibilidades como cálculos precisos de volume e área. Os produtos tridimensionais também serviriam para múltiplas finalidades, como licenciamento ambiental e ecoturismo, entre outras. Esta dissertação apresenta uma análise de três alternativas de reconstrução de cavernas *low-cost* utilizando o iPhone 13 Pro Max e o sensor Intel RealSense L515. As reconstruções obtidas com cada alternativa e o processo de aplicação para captura, processamento, visualização e estimativas de área e volume dos dados são apresentados. As três técnicas de reconstrução de baixo custo demonstraram potencial para reconstruir cavernas de pequena escala e objetos/características específicos dentro delas, sendo que a abordagem usando o scanner LiDAR incorporado no iPhone 13 Pro Max é a mais eficiente em termos de tempo e facilidade de uso. No entanto, o alcance limitado de captura de todos os sensores testados não permite capturar objetos muito distantes, e como consequência a reconstrução de cavernas de grande porte pode não ser possível com as abordagens propostas. Considerando os resultados desta dissertação surgem novas oportunidades de pesquisa, como testes dos processos de reconstrução propostos em novas cavernas, entre outras.

Palavras-chave: modelagem 3D; cavernas; LiDAR; fotogrametria; reconstrução de baixo custo; sequência de reconstrução 3D.

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1 INTRODUCTION

1.1 MOTIVATION

Caves are natural openings in the ground extending beyond direct sunlight that result from diverse geological processes in certain types of rock (Davies & Morgan, 1991). These geoforms present a wide variety of sizes and shapes given by erosive attributes (i.e., walls, ceiling, floor, conduits, etc.) and depositional features (speleothems, like stalactites and stalagmites) (Tarbuck et al., 2005). Those macro and micro characteristics define spatially irregular environments. Besides their morphological complexities, caves can be hidden from view and therefore not be apparent on topographic maps, aerial photographs, and satellite imagery (Kambesis, 2007). Consequently, documenting them is not a trivial task. The frequent lack of light in their interior makes their study even more challenging (Giordan et al., 2021). In addition, the fragility given by the presence of troglobites (cave-dwelling fauna) and different species that frequent these sites, as well as archeological artifacts, rock paintings and other types of prehistoric remains, make the use of remote techniques to study these environments necessary to minimize potential impacts in their interior (Iniesta et al., 2013; Büyüksalih et al., 2020; Gautier et al., 2020).

The advent of 3D reconstruction techniques based on laser scanning systems in recent years has enabled high fidelity mapping and quantification of the Earth surface properties and processes (Eitel et al., 2016). Three-dimensional representations allow comprehensive documentations of caves, including precise estimations of volume and area, all useful information for better understanding, managing, and preserving these environments. A 3D reconstruction consists of three main steps: a) data collection; b) data processing and generation of 3D mesh; and c) visualization and interpretation of results (Buckley et al., 2008). Data capturing is the cornerstone of the whole process, as the quality of the final model will be defined mainly on this stage. Different data capture equipment can be adopted for this purpose, being laser technology LiDAR (Light Detection and Ranging, also called Laser Scanning) the most extensively used (Buchroithner et al., 2009; Núñez et al., 2013; Berenguer-Sempere et al., 2014; Cosso et al., 2014; Gallay et al., 2015; Silvestre et al., 2015; Fabbri et al., 2017; Idrees & Pradhan, 2019). Alternatively, other data collection methodologies can be used to map natural underground cavities, like photogrammetry (Dabove et al., 2019), even though many photogrammetric approaches involve the use of TLS to some degree (Rodríguez-Gonzálvez et al., 2012; De Waele et al., 2018; Pukanská et al., 2020; Giordan et al., 2021).

1.2 PROBLEM DEFINITION

Despite the potential of LiDAR scanners for 3D reconstruction of caves, the adoption of this technology in Brazil is not widely spread mainly due to three reasons (Teixeira et al., 2023):

a) Costs: Laser scanner prices can reach tens of thousands of US dollars[1].
b) Difficulty of acquisition: In general, the necessary equipment can only be acquired through importation, demanding bureaucratic, time-consuming processes.
c) Handling: Large data volumes generated by such systems usually require high performance computers.

The prohibiting high costs and difficulty of acquisition restrict the possibilities of use of laser scanners to a limited number of companies and laboratories (Grohmann et al., 2019). Moreover, complex big data manipulation involving different software can make the use of such equipment tough for lay users (Cosso et al., 2014). The more challenging data collection and data processing are, the more setbacks they can produce. This can be problematic when time and funding for research activities are limited.

Considering that there are around 23,000 caves registered in Brazil (CECAV, 2023), and estimations indicate that many more have not yet been inventoried, the enormous speleological potential of the Brazilian territory is undeniable (Piló & Auler, 2011). Being able to conduct affordable 3D representations of caves would allow a more extensive documentation of Brazilian speleological environments, with precise calculations of their areas and volumes. Accurate surveys of caves would also make it possible to understand their origin and the processes that have led to their current state (speleogenesis), as well as to provide information to predict future processes that can take place inside them (Idrees & Pradhan, 2016). Furthermore, quantitative information of cave morphometrics acquired with 3D models could be useful when studying karst

[1] Starting prices for Terrestrial LiDAR scanners are around 15,000 USD (https://www.geo-matching.com).

aquifer too (Jouves et al., 2017). The three-dimensional products would also serve other purposes, like environmental licensing, geotourism and heritage preservation, amongst others (Gautier et al., 2020; Büyüksalih et al., 2020).

Low-cost alternatives to laser scanning for 3D reconstructions of caves have recently been studied, like mobile LiDAR (Chaves Fitzgerald et al., 2022) and RGB-D cameras (Hämmerle et al., 2014; Gautier et al., 2020; Teixeira et al., 2023). However, bibliography with that focus is not extensive.

Based on the above-mentioned facts, the proposed research question is: which low-cost, easy-to-use alternatives exist to carry out 3D reconstruction of caves, what are their advantages and disadvantages and how do they compare to one another?

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1.3 AIMS AND OBJECTIVES

The present Master's dissertation aims to study low-cost alternatives for 3D reconstruction of caves using different technological solutions that combine hardware and software to serve geologists, biologists, and speleologists in general, regardless of their computational skills. An end-to-end pipeline for 3D reconstruction of caves with each of the studied solutions will be defined. The process to be presented will not only include the generation of a 3D model, but also the extraction of quantitative information like area and volume. Additionally, a usability and time-efficiency comparison will be carried out to understand how the proposed alternatives compare to one another.

For that, the specific objectives of this dissertation are:

a) Compile and analyze the existing technological solutions for 3D reconstruction of caves through an analysis of related work.
b) Classify data acquisition devices mentioned in academic papers and/or available in the market according to their cost and portability and select the ones that best fit the research's aims for testing.
c) Collect information about 3D data processing solutions and select the most suitable ones for testing.

d) Collect information on 3D visualization tools and area and volume measurement solutions and select the most appropriate ones for testing.
e) Carry out fieldwork to collect data with the selected capture devices in real speleological environments.
f) Test the selected data processing and visualization software with the collected field data to generate 3D models.
g) Synthesize the reconstruction process with each proposed solution in an end-to-end flowchart.
h) Compare the reconstruction solutions in accordance with the defined criteria.

1.4 DISSERTATION OUTLINE

This dissertation is organized as follows:

Chapter 1 presents the motivation for the study of low-cost solutions to reconstruct speleological environments. The problem definition and the general and specific dissertation goals are introduced, as well as the proposed research question.

In Chapter 2, the theoretical framework on 3D reconstructions is presented and discussed. Data collection devices and data processing and visualization solutions are presented.

Chapter 3 details the methodological approach adopted in this study. The complete data capture, processing, result visualization and measurement process followed with each device is described, as well as the fieldwork conducted, including the studied caves' localization and general morphological characteristics.

Chapter 4 presents the resulting reconstructions obtained with the alternatives tested, as well as processing times and area and volume estimations. The reconstruction workflows proposed for each solution are also presented.

Chapter 5 includes the discussion session, where the results are assessed and the proposed reconstruction alternatives are compared based on the assessment criteria defined in Chapter 3.

Finally, Chapter 6 brings the final considerations, as well as contributions and suggestions for future work in the topic.

Chapter 7 includes the references of this work.

2 THEORETICAL FRAMEWORK

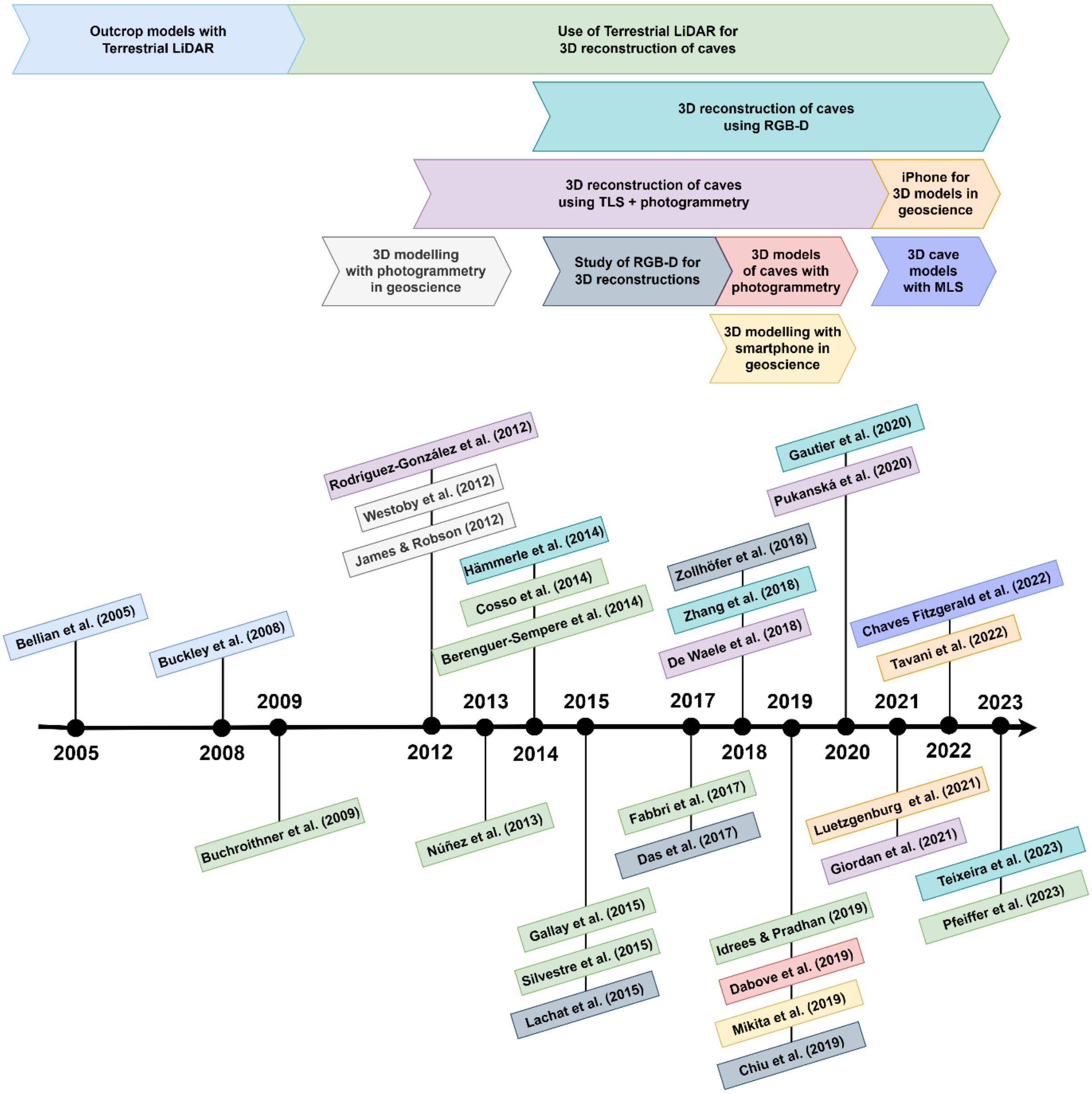
The need to gather qualitative and quantitative information for better understanding and managing speleological environments has led researchers to work on three-dimensional reconstructions of caves, especially since the 2000'. The motivations for such reconstructions go from academic to touristic and heritage preservation purposes (Berenguer-Sempere et al., 2014; Büyüksalih et al., 2020; Cosso et al., 2014). The fragility of cavernous environments, given by their constituting rock formations, the biodiversity that finds shelter in them, and the archeological materials many times present (Iniesta et al., 2013; Büyüksalih et al., 2020; Gautier et al., 2020), demands remote sensing techniques for their mapping to minimize any potential impacts. Different data collection methods can be adopted for this purpose, being laser technology LiDAR the most widely used (Buchroithner et al., 2009; Núñez et al., 2013; Berenguer-Sempere et al., 2014; Cosso et al., 2014; Gallay et al., 2015; Silvestre et al., 2015; Fabbri et al., 2017; Idrees & Pradhan, 2019). Alternatively, three-dimensional modeling of natural underground cavities can be based on photogrammetric techniques alone (Dabove et al., 2019), or used together with TLS (Rodríguez-Gonzálvez et al., 2012; De Waele et al., 2018; Pukanská et al., 2020; Giordan et al., 2021). In addition, the use of RGB-D cameras is also gaining importance in the 3D reconstruction of caves field (Hämmerle et al., 2014; Zhang et al., 2018; Gautier et al., 2020; Teixeira et al., 2023). A discussion on the mentioned technologies is presented below, with an emphasis on the reasons brought in academic literature for using each of them. After that follows a discussion on the main processing solutions used to generate three-dimensional meshes as well as solutions that allow both their visualization and interpretation. A description of alternatives for extraction of quantitative information is also presented at the end of this section.

2.1 DATA CAPTURE TECHNIQUES

To reconstruct a physical environment, it is necessary to capture 3D information. 3D data collection is the act of gathering information from the real world, with X, Y and Z coordinates, and making it digital (Pfeifle & Spar Point Group, 2012). As mentioned above, different 3D data acquisition methods exist, including laser scanning, photogrammetry and RGB-D sensors (Chaves Fitzgerald et al., 2022;

Dabove et al., 2019; Teixeira et al., 2023). A description of these techniques is presented in the following sections. To provide a temporal sense regarding the advances in the use of each technology, Figure 1 illustrates the type of sensor and the context of application brought in the related work consulted.

Figure 1 – Timeline of the publication of the consulted papers on 3D modeling. The technology for data capture adopted in each of them and the context of application is indicated with different colors.



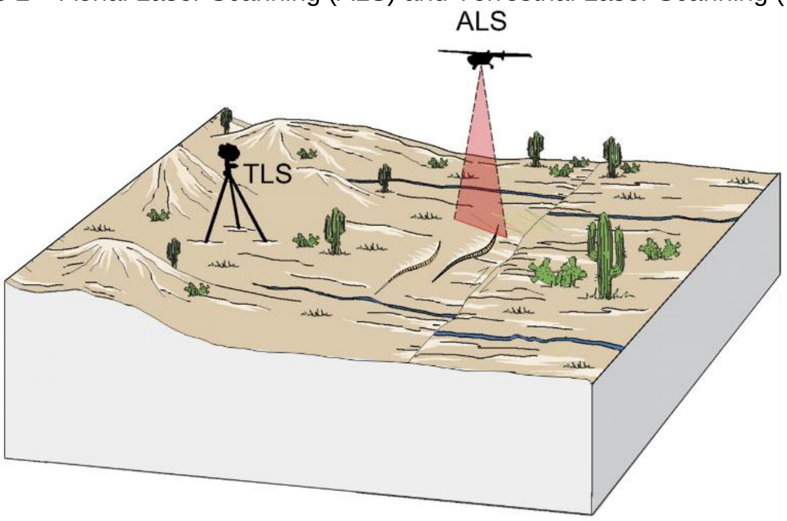
Source: the author (2023).

2.1.1 LiDAR sensors

LiDAR sensors are based on the emission of thousands of laser pulses per second that travel to remote targets, bounce off them, and return to a detector within the device (Bellian et al., 2005). The X and Y positions of each point reached on the surface of interest is calculated from the angle of the emitted pulse, whilst to obtain the distance Z, two different principles can be followed: a) Time of Flight (ToF), in which the two-way travel time of the emitted pulse is divided in half and multiplied by the speed of light; or b) Phase recognition or phase shift, that considers the phase shifting between the transmitted and received sinusoidal wave (Bellian et al., 2005; Gallay et al., 2015; Eitel et al., 2016). This way, a point cloud with high resolution X, Y and Z coordinates can be obtained to digitally reproduce the environment. The fact that LiDAR scanners are active sensors represents an advantage compared to other instruments, as they do not depend on an external source of light to capture data.

For regional studies, Airborne Laser Scanning (ALS) using aerial platforms are a commonly used form of data collection, while for detailed surveys, static terrestrial platforms are used. This last approach is known as Terrestrial Laser Scanning (TLS) (James & Robson, 2012; Eitel et al., 2016), and is the most widely employed technique in medium range studies in Geosciences (Figure 2).

Figure 2 – Aerial Laser Scanning (ALS) and Terrestrial Laser Scanning (TLS).

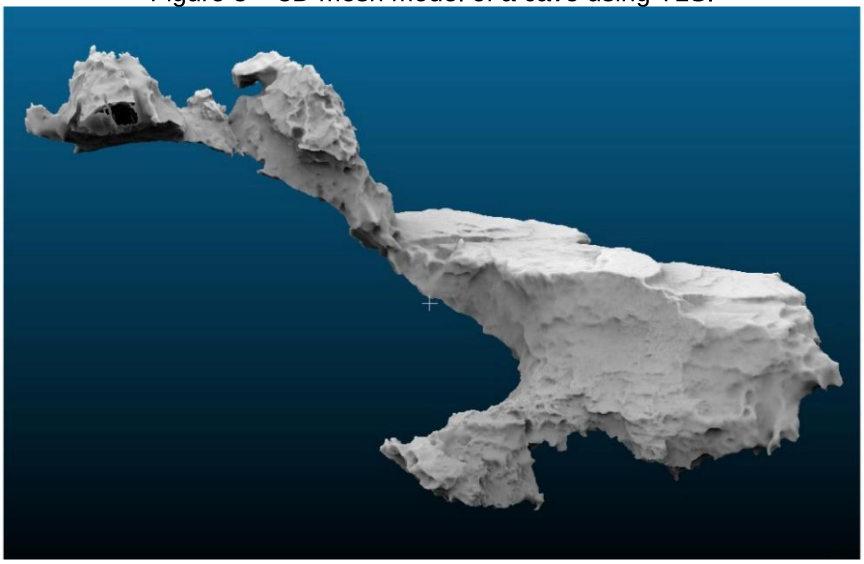


Source: Modified from Haddad et al. (2012, p. 772).

2.1.1.1 Terrestrial Laser Scanning

The wide adoption of this tool for the study of caves is explained by its speed of acquisition of large amounts of data and its unprecedented spatial resolution and precision (Pfeiffer et al., 2023). The highly realistic three-dimensional models obtained with this instrumental make the visualization of physically inaccessible areas possible, as well as the extraction of qualitative and quantitative information from mapped surfaces (Bellian et al., 2005; Buckley et al., 2008; Berenguer-Sempere et al., 2014; Silvestre et al., 2015; Fabbri et al., 2017; Pukanská et al., 2020) (Figure 3). Amongst the information that can be extracted from high resolution models obtained with TLS, are: i) areas and volumes, which serve to monitor the evolution of the environment, susceptible to changes over time; ii) cartographic products such as maps and cross sections; iii) correlation of three-dimensional information with other data, to deepen the understanding of the environment; iv) identification of objects not easily recognizable in the field and the extraction of their morphometric measurements, which would otherwise not be possible to obtain (Cosso et al., 2014; Fabbri et al., 2017).

Figure 3 – 3D mesh model of a cave using TLS.



Source: Cosso et al. (2014, p. 184).

The portability and robustness that TLS equipment has achieved over time favors its use in hostile environments, where temperature and humidity conditions, in addition to the presence of mud and dripping water, can be harmful to electronic devices in general (Buchroithner et al., 2009). When choosing the appropriate instrument, its minimum range should be considered, since this parameter defines the accuracy of measurements in short distances, which will have an influence in gathering information in narrow spaces inside the cave; the maximum range, on the other hand, is less critical in this sense, as the ranges of work in these environments do not exceed tens of meters (Gallay et al., 2015).

In recent studies, different approaches for the use of Terrestrial Laser Scanning in the development of three-dimensional models of speleological environments are presented (Pukanská et al., 2020; Giordan et al., 2021; Pfeiffer et al., 2023). The main manufacturers of TLS equipment used in those 3D investigations of caves include FARO, Leica Geosystems, Riegl Laser Measurement Systems, Trimble and Zoller + Frohlich GmbH (Idrees & Pradhan, 2016). The most popular models mentioned in the consulted literature are the FARO Focus 3D sensors family (Gallay et al., 2015; Fabbri et al., 2017; Dabove et al., 2019; Idrees & Pradhan, 2019), Leica ScanStation C10 (Silvestre et al., 2015; Pukanská et al., 2020), Riegl LMS-Z420i (Buchroithner et al., 2009; Núñez et al., 2013; Giordan et al., 2021), Riegl VZ-400 (Hämmerle et al., 2014; Büyüksalih et al., 2020), Riegl VZ-2000i (Pfeiffer et al., 2023), Trimble GS200 (González-Aguilera et al., 2009), Trimble GX (Rodríguez-Gonzálvez et al., 2012), and Z+F IMAGER 5010 (Cosso et al., 2014). It is worth noting that all of the models listed are valued at several thousands of dollars.

Another reason for the great adoption of this technology is the possibility of texturing the resulting model with digital photographs captured during the field information surveys; however, the use of appropriate equipment to improve the natural light conditions of the environment to take quality photos can be a limiting factor (Bellian et al., 2005; Buckley et al., 2008; Gallay et al., 2015).

All the above being said, it is clear that the choice of this technology for mapping in underground contexts has been motivated by the high precision and resolution of the collected data. Nonetheless, there are some challenges related to the use of Terrestrial Laser Scanning. The large amount of 3D points generated with this scanner can complicate their manipulation and interpretation, as well as the integration with other spatial information in Geographic Information Systems (GIS) (Bellian et al., 2005; Buckley et al., 2008; Cosso et al., 2014; Gallay et al., 2015; Silvestre et al., 2015). Transporting the TLS equipment inside the cave can also be problematic, due to access difficulties in some sectors, in addition to the fact that the scanner has to be placed securely on firm ground during each scanning position (Cosso et al., 2014; Gallay et al., 2015) (Figure 4). This last condition also requires prior planning of the positions of the scanner for capture, adding one more procedure to its use (Berenguer-Sempere et al., 2014; Cosso et al., 2014; Idrees & Pradhan, 2019; Pukanská et al. al., 2020).

Figure 4 – Mapping of caves using TLS.

Source: (Left) Cosso et al. (2014, p. 182); (Right) Rodríguez-González et al. (2012, p. 575).

This capture solution has a price that is proportional to the quality of its results. As already mentioned, a high-resolution LiDAR scanner can cost tens to hundreds of thousands of dollars[2]. As an example, according to the Laser Scanning Forum[3], the RIEGL VZ 400i TLS scanner can cost between 110,000-120,000 USD. Along with the elevated costs of the instrument, its difficult acquisition (through importation) restricts the possibilities of its use in Brazil, preventing it to be adopted as a conventional and universal method. It is no coincidence, as evidenced by Idrees & Pradhan (2016), that there is a predominance of research on 3D reconstruction of caves from Europe in relation to other parts of the world, but rather a consequence of economic and access possibilities to the appropriate instruments (due to the fact that most TLS manufacturers are located on the European continent).

2.1.1.2 Mobile Laser Scanning

Portable versions of TLS scanners are the so-called Mobile Laser Scanners (MLS). These sensors have a wide range of prices; however, low-cost alternatives exist: It is the case of Apple’s latest iPhone Pro smartphones with built-in LiDAR

[2] The geo-matching.com website states that prices for Terrestrial Laser Scanners can range between 15,000 to 120,000 USD depending on its data acquisition capabilities like range, accuracy and others.
[3] https://www.laserscanningforum.com

scanners, which can be acquired in the Brazilian market for a price starting at approx. 1,600 USD[4]. Since releasing the iPhone 12 Pro in late 2020, Apple has been incorporating LiDAR sensors to its most recent Pro devices[5]. The portability and ease of use make smartphone LiDARs an interesting option for 3D modeling applications in challenging environments. Given its recent introduction to the market, the available academic bibliography of iPhone LiDAR application in geoscience is scarce; however, the studies already published testing this equipment in geological contexts have had encouraging results (Luetzenburg et al., 2021; Tavani et al., 2022).

In addition to smartphone-incorporated LiDAR, some sensor developers have introduced their own low-cost mobile laser scanners. The Intel RealSense L515[6] device, launched in December 2019, serves as an example. This LiDAR sensor can be acquired in Brazil for approximately 2,600 USD[7]. Its integrated RGB camera allows capturing color data, making it a promising alternative for cave mapping. However, similarly to the case of smartphone LiDAR scanners, there is a lack of scientific studies regarding the use of these instruments in caves, making it necessary to analyze their performance in these environments (Chaves Fitzgerald et al., 2022).

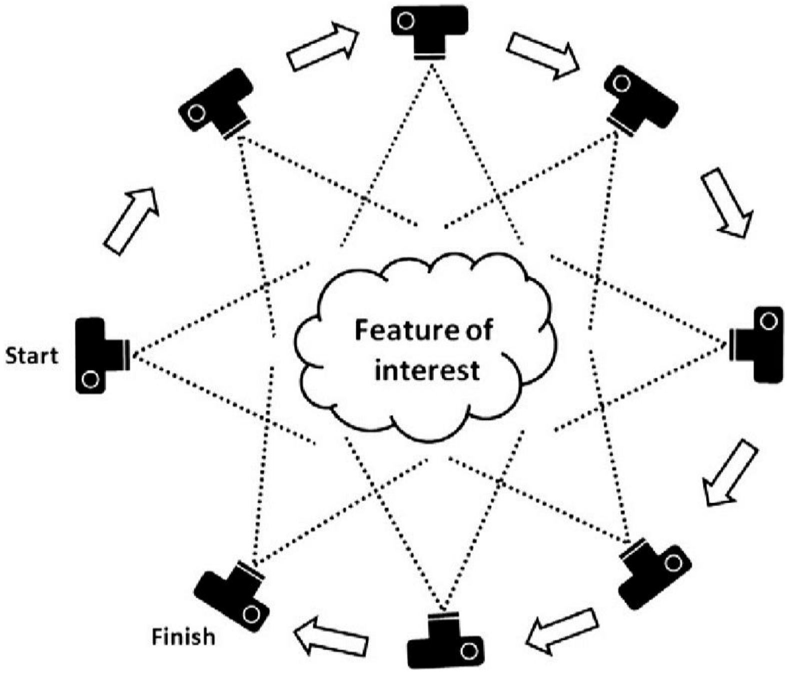
2.1.2 Photogrammetry

Photogrammetry is the technique to accurately determine shape, size, position and distance of objects through the use of photographs (De Waele et al., 2018; Giordan et al., 2021). To perform a 3D reconstruction with this technique, 2D overlapping photographs of the element of interest must be taken from different angles (Westoby et al., 2012) (Figure 5). These photos are then processed, usually by applying the Structure from Motion (SfM) method (De Waele et al., 2018; Dabove et al., 2019; Pukanská et al., 2020; Giordan et al., 2021). That way, a 3D point cloud from images is generated without the need to specify the position and orientation of the camera, as they are automatically obtained from the union of coincident elements in the multiple photographs provided (James & Robson, 2012; Westoby et al., 2012). Photos can be taken both with professional or low-cost personal digital cameras such as the

[4] iPhone 13 Pro Max 128GB (https://www.iplace.com.br)
[5] https://www.apple.com
[6] https://www.intelrealsense.com/lidar-camera-l515/
[7] https://www.americanas.com.br

smartphone or tablet cameras, which constitutes an advantage over the use of Terrestrial Laser Scanning. To illustrate this contrast in pricing, a Canon semiprofessional digital camera can be bought for around 1,300 USD[8] in Brazil, representing less than 10% of the previously mentioned 15,000 USD starting cost for TLS scanners.

Figure 5 – Capture of photographs for 3D photogrammetry.



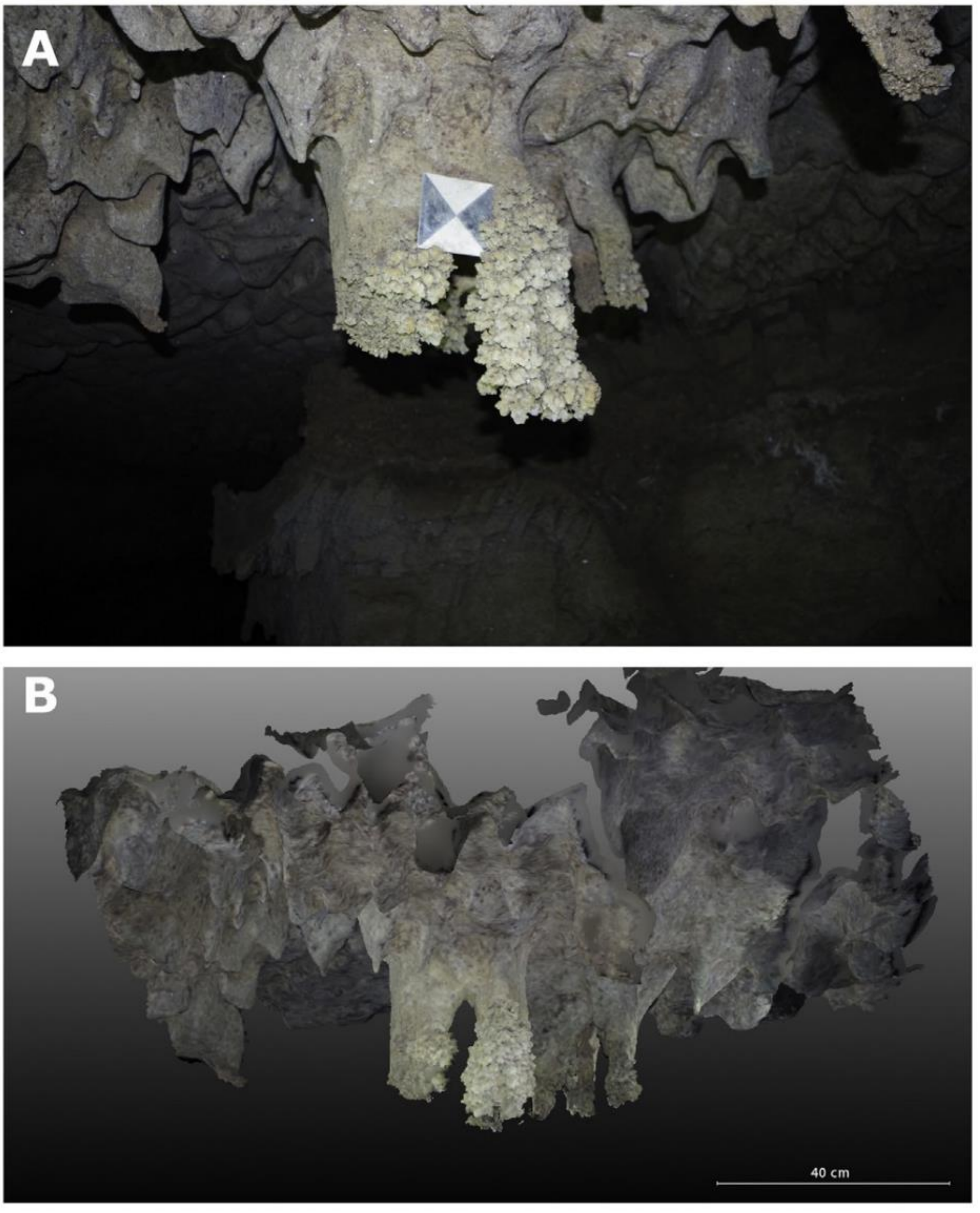
Source: Westoby et al. (2012, p. 301).

Short-range digital photogrammetry has a potential similar to TLS, which is why it has also been used in the creation of three-dimensional models of high-resolution caves in morphometric detail studies (Pukanská et al., 2020). Often used as a complement to Laser Scanning techniques, photogrammetry adds color details and acts as an auxiliary capturing device in inaccessible areas to TLS equipment (De Waele et al., 2018; Mikita et al., 2020). The accuracy of the resulting 3D point cloud depends on the size of the captured objects, their distance to the center of the photograph, and the camera resolution (De Waele et al., 2018). It is necessary to highlight that the photorealistic point cloud obtained with digital photogrammetry is more detailed than that created with TLS, favoring its use especially when it is necessary to obtain information from smaller elements within the cave (Figure 6). Nevertheless, this technique can be more laborious than laser scanning in large areas,

[8] Canon EOS T7i (https://www.magazineluiza.com.br)

making it inefficient in those contexts (Rodríguez-Gonzálvez et al., 2012; Pukanská et al., 2020).

Figure 6 – Detailed photogrammetry applied to the reconstruction of speleothems. (A) Picture of the surveyed area. (B) 3D model.



Source: De Waele et al. (2018, p. 60).

In Pukanská et al. (2020), the authors present a summary of the positive and negative aspects of using digital photogrammetry with Structure from Motion and Terrestrial Laser Scanning in mapping natural underground cavities (Chart 1).

Chart 1 – Comparison between TLS and SfM photogrammetry.

	TLS	SfM Photogrammetry
+	High accuracy guaranteed by the manufacturer	Accuracy comparable to TLS for distances typical in cave spaces
	Quicker terrain survey of complex areas	High-resolution of small-scale morphological features
	Direct result of the terrain survey is the final point cloud	More suitable financial demands
	No need for special illumination (only if photo-textured point cloud is not needed)	Easy recording of all parts
-	High financial demands	Need for artificial illumination
	Difficult instrumentation handling in narrow cave spaces	More time and data demanding survey of larger areas
	More time and effort demanding terrain survey	Getting the final data (point cloud) can be computationally demanding

Source: Modified from Pukanská et al. (2020, p. 16).

Although photogrammetry is an alternative with great capacity for 3D reconstruction of underground environments, most authors combine this technique with TLS to obtain better results in the reconstruction of complex speleological systems, restricting its use to the mapping of smaller features within these environments. In addition, the absence of light inside caves requires consistent artificial lighting sources, which can create unwanted shadows that are problematic in subsequent processing (Fabbri et al., 2017; De Waele et al., 2018; Giordan et al., 2021) (Figure 7). High levels of humidity inside these environments are another negative point: surfaces covered in water increase their reflectivity, deteriorating the quality of the captured images and, therefore, the resulting model (Dabove et al., 2019).

2.1.3 RGB-D cameras

Another existing alternative for 3D reconstructions are RGB cameras with active depth sensors (Lachat et al., 2015; Chiu et al., 2019). RGB-D cameras have lower resolution than LiDAR scanners, but their prices are more modest as well (Hämmerle et al., 2014; Lachat et al., 2015). This technology provides color, position, and depth information for each point through the emission of infrared light (Hämmerle et al., 2014). RGB-D cameras may be based on ToF, structured light or stereoscopic vision approaches (Zollhöfer et al., 2018; Chiu et al., 2019). The structured light technique consists of determining the distance between the mapped object and the camera from the projection of a light pattern and the observation of its deformation on the surface of the object, as a result of variations in depth on that surface (Zollhöfer et al., 2018; Chiu et al., 2019). The stereoscopic vision technique, on the other hand, uses several cameras to record images of the same object and find equivalent points between them to calculate the corresponding distance (Chiu et al., 2019).

Figure 7 – Artificial lighting in cave for data capture with passive sensors.

Source: Zhang et al. (2018, p. 410).

The popularity of this technology in three-dimensional mapping is explained by its affordable price, which, according to a market survey, varies between 200 and 1000 dollars[9][10]. The high portability is also a positive feature of these sensors, allowing capturing data in areas with difficult accessibility. Both qualities (cost and portability) enable multi-temporal studies of dynamic phenomena, such as erosional processes, among others (Hämmerle et al., 2014). Nonetheless, the quality of the results may be compromised due to a more limited range and precision than the previously described technologies. Color and reflectivity of mapped objects can negatively influence the quality of the captured data as well: materials with high reflectivity or, on the contrary,

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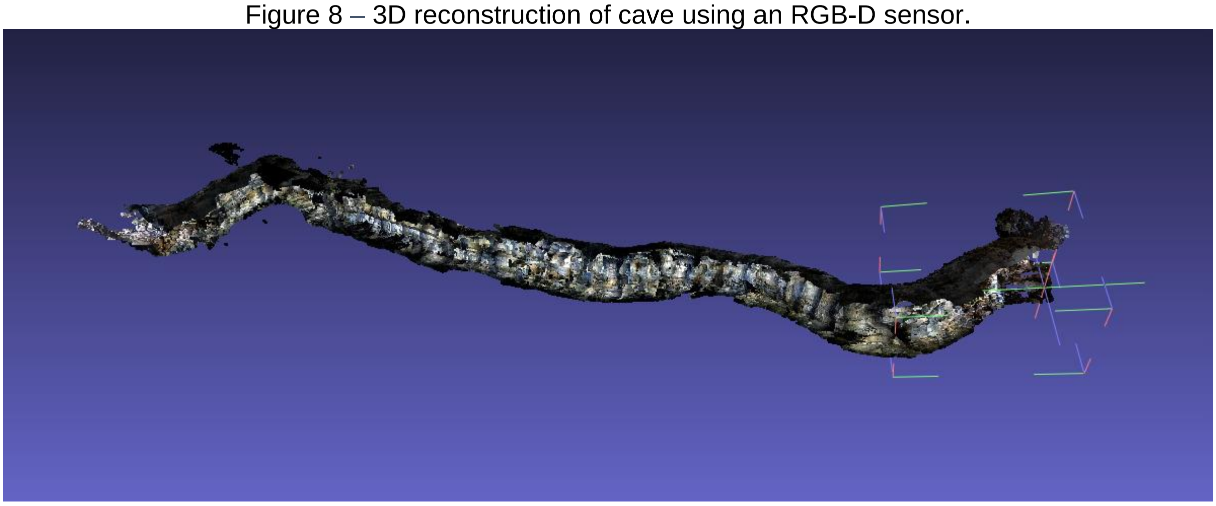
[9] Intel RealSense cameras (https://www.intelrealsense.com)
[10] Kinect sensor (https://www.microsoft.com)

very dark surfaces, generate changes in the measured depth values (Lachat et al., 2015).

Even though there are some large-scale surveys in caves with RGB-D sensors (Zhang et al., 2018; Gautier et al., 2020; Teixeira et al., 2023) (Figure 8), the main uses of these cameras is in the reconstruction of medium and small pieces, such as speleothems (Hämmerle et al., 2014), archaeological artifacts (Lachat et al., 2015), paleontological remains (Das et al., 2017), and even the human body (Chiu et al., 2019). For large environments, some authors consider that the survey with Terrestrial Laser Scanning remains the best option, due to its greater precision and speed for data collection (Lachat et al., 2015).

Figure 8 – 3D reconstruction of cave using an RGB-D sensor.



Source: Teixeira et al. (2023, p. 7).

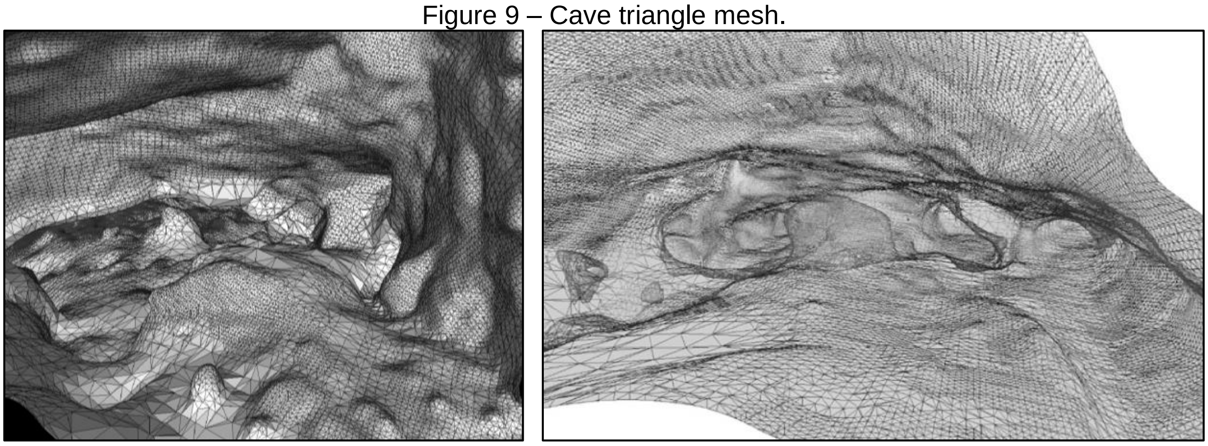
As showed in this section, different tools for 3D data capture exist, with varying costs and capturing capacities: LiDAR scanners, digital cameras and RGB-D sensors. After data is collected with one of the presented tools, the information must be processed to generate a three-dimensional mesh that allows its visualization and subsequent analysis. A description of these data processing and visualization solutions is presented in the next section.

2.2 3D RECONSTRUCTION AND VISUALIZATION SOLUTIONS

The processing sequence starts with the matching of separate point clouds (generated when, for example, the Terrestrial Laser Scanner collects information from different positions) and the suppression of erroneous and unnecessary points (Idrees

& Pradhan, 2019); Consecutively, the 3D mesh is generated, being the triangle structure the most widely adopted meshing technique (Cosso et al., 2014; Idrees & Pradhan) (Figure 9). Finally, the last step is post-processing, which consists of filling in the existing holes in the model and correcting any other defects (Idrees & Pradhan, 2016). Within open-source solutions used for this purposes, RTAB-Map (Real-Time Appearance-Based Mapping) stands out, a real-time reconstruction solution using the SLAM (Simultaneous Localization and Mapping) technique that can be used both with LiDAR and RGB-D data inputs (Labbé & Michaud, 2019; Da Silva Neto et al., 2020; Teixeira et al., 2023). ORB-SLAM2 is another popular highly accurate real-time 3D reconstruction SLAM system that works with RGB-D cameras (Mur-Artal & Tardós, 2017). Both solutions (RTAB-Map and ORB-SLAM2) are studied by Gautier et al. (2020) in their work about natural caves surveying using RGB-D devices.

Figure 9 – Cave triangle mesh.



Source: (Left) Cosso et al. (2014, p. 184). (Right) Idrees & Pradhan (2019, p. 1033).

Cosso et al. (2014), in their mapping of a cave in northwest Italy, employed the open-source software MeshLab to merge point clouds generated with LiDAR and delete inaccurate points to obtain a complete (and textured) triangle mesh. The authors also used CloudCompare for filtering operations and information extraction. The latter solution, originally conceived to compare 3D point clouds and triangle meshes, was later extended to a more generic processing software[11]. It is also used by Hämmerle et al. (2014) for noise filtering in a TLS point cloud, prior to the generation of the final mesh; by De Waele et al. (2018) for the visualization and morphology analysis of a 3D model obtained with LiDAR; and by Dabove et al. (2019) to compare point clouds obtained with different capture and processing methods (TLS and a smartphone

[11] https://cloudcompare.org/

camera). Niederheiser et al. (2016) tested the combination of three free software, CloudCompare, VisualSfM and SURE, to create and edit a dense point cloud generated from photographs of a rocky, vegetated site. VisualSfM and SURE are used to obtain the dense point cloud with a Structure from Motion approach, while CloudCompare allows the subsequent point cloud joining, the identification of duplicate points and the filtering of the result, among other functions. VisualSfM is also cited in cave modeling studies as an option for three-dimensional processing (Dabove et al., 2019).

Regarding MeshLab, Gallay et al. (2015), Silvestre et al. (2015) and Idrees & Pradhan (2019) make use of this program to generate a three-dimensional cave mesh from data obtained with Terrestrial Laser Scanning (which was previously manipulated in a different software, usually from the capture device manufacturer). However, De Resende Filho (2021), in his work about reconstruction of caves, galleries and mining confined spaces, specifies that it is not possible to obtain 3D reconstructions using a photogrammetric approach solely with this software. This author used, instead, the AliceVision Meshroom framework, a solution that allows 3D reconstructions with unordered images (Griwodz et al., 2021). Another available and open-source alternative is COLMAP, an SfM reconstruction tool employed to manipulate dense point clouds and create 3D meshes (Schonberger & Frahm, 2016; Griwodz et al., 2021; Kloc et al., 2021).

KinectFusion is also one of the reconstruction techniques used with depth cameras in geosciences (Hämmerle et al., 2014). Images captured from different perspectives with RGB-D sensors serve as input for a series of algorithms to join and create precise three-dimensional models in real time (Izadi et al., 2011; Chiu et al., 2019).

In addition to all the mentioned processing solutions, it is worth mentioning SCANN3D, a smartphone application available for Android devices that can be used for implementing 3D reconstructions with photogrammetry. This app was tested by some authors in the survey of parts of caves (Dabove et al., 2019) and small rocky outcrops (Mikita et al., 2020). However, the quality of the results obtained in these studies is not comparable to the products generated with other commercial and open-source software. The 3D Scanner App for iOS devices is another smartphone app that has been tested in geosciences (Luetzenburg et al., 2021). It allows processing, editing and visualization of 3D data captured using both the iPhone’s LiDAR scanner and camera photos. One of its advantages lies in the fact that data collection and processing are both executed within the app, with no need to use different capture and processing solutions. It also works for simple mesh editing, basic measurements and visualization of the final product.

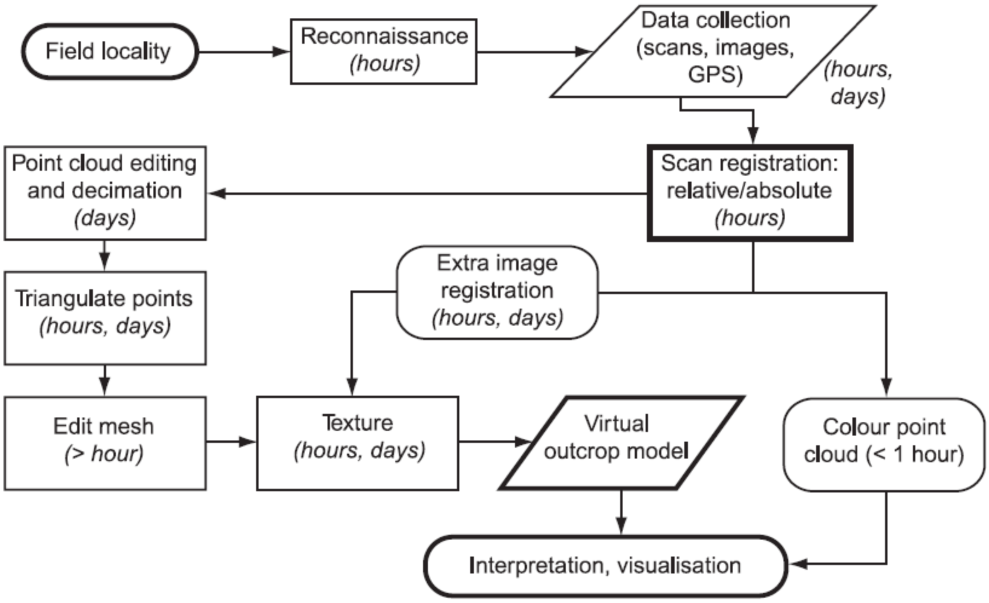
As can be seen, there are many existing alternatives for processing 3D data that can be used in cave reconstruction contexts. After the reconstruction phase, the model can be visualized and interpreted, generally within the same processing tool. Furthermore, volume and area calculations, along with distance measurements, can be estimated to increase the understanding of the studied environment. Many of the introduced solutions in Section 2.2 serve these purposes, especially MeshLab and CloudCompare.

In this chapter, the theoretical framework on 3D reconstruction of caves was described. Three different data capture methodologies were presented: laser scanners, photogrammetry and RGB-D cameras. The main reconstruction and visualization solutions were also presented, some of them being the most generally used tools for area and volume calculation as well. In Chapter 3, the research methodology adopted in this dissertation will be introduced, including the chosen data capture, processing, visualization, and measurement solutions and their general settings. Fieldwork carried out in three different caves will also be described.

3 RESEARCH METHODOLOGY

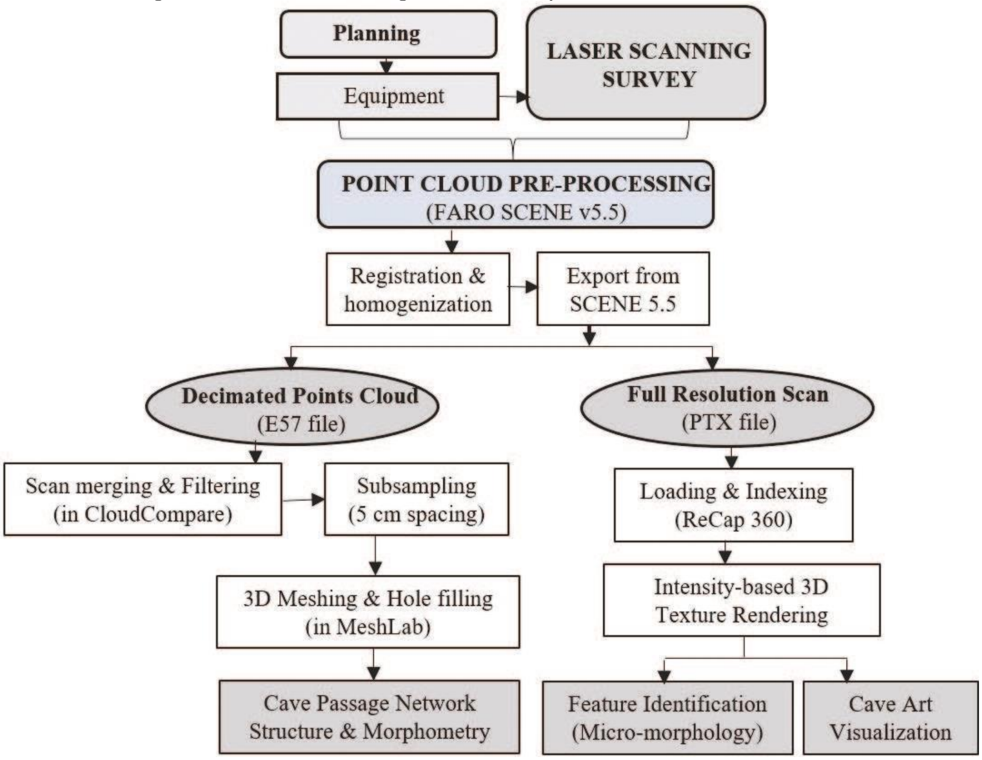
The general step-by-step process for 3D reconstruction of natural environments is very similar amongst scientific literature. Buckley et al. (2008) provide a description of the typical workflow involved in 3D reconstruction of outcrops using LiDAR in Geology. Apart from data collection, point cloud editing, and mesh generation, the authors include a texturing step with digital imagery on the final mesh to create a realistic virtual product suitable for interpretation and measurement (Buckley et al., 2008). This workflow, along with the relative duration of each stage, is summarized in Figure 10. Concerning speleological reconstructions, Gallay et al. (2015) present a methodological framework for TLS surveying in a cave system that consists of four major phases: (I) collection of existing data and preliminary mapping, (II) laser scanning, (III) data post-processing and georeferencing, and (IV) visualization. Their final georeferenced model allows visualization and analysis of morphological aspects of the cave that had not been possible to map by traditional methods, and some of them can be indicative of speleogenesis (Gallay et al., 2015). Idrees & Pradhan (2017) describe their methodological procedure for the 3D laser scanning survey of a cave in Malaysia (Figure 11). Its first step consists of field reconnaissance and data collection activities, and, after point data capture, point cloud processing is carried out (Idrees & Pradhan, 2017). Either a full-resolution scan or a decimated point cloud is proposed in the study of Idrees & Pradhan (2017), and depending on which one is used, the processing stage diverges. The former format is not computationally efficient to generate the complete 3D reconstruction and for rock structural analysis, so these authors suggest its use for identification of micro-morphological features (Idrees & Pradhan, 2017). The latter, on the other hand, is useful for macro-morphological analysis, and consists of several phases: alignment of individual scans into one set of point cloud; filtering of the resulting point cloud to eliminate noise and undesired points; sub-sampling the cleaned point cloud using a predetermined distance spacing between points for efficient mesh generation (Idrees & Pradhan, 2017). After that, the 3D mesh is generated. Likewise, the cave reconstruction by Tometzová et al. (2020) involved a preparation stage, where terrain reconnaissance was performed; a laser scanning stage, in which a TLS was used to map the cave; a processing stage, where some basic editing in the model was carried out in the scanner manufacturer’s solution as well; the 3D modeling stage, in which data was imported into CloudCompare and the final 3D model of the cave was generated; and finally, the analysis of data derived from the model (area, volume, ground plan, cross-sections, etc.) (Tometzová et al., 2020). In addition, the authors generated multimedia content presentation purposes. Their surveying and processing workflow is shown in Figure 12.

Figure 10 – Workflow for geological outcrop reconstructions using LiDAR.



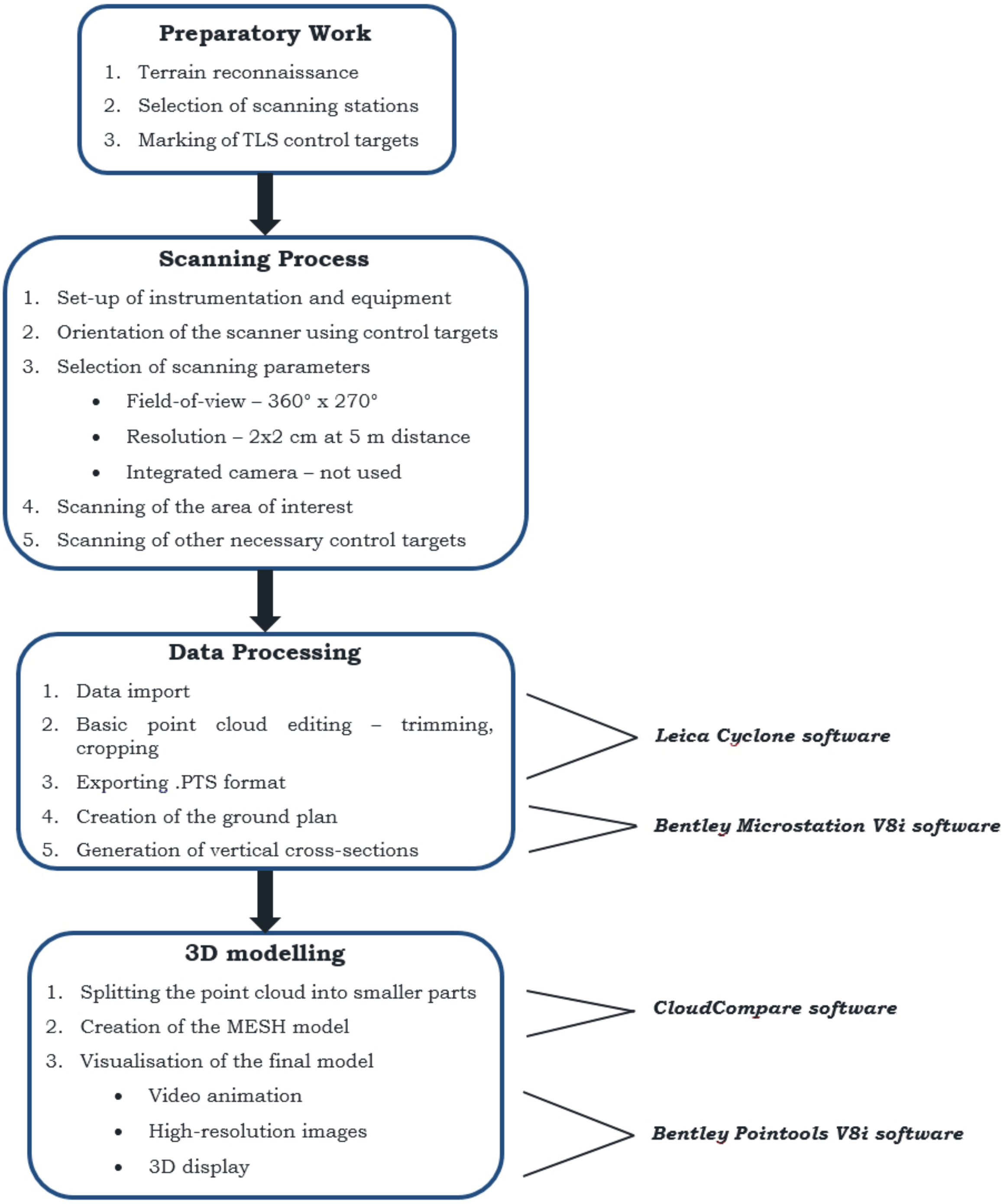
Source: Buckley et al. (2008, p. 635).

Figure 11 – Methodological roadmap for cave reconstruction.



Source: Idrees & Pradhan (2017, p. 8).

Figure 12 – General workflow diagram from the work of Tometzová et al. (2020)



Source: Tometzová et al. (2020, p. 97).

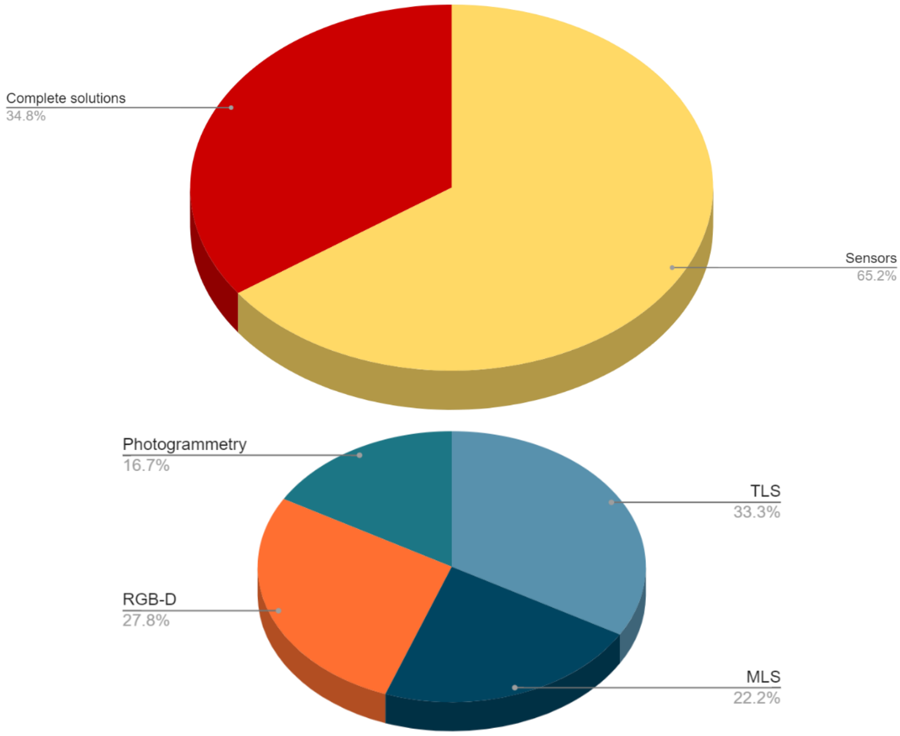
The methodological approach adopted in this dissertation is based on the above-cited studies (Buckley et al., 2008; Gallay et al., 2015; Idrees & Pradhan, 2019; Tometzová et al., 2020) and can be simplified in the following macro stages: 1) Survey of information about 3D data capture, processing, visualization, and measurement solutions; 2) 3D reconstruction of caves (this step involves field data collection, processing, visualization and 3D model measurements), and 3) Results assessment and methodologies comparison.

3.1 3D RECONSTRUCTION SOLUTIONS SURVEY

An unstructured analysis of scientific work was carried out to understand the existing technological solutions utilized for 3D data collection in caves and other geological environments. This analysis was based on the research team experience. Websites of manufacturers of these technologies were consulted as well.

Fifteen single sensors and eight complete three-dimensional modeling solutions were found and listed during the survey (Figure 13). These devices were classified and compared according to the scanning technique used (LiDAR, RGB-D or photogrammetry), their advantages and disadvantages, and their cost. Based on these findings, the most cost-effective solutions selected for later field testing was the Intel RealSense L515 camera. It is worth mentioning that any sensor with a price of 1/10 or less of the average cost of a top-quality, high-end LiDAR (which was estimated at 30,000 USD) was considered a ‘low-cost’ device.

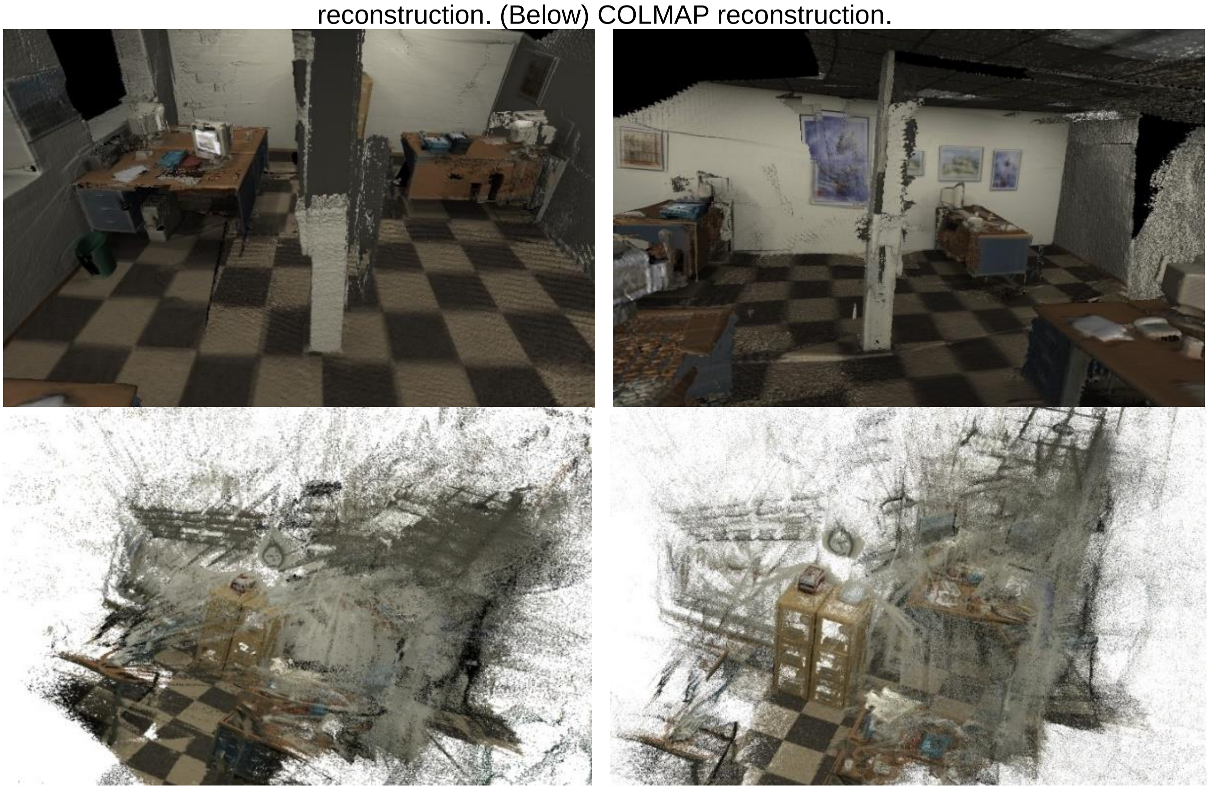
Figure 13 – Data capture devices survey. (Above) A wide variety of sensors for capturing data and, to a lesser extent, complete solutions for 3D reconstruction of environments were analyzed in this stage. (Below) Scanning techniques found.



Source: the author (2023).

Regarding 3D processing tools, information on solutions for point cloud obtention and mesh generation was gathered through an unstructured analysis of scientific studies. The topic of the papers was not limited to 3D reconstructions in speleological environments; the focus was, instead, on 3D reconstructions in general. The analysis of the material was also based on the research team experience. GitHub[12] platform was explored as well. These activities resulted in nineteen findings. The selection criteria to determine which of those findings would be tested included current, free open-source solutions, with enough documentation available on how to implement them. That way, Open3D and COLMAP were selected. Reconstruction tests were executed on an Intel Xeon 96GB RAM computer with an RTX 3090 24GB graphics card and 960GB SSD, using Windows 10 Pro operating system. The input data used to assess both solutions was downloaded from Redwood Datasets[13] and included RGB and Noise Depth Sequence data. Open3D showed a better time-processing performance and quality of the results, with better definition of object geometry and walls (Figure 14).

Figure 14 – Reconstructions of an office dataset from Redwood database. (Above) Open3D reconstruction. (Below) COLMAP reconstruction.



Source: The author (2023).

[12] https://github.com
[13] redwood-data.org/

After understanding that the Open3D was the processing technique to use, an additional reconstruction was executed using this solution, this time with a living room dataset where noise information had been previously filtered. The resulting reconstruction is presented in Figure 15.

Following those tests, information on model visualization and measurement was collected through an unstructured web search, and a total of forty-eight potential solutions were identified. Those solutions were classified according to their cost, the input data they accepted and the compatibility with different operating systems. Based on that classification, eleven of them were tested using the new living room 3D mesh generated in Open3D. From those eleven solutions, four appeared to be the most promising in terms of model visualization quality: software systems CloudCompare and MeshLab, and online tools Online 3D Viewer and Creators 3D. In addition, MeshLab showed potential to carry out both visualization and area and volume measurements, while Creators 3D proved useful visualization features, so both of them were selected for analysis with real field data.

Figure 15 – Reconstruction of living room dataset using Open3D. The input dataset had already been filtered and did not include noise data.

Source: The author (2023).

To summarize, following the described survey, the selected solutions for 3D reconstruction were:

- For data capture: Intel RealSense L515
- For data processing: Open3D
- For 3D visualization: MeshLab / Creators 3D

In September 2021, after the mentioned survey was carried out, the iPhone 13 Pro with a built-in LiDAR sensor is launched. Even though the iPhone 12 Pro model was the first iPhone to include a laser scanner, the introduction of a new model with a laser scanner meant the consolidation of the incorporation of this kind of sensor in Apple’s Pro devices. Consequently, the iPhone 13 Pro was also chosen for data capture in this study. For processing of the data captured with the iPhone, the 3D Scanner App was adopted, as it was exclusive for iOS devices and had already been tested in geoscientific contexts (Luetzenburg et al., 2021). For 3D visualization, the previously selected solutions would be used as well. In conclusion, a second reconstruction alternative was defined as follows:

- For data capture: iPhone 13 Pro Max
- For data processing: 3D Scanner App
- For 3D visualization: MeshLab / Creators 3D

3.2 3D RECONSTRUCTION PROCESS

To test the selected solutions with real speleological data, the methodology used in each reconstruction stage is described below.

3.2.1 Data Capture and Processing

To capture and process three-dimensional data, two approaches were undertaken: laser scanning and photogrammetry. Laser scanning was applied using the iPhone 13 Pro Max and the 3D Scanner App, and the Intel RealSense L515 camera with the Open3D library. Photogrammetric data was captured with the iPhone 13 Pro Max digital camera and the 3D Scanner App. A further explanation of the used procedures is presented in the next subsections.

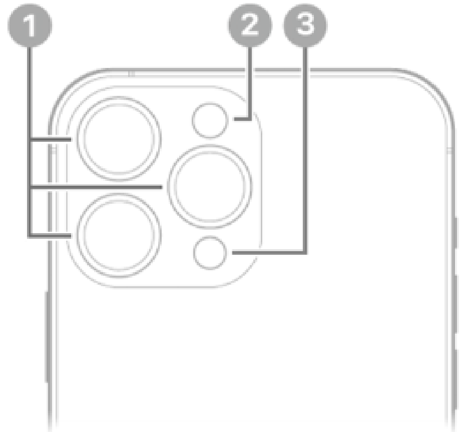
3.2.1.1 iPhone 13 Pro Max

Data was captured using a 128-GB-capacity iPhone 13 Pro Max. As already stated, this smartphone can be purchased in Brazil for approximately 1,600 USD[14]. Its dimensions are 160.8 x 78.1 x 7.65 mm, and it weighs 240 grams. It is splash, water, and dust resistant, which makes it an appropriate equipment for speleological

[14] https://www.iplace.com.br/

environments. It includes a LiDAR Scanner and a 12 MP camera system with image stabilization and night mode improved by the LiDAR scanner (Figure 16). Thanks to those two features, both LiDAR and photogrammetric reconstruction techniques could be tested.

Figure 16 – iPhone 13 Pro Max cameras and sensors. 1. Rear cameras. 2. Flash. 3. LiDAR Scanner.



Source: Modified from Apple Technical Specifications (2023, https://support.apple.com/).

Data collection and processing were carried out using the 3D Scanner App version 2.0.13 on iPhone 13 Pro Max. 3D Scanner App[15] is an intuitive, free application that works on iOS devices. Two data capture modes can be used with this app: LiDAR Mode, or Photos Mode.

For data capture in LiDAR Mode, the smartphone camera was aimed towards the surfaces of interest and the scanning was taken slowly. When a scan was complete, texture was automatically applied during processing.

Alternatively, a photogrammetric approach was applied using the Photos mode. Enabling cloud photogrammetry in the scan settings is required before starting the scanning process. Photos can be taken automatically or manually, so Auto Capture mode was used, with pictures being made every 0.9 seconds. According to the 3D Scanner App user guide, a maximum of 250 photos per reconstruction should be taken, so this limit was not exceeded. Following photo capture, data processing was executed in the cloud.

After data was collected both in LiDAR and Photos mode, and processing was carried out, the 3D models were ready for visualization. 3D Scanner App includes on-

[15] https://www.3dscannerapp.com/

device 3D editing and cleaning up of the collected data. However, no manual editions were made. Moreover, later extension of existing scans is also possible, but this possibility was not employed. The app allows viewing images captured during scan and the camera trajectory, as well as letting the user capture floorplan images of scans and providing scan extension. All these accessory features the app offers were exploited. In the post-processing phase, measurements such as distances and volumes can also be taken from the generated model, but a different solution (MeshLab – see Section 3.2.2) was used instead. The final product can be shared via web link, or saved in different file formats (i.e., OBJ, USDZ, GLTF, GLB, STL, etc.). For this study, the resulting 3D models were exported in OBJ format as it is a common 3D file format that works in all the selected visualization solutions. Sharing via web link was also carried out.

3.2.1.2 Intel RealSense L515

In addition to iPhone 13 Pro Max, data was also captured using Intel RealSense L515[16], a small-size, time-of-flight based LiDAR mobile scanner with a 2MP RGB camera incorporated. As previously mentioned in Chapter 2, this sensor can be found in the Brazilian market for up to 2,600 USD[17]. Its long-range depth capture (from 0.25 to 9 m) allows covering small to medium size caves. Its portability (95 g, diameter of 61 mm and 26 mm height), as well as its lower price than commonly used TLS equipment for 3D reconstructions makes it suitable for this dissertation's proposed objectives. As mentioned in its User Guide, all depth calculations run on the device, so it has low host platform requirements. Therefore, the sensor was coupled to a Motorola Moto G30[18] Android Smartphone via USB type-C connection. The Moto G30 smartphone has a built-in capacity of 128 GB, a weight of 197 grams and its dimensions are 165.22 x 75.73 x 9.14 mm, making it a portable device to use along with the camera. It can be acquired in Brazil for 350 USD[19].

Data was captured using the RS Camera App[20]. Among camera controls available to the user, the 'No Ambient Light' and 'Low Ambient Light' settings were

[16] https://www.intelrealsense.com/lidar-camera-l515/
[17] https://www.americanas.com.br/
[18] https://www.motorola.com.br/
[19] https://www.motorola.com.br/
[20] https://play.google.com/store/apps/details?id=com.intel.realsense.camera

used in this research, as speleological environments generally lack good illumination in their interior.

The collected data had a .bag file extension and was automatically saved in the smartphone. These files contained information on the depth of the scanned environment, along with its color frames. As the computer previously used for testing during the survey stage was unavailable, the result was transferred for processing to an Alienware 15 R2 computer with the following characteristics:

- CPU: Intel i7-6820HK @ 3.600GHz;
- RAM: 16 GB DDR4 @ 2667 MHz;
- GPU: NVIDIA GeForce GTX 980M (8GB);
- Disk: SSD NVMe GamerKing 1TB.

For data processing, Open3D[21] was used. This 3D reconstruction solution has Intel RealSense cross-platform SDK library integrated, so it fully supports a wide variety of Intel RealSense depth cameras, including the L515 model. The Reconstruction System Python script from Open3D GitHub repository[22] was used (Figure 17). Its tutorial suggested step-by-step process was followed; all the information on what each pipeline step does, can be found in detail on the Open3D informational website[23]. The processed 3D reconstructions were exported in PLY format for visualization and measurement.

Figure 17 – Code used to execute the reconstruction pipeline.

```
python3 run_system.py config/realsense.json --make --register --refine --integrate
```

Source: the author (2023).

3.2.2 Model Measurements and Visualization

For area and volume calculations, the OBJ and PLY files were imported in MeshLab version 2021.07. MeshLab[24] is a free, open-source program for editing, measuring and analyzing 3D triangle meshes. This software is compatible with the most common 3D file formats, including OBJ, STL, PLY, 3DS, PTX, PTS, XYZ, ASC, X3D and VRML (Silvestre et al., 2015). As most of the meshes processed in MeshLab had holes, and therefore, were not closed meshes, some extra processing had to be

[21] https://www.dotproduct3d.com
[22] https://github.com/isl-org/Open3D/tree/master/examples/python/reconstruction_system
[23] https://www.open3d.org
[24] https://www.meshlab.net

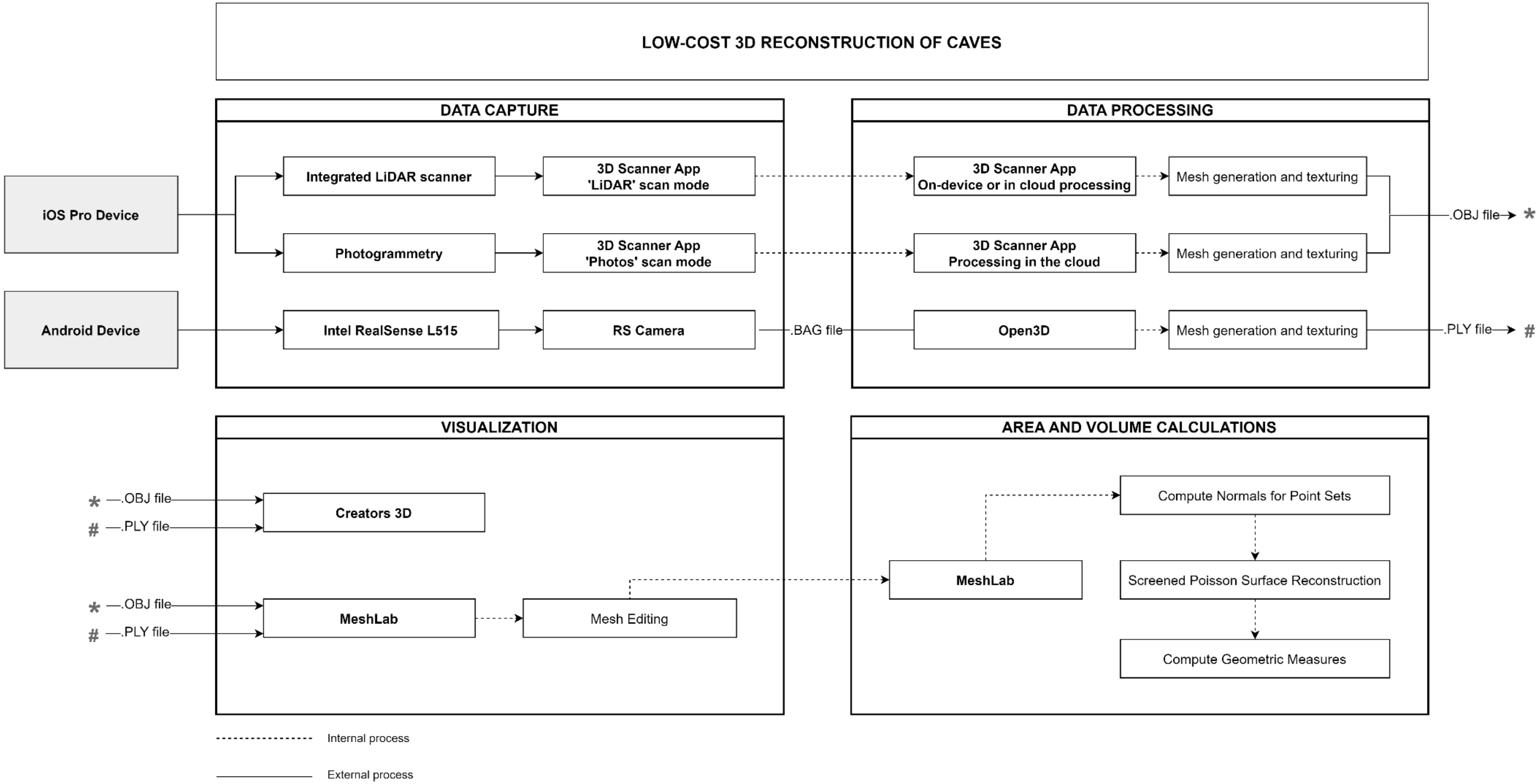
executed to estimate their areas and volumes. Vertices' normals and their perpendicular tangent planes were computed using the Compute Normals for Point Sets feature (default settings applied). Screened Poisson Surface Reconstruction algorithm was then used to create watertight surfaces from the oriented points, that is, a closed-surface mesh. Default configuration was used as well. That way, it was possible to estimate each reconstruction's area and volume using the Compute Geometric Measures feature. It should be borne in mind that disconnected parts from the main mesh should be deleted before volume calculations. In addition, the Poisson surface reconstruction may not work well with point clouds/meshes with too many holes. This is because before applying the Poisson surface method, it is necessary to calculate mesh normals. Calculating all the normals requires evaluating a set of points around the desired point. Thus, when there are no surrounding points, that is, there are large holes, it is not possible to obtain the normals and it becomes impossible to obtain the completely closed Poisson surface. For small holes, it is possible to calculate this surface. However, it is expected that the volume of the calculated surface is distorted in reaction to the real volume, being larger than it should be. On the contrary, if there are small holes in the original mesh, the Poisson surface method can smooth them out.

Both MeshLab and Creators 3D[25] can be employed for visualization purposes. Creators 3D is an online 3D viewer, so no download/installation was needed. Moreover, the solution automatically hid the first layer of the mesh, allowing the visualization of the interior of the cave with no need to zoom in the model, making navigation in the model simpler than other viewing solutions. 3D Creators also allows uploading and sharing a model directly using a link, facilitating the visualization of the mesh to any user.

A summary of the solutions adopted for each reconstruction stage is presented in Figure 18.

[25] https://www.creators3d.com

Figure 18 – Summary of processes and tools used with the proposed alternatives.



Source: the author (2023).

3.3 3D SOLUTIONS COMPARISON

Several criteria for assessing results can be found in 3D reconstruction literature. One of the most widespread methodologies consists of comparing the obtained reconstruction with reference models (Giordan et al., 2021; Armstrong et al., 2017). These comparisons are often based on sampling points in the different data sets, to later superimpose the models obtained and measure the distances between the selected points. As an example, in the study of Armstrong et al. (2017), free software (CloudCompare and Meshlab) was employed to determine the statistical variation between data sets obtained with laser scanning and with photogrammetry, using visible sampling points in both point clouds. Similarly, in Giordan et al. (2021), models obtained with Terrestrial Laser Scanner (TLS), Portable LiDAR (PLS) and Structure from Motion (SfM) were compared through manual distance measurements between homogeneous features in the point clouds.

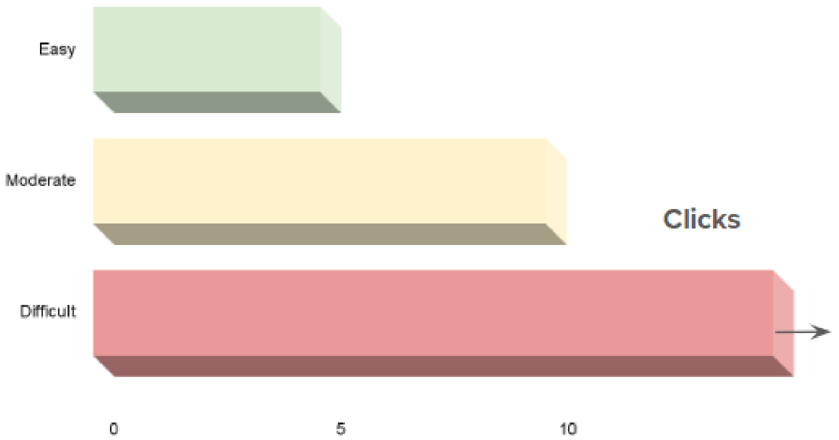
Although comparisons between models are commonly conducted, there is not a unique, standard method for assessing reconstruction results. In some studies, qualitative evaluations of the reconstructions are carried out to understand how faithfully the model reproduced the appearance and geometry of the real site to allow its study (Iturbe et al., 2018). Bustillo et al. (2015), in the 3D mapping of a church, consider time allocated to complete the reconstruction process as a way of evaluating it. In the field of application development, the systematic study of ways to evaluate health apps by BinDhim et al. (2015), is a broad mapping of quality assessment methodologies in the scientific literature.

The comparison criteria defined for the present research focused on each reconstruction alternative performance and usability, and included:

1. Ease of use of each reconstruction alternative. This assessment was made considering the number of steps needed to complete each task indicated above. For that, the number of clicks to achieve the objective was considered: Five steps (clicks) was considered easy, between five and ten was considered moderate, and ten or more clicks classified the activity as difficult (Figure 19). The ease of use was assessed for:
    - Installing the solution
    - Capturing data
    - Processing

- Exporting the final model
- Visualization of the results
- Area and volume estimations

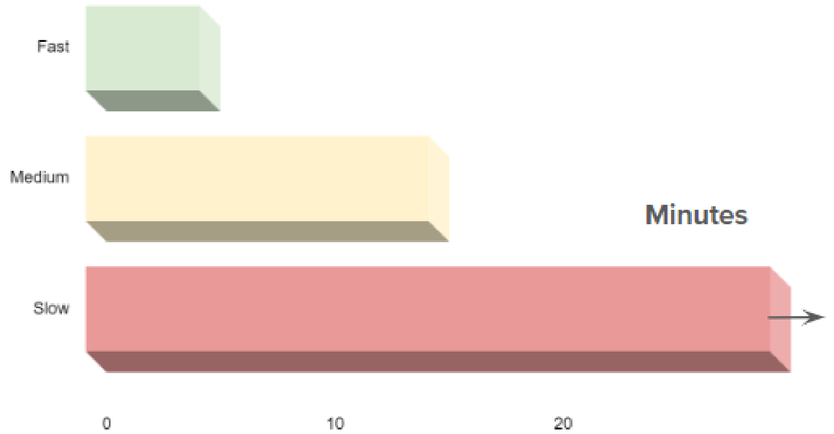
Figure 19 – Classification of ease of use of each step of the proposed alternative.



Source: the author (2023).

2. Time to complete each process with each proposed solution. 0-5 minutes was considered a fast execution time, 5-15 was considered medium and > 15 minutes was considered a slow process (Figure 20). The activities considered for this evaluation were:
    - Data capture
    - Processing
    - Exporting model
    - Area and volume extraction
    - Visualization

Figure 20 – Classification of time efficiency.



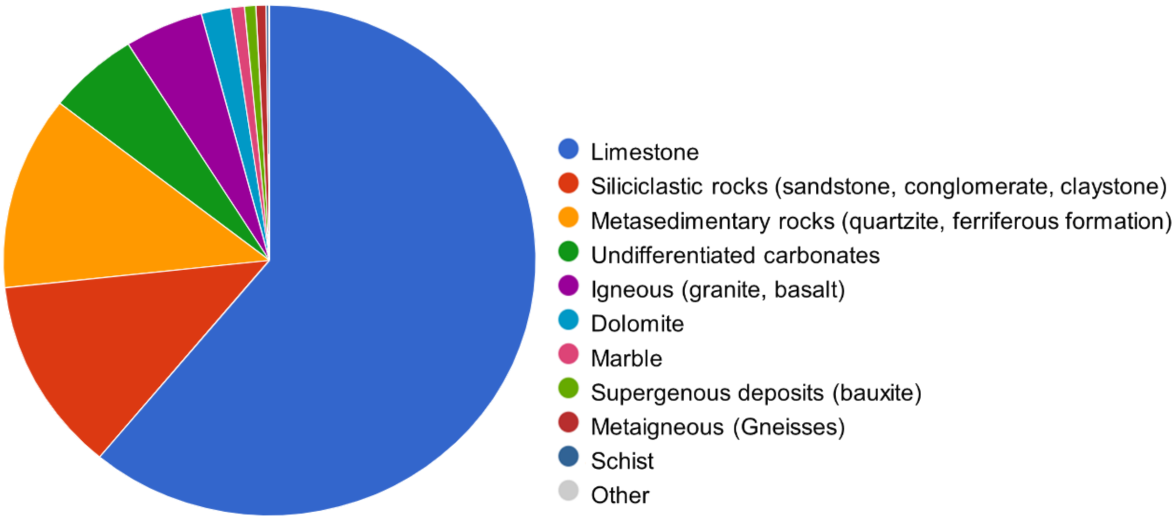
Source: the author (2023).

Additionally, a simplified cost-benefit analysis was carried out, which included the comparison of price and essential technical characteristics of the iPhone 13 Pro Max LiDAR, the Intel RealSense L515 camera and the RIEGL VZ-400i scanner. This latter device is a high-end, top-of-the-line LiDAR sensor that has been previously used for the reconstruction of some of the biggest speleological environments in the world (Walters & Hajna, 2020).

3.4 FIELDWORK

According to the National Cave Registry[26] of the Brazilian Speleological Society, limestone caves represent 61% of the speleological sites found in the country, and 12.3% are of siliciclastic composition (sandstones, conglomerates and claystone) (Figure 21). Therefore, efforts were put into understanding the performance of the selected equipment for 3D reconstruction in these types of lithologies. In consequence, fieldwork was carried out at the Lapinha and Macumba calcareous caves in the Sumidouro State Park in the state of Minas Gerais, and at the artificial sandstone Lourdes grotto in the city of Recife, in Pernambuco.

Figure 21 – Lithology of caves in Brazil.



Source: National Cave Registry - Brazilian Speleological Society (CNC) (https://sbecnc.org.br/Stats.aspx).

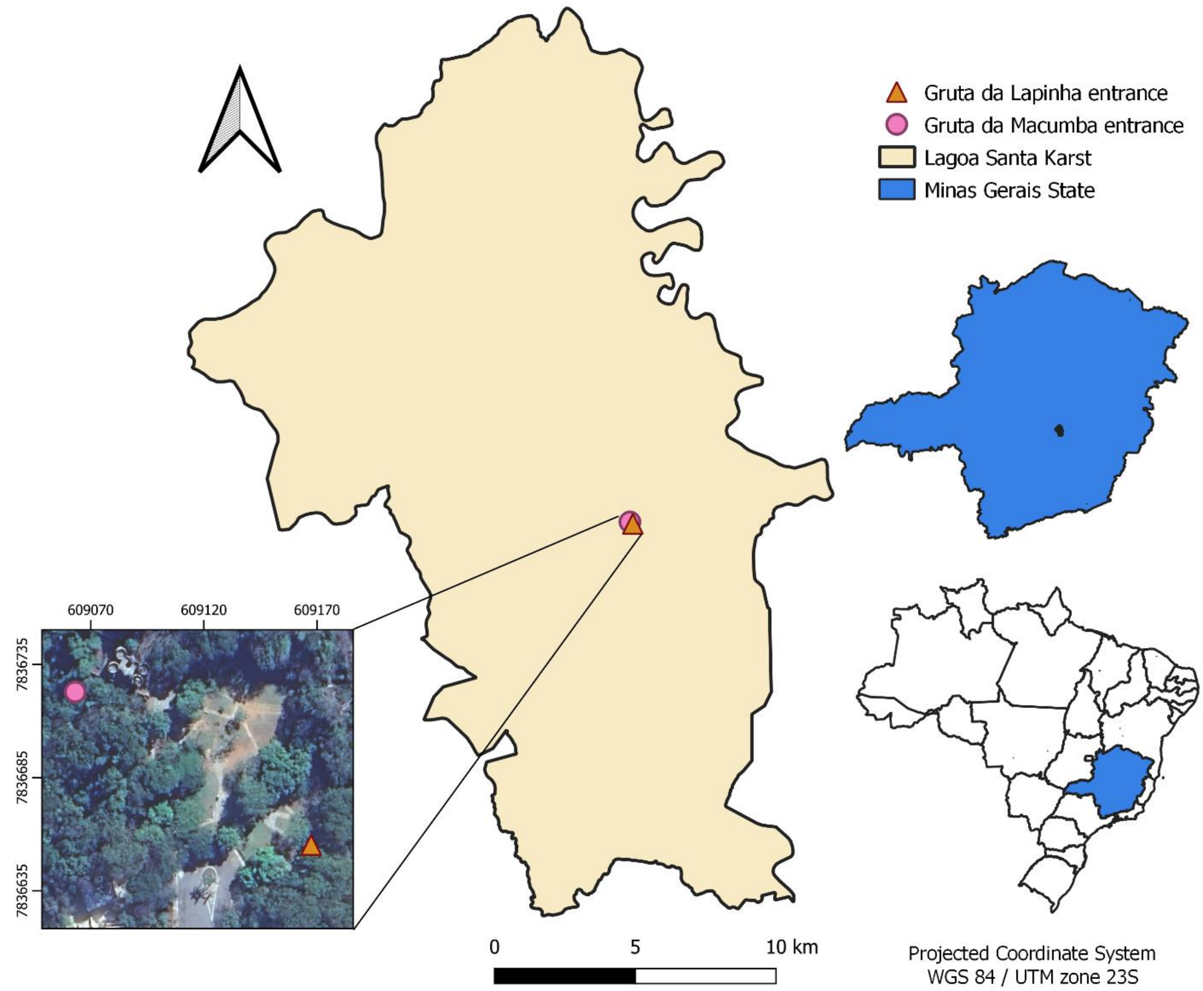
[26] https://sbecnc.org.br/

3.4.1 Lapinha and Macumba caves

The Lapinha and the Macumba caves are both located in the Sumidouro State Park, a Conservation Unit in the State of Minas Gerais, southeastern Brazil. The park is situated 50 km north of Belo Horizonte, the state capital, between the Lagoa Santa and Pedro Leopoldo municipalities. It is part of the Lagoa Santa Karst Environmental Preservation Area, a 37,000 ha protected site (Figure 22).

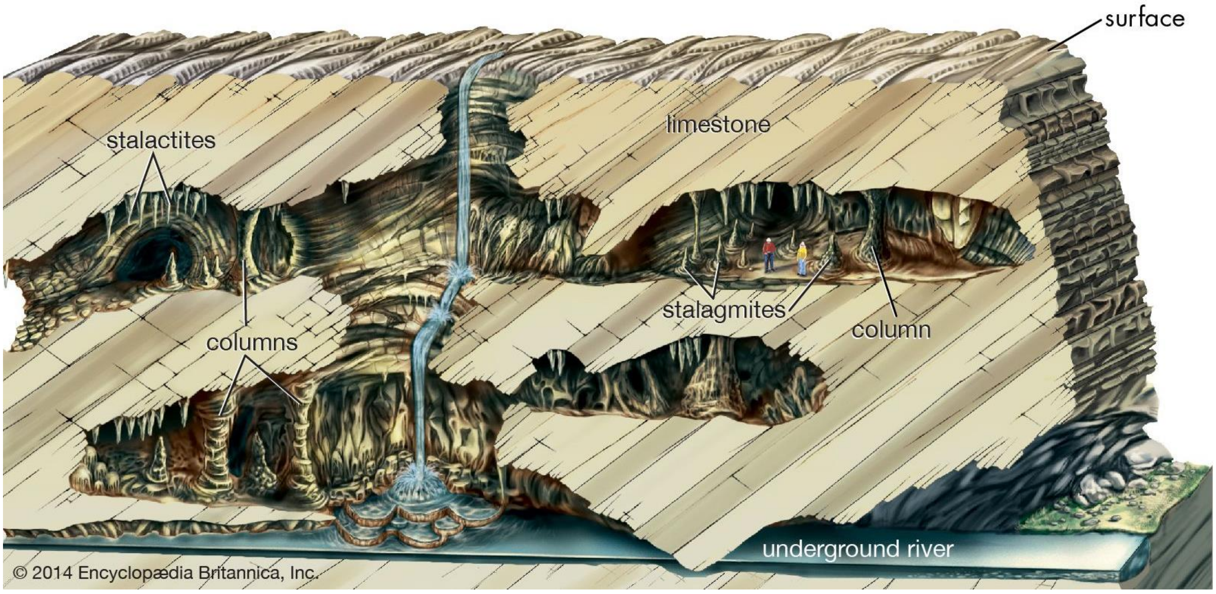
The geology of the Sumidouro State Park is dominated by carbonate rocks, mainly limestones, dolomites, calcisiltites and calcarenites from the Bambuí Group (Instituto Estadual de Florestas, 2010; Pizani et al., 2020). These rocks favor the presence of solution caves, which form by a dissolution reaction that occurs between the bedrock and circulating water (Davies & Morgan, 1991). The circulating water carries carbon dioxide from the air and soil outside, and eventually turns into a weak carbonic acid which slowly dissolves out the carbonatic rock along zones of weakness, where it can percolate (such as joints, bedding planes and fractures) (British Geological Survey, 2023). That way, the dissolved parts may become big enough to form cave systems (Figure 23).

Figure 22 – Lapinha and Macumba caves localization map.



Source: the author (2023).

Figure 23 – Cross section of a cave.



Source: Encyclopaedia Britannica (2023, https://www.britannica.com/science/karst-geology).

With an area of 2,004 ha, the Sumidouro State Park is home to a wide number of endo and exo karst features, which can be found especially south of the Sumidouro Lagoon. According to the Minas Gerais State Forestry Institute (IEF)[27], the Lagoa Santa Karst Environmental Preservation Area has the highest cave density in Brazil: 400 caves are registered in the database of the National Center for Research and Conservation of Caves (CECAV), with 49 of them located at the Sumidouro State Park (Instituto Estadual de Florestas, 2010; Pizani et al., 2020). The Park is also relevant due to its rich archaeological and paleontological content. Many findings in this area relate to the first humans that inhabited the American territory, and some animal fossil records evidence the megafauna that once existed in the region.

Caves in the Sumidouro State Park have an economic importance for the region, as many of them are open for speleotourism, making them a popular destination: that is specially the case of the Lapinha and the Macumba caves (Iniesta et al., 2013).

The Lapinha cave (entrance coordinates 19°33'42"S - 43°57'33"W, 735 m.a.m.s.l.) constitutes the main attraction of the Sumidouro State Park. It is a 600-million-year-cave that extends for 511 m and goes as deep as 40 m underground[28]. It has a variety of rooms and galleries in its interior, with many speleothems of the most diverse morphologies, including stalactites, stalagmites, pillars, columns, flowstones and draperies (Figure 24). Many scallops present on the cave ceilings indicate water-flow inside the cave during speleogenesis. The ceiling of its main room, the Cathedral room, goes up to 25 m high. Since it is a touristic site, it has suffered many anthropological modifications: leveling of its floor, the placement of metal stairs, the carving of steps on the rock, and the installation of an artificial illumination system (Iniesta et al., 2013).

Field activities in this cave were easily conducted, as the presence of artificial lighting facilitated both mobility and data capturing inside the cave (Figure 25). In addition, the illumination represented a great advantage for 3D reconstructions, as there was no need to use other forms of lighting to capture color information for model texturing.

[27] www.ief.mg.gov.br/
[28] https://www.circuitodasgrutas.com.br/gruta-da-lapinha/

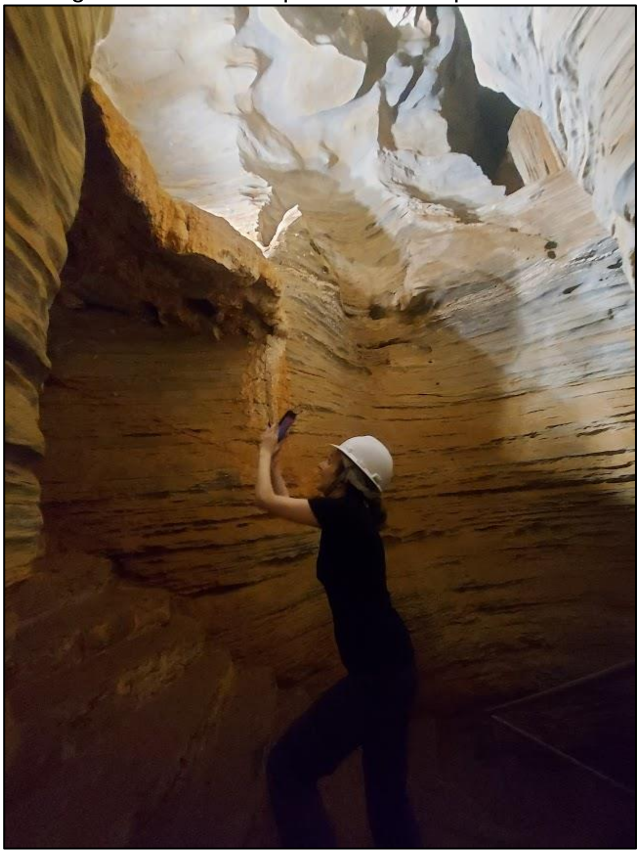
The Macumba cave (entrance coordinates 19°33'41''S - 43°57'37''W, 726 m.a.m.s.l.), on the other hand, is a “T” shaped cave with a 200 m extension, consisting of three galleries linked in the cave’s central room (Guimarães et al., 2011; Rodet et al., 2017). The cave served as a religious cult place for Afro-Brazilian rituals and owes its name to those ceremonies.

Differently to the Lapinha cave, the Macumba cave has no electrical installations in its interior, so it is predominantly an aphotic cave. This, nonetheless, is not an unaltered cave either. The morphology of the cave has also been modified by the presence of human activity, with altars distributed in the main room where rites were carried out, and a door frame carved on the wall that constitutes the passage from one of the galleries to that room (Figure 26).

Figure 24 – Speleothems and water-flow indicators at the Lapinha cave.

Source: the author (2023).

Figure 25 – Data capture in the Lapinha cave.



Source: the author (2023).

Figure 26 – Door frame built in the Macumba cave. (Left) Picture captured with iPhone 13 Pro Max and the Scanner 3D App. (Left) Reconstruction of the doorframe.

Source: the author (2023).

The conduction of fieldwork was somewhat more challenging than in the Lapinha cave, as the low visibility resulting from the absence of light made the use of portable lamps necessary (Figure 27). The presence of arachnids, specially from the Ctenidae family (popularly known in the region as *aranhas armadeiras)* and other species (some of which may be consulted in Iniesta et al., 2013) required special attention while transiting the cave.

Figure 27 – Headlamp and flashlight used for data capture at the Macumba cave.

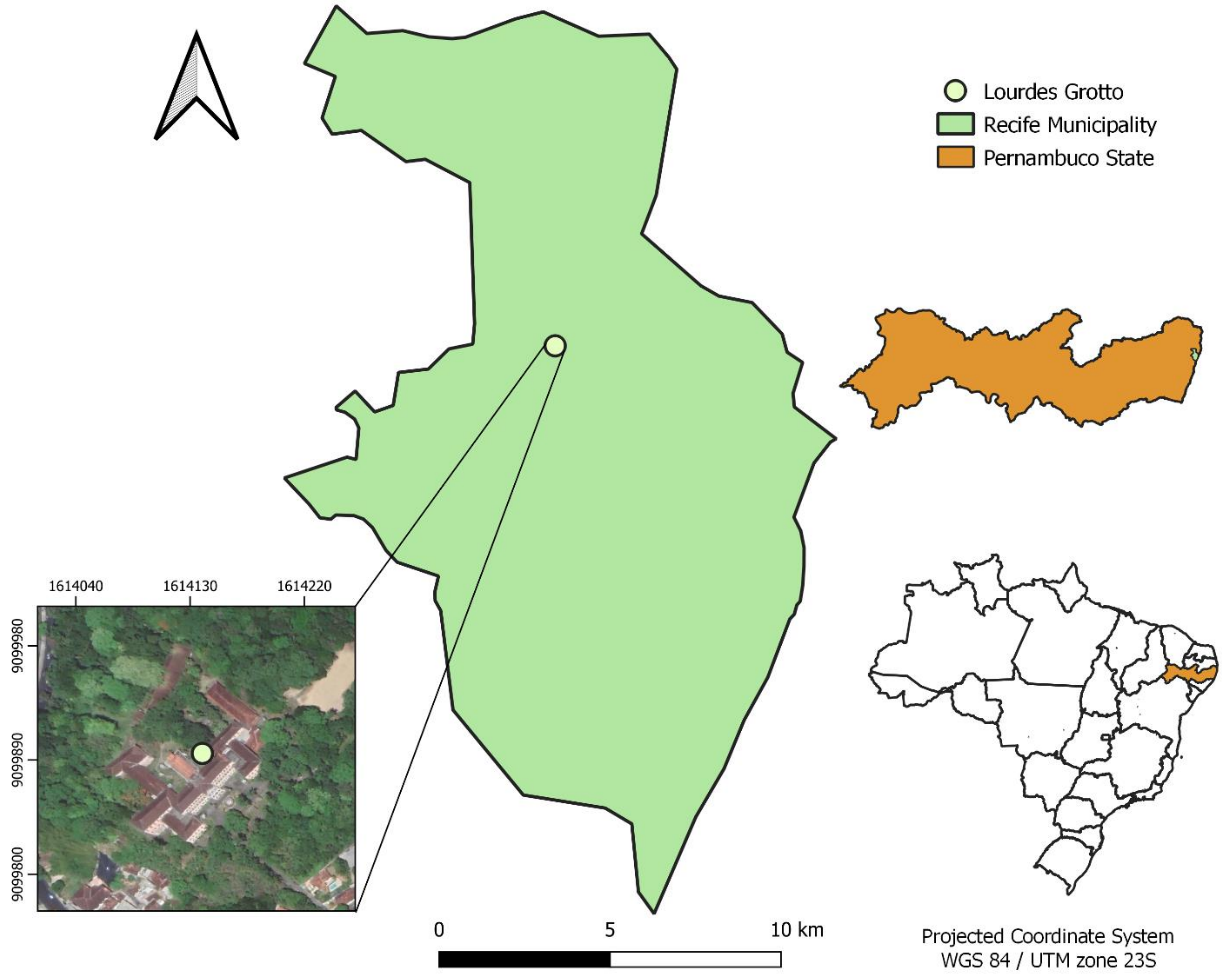
Source: the author (2023).

3.4.2 Lourdes grotto

The Nossa Senhora de Lourdes artificial cave (8°1'8"S - 34°56'23"W, 40 m.a.m.s.l.) is located in Recife, capital of the State of Pernambuco, Northeastern Brazil (Figure 28). This small grotto is surrounded by dense vegetation, with large size trees that attenuate the natural incidences of light in it.

The Lourdes grotto is a small yet considerably deep cave, which allowed the analysis of camera performance in areas with intense lighting (in the external part of the cave) and with less natural illumination (in the internal part of the cave) (Figure 29). The cave’s dimensions also made it possible to evaluate the quality of reconstructions in terms of distance, as both short and long-distance data were collected (Figure 30).

Figure 28 – Lourdes grotto localization map.

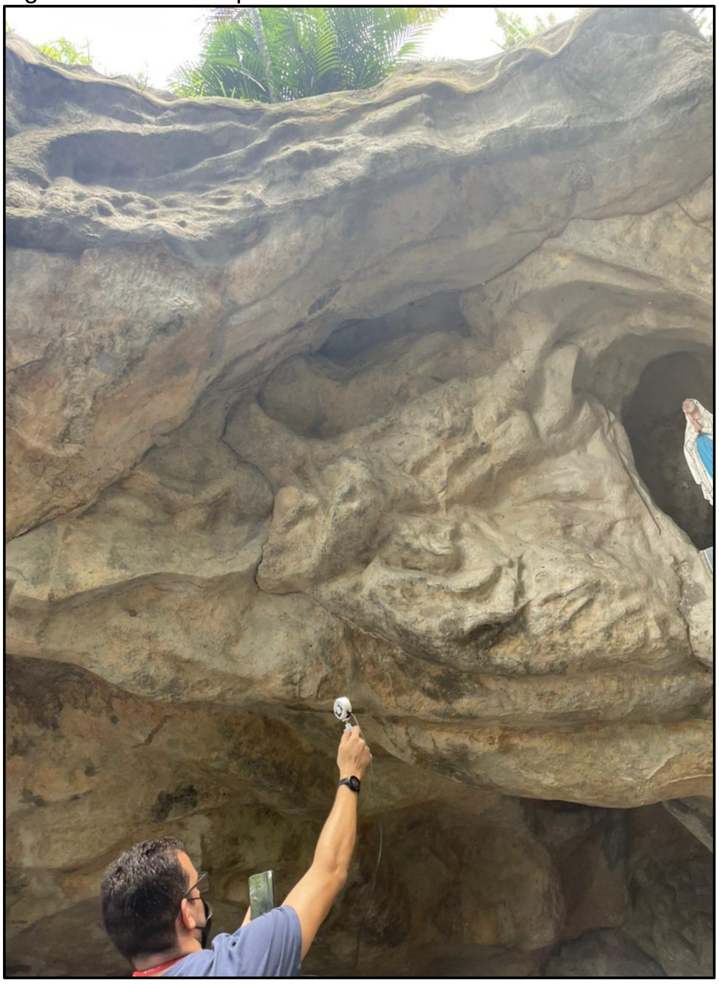


Source: the author (2023).

Figure 29 – The Lourdes grotto from the outside.

Source: the author (2023).

Figure 30 – Data capture with Intel RealSense L515 camera.



Source: the author (2023).

In this chapter, the methodology adopted in this dissertation was presented. An unstructured analysis of papers and the web was conducted to understand the existing data capture, processing and visualization tools available. That survey allowed the selection of all the solutions that were used with real data afterwards. For data capture, two different pieces of equipment were chosen: iPhone 13 Pro Max and the Intel RealSense L515 camera. Data collected with iPhone 13 Pro Max was processed using the 3D Scanner App, while Open3D was the solution chosen to process the Intel RealSense L515 data. All the obtained models were visualized and measured in MeshLab. They were also imported into Creators 3D web tool for visualization. Fieldwork carried out in three different caves was also described. As shown, each location offered advantages and challenges for data capturing. All of them were useful to test light intensity performance and distance-range capacities of the proposed data collection alternatives. In the following chapter, the obtained reconstructions and their characterization are presented.

4 RESULTS

The 3D products obtained with laser scanning and photogrammetry are shown in this chapter[29], along with their processing times and area and volume estimations. In addition, the complete reconstruction workflows proposed for each solution are presented, as well as a comparison on their usability and time-performance.

4.1 RECONSTRUCTIONS

After fieldwork was carried out in the Lapinha and Macumba caves and the Lourdes grotto, the collected information was processed and visualized. Furthermore, geometric information was extracted from the obtained models. Illustrations of the generated meshes and their measurements are here provided.

4.1.1 Lapinha cave

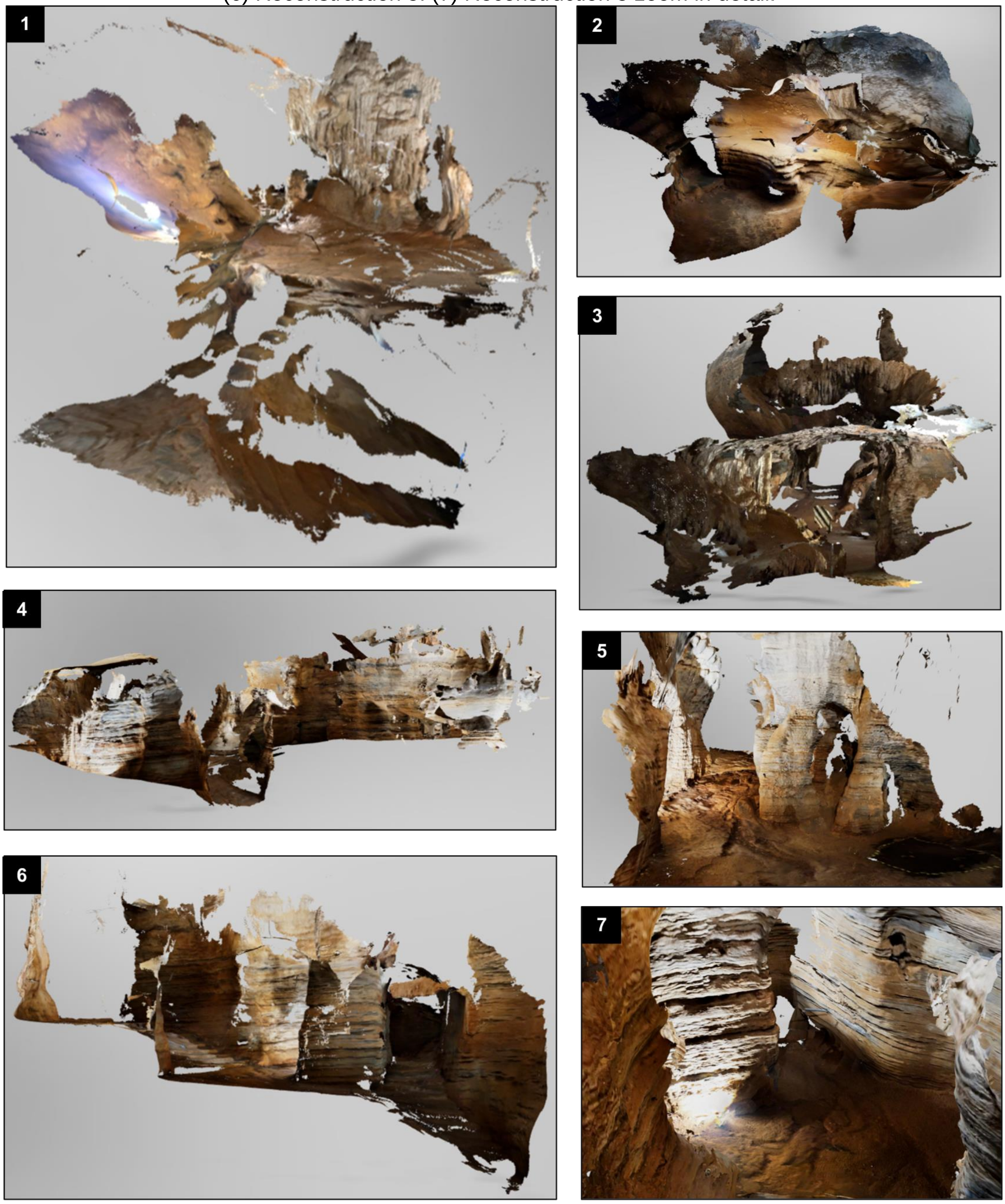
As mentioned in previous sections, the Lapinha cave was reconstructed using the 3D Scanner App LiDAR and Photos mode.

4.1.1.1 LiDAR Mode

The Lapinha cave was mapped using the iPhone 13 Pro Max built-in LiDAR scanner and the 3D Scanner App. This app was also used to process data. The resulting 3D models are presented in Figure 31, and their processing time and area and volume estimations are shown in Table 1. As can be seen, 7 reconstructions were obtained. Their processing time did not exceed 4 minutes. For reconstruction 1, the resulting model had too many holes as a consequence of the limited maximum range of the smartphone sensor, so obtaining a watertight Poisson mesh was not possible and therefore, no volume information could be extracted. In the case of Reconstruction 7, MeshLab was unable to open the .obj file, so no area and volume information was calculated.

[29] Results can be accessed at https://drive.google.com/drive/folders/1kMAjGfFxgtM_RjVOEXBwAhfQN0ARzLeQ?usp=share_link

Figure 31 – 3D reconstructions of the Lapinha cave using the iPhone’s LiDAR. (1) Reconstruction 1; (2) Reconstruction 2; (3) Reconstruction 3; (4) Reconstruction 4: (5) Reconstruction 4 zoom in detail; (6) Reconstruction 5: (7) Reconstruction 5 zoom in detail.



Source: the author (2023).

Figure 31 (continued) – 3D reconstructions of the Lapinha cave using the iPhone's LiDAR. (8) Reconstruction 6; (9) Reconstruction 6 zoom in detail; (10) Reconstruction 7.

Source: the author (2023).

Table 1 – Quantitative data of Lapinha cave reconstructions with iPhone's LiDAR.

Reconstruction	File size	Processing time	Area	Volume
Reconstruction 1	249 MB	2 minutes	307.88 m^2	*
Reconstruction 2	191 MB	1 minute	157.18 m^2	74.09 m^3
Reconstruction 3	203 MB	2 minutes	527.38 m^2	363.09 m^3
Reconstruction 4	543 MB	4 minutes	972.60 m^2	1219.16 m^3
Reconstruction 5	421 MB	3 minutes	563.68 m^2	533.07 m^3
Reconstruction 6	261 MB	2 minutes	249.21 m^2	125.73 m^3
Reconstruction 7	447 MB	4 minutes	-	-

Source: the author (2023).

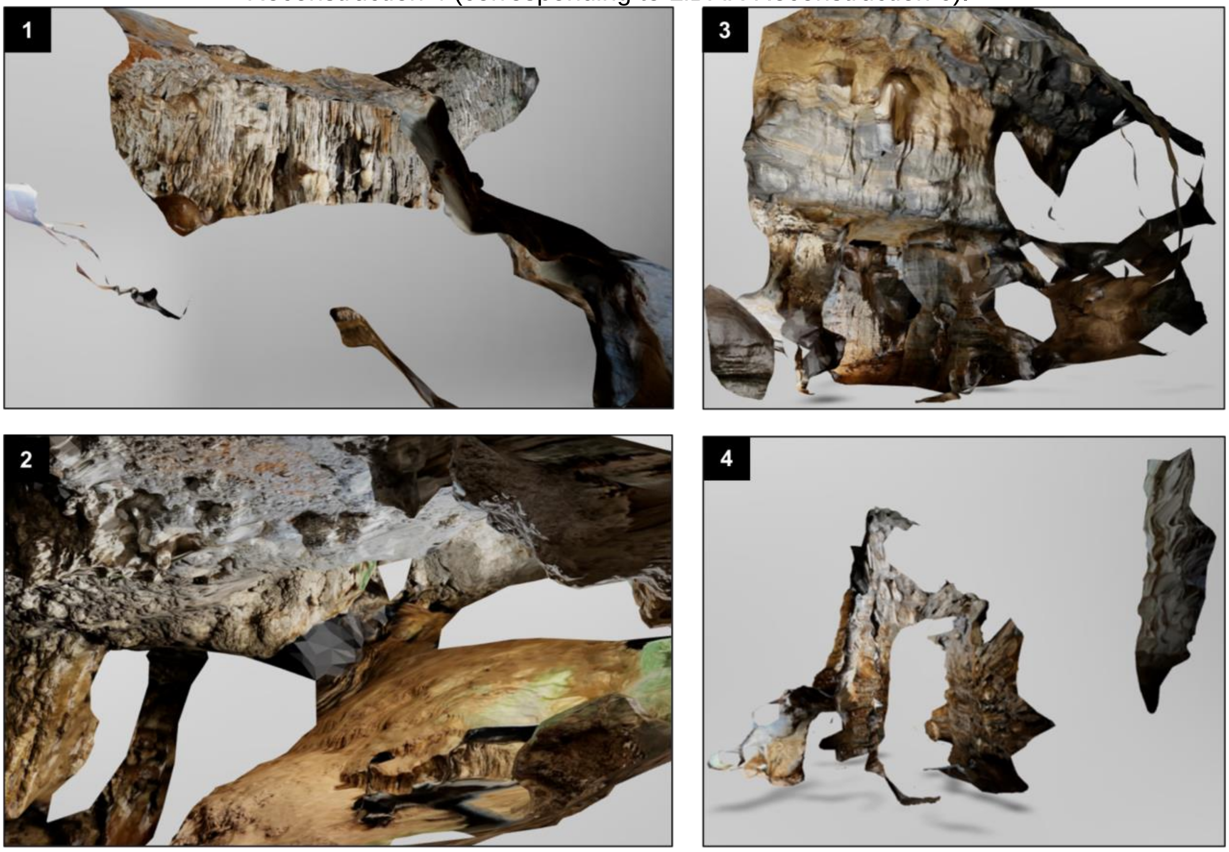
* As the original mesh had too many holes, obtaining a watertight Poisson mesh was not possible and therefore, no volume information could be extracted.

- MeshLab was unable to open the .obj file.

4.1.1.2 Photos Mode

The Lapinha cave was also reconstructed with iPhone 13 Pro Max using a photogrammetric approach. The final results, along with the processing time of each reconstruction and area and volume calculations are presented in Figure 32 and Table 2. Processing time was more delayed than with the LiDAR method, taking up to 20 minutes to complete in one case. Due to the incomplete reconstructions that were generated, no volume information could be extracted in 3 out of 4 reconstructions.

Figure 32 – Photogrammetric reconstructions of the Lapinha cave. (1) Reconstruction 1 (corresponding to LiDAR Reconstruction 1); (2) Reconstruction 2 (corresponding to LiDAR Reconstruction 3); (3) Reconstruction 3 (corresponding to LiDAR Reconstruction 4); (4) Reconstruction 4 (corresponding to LiDAR Reconstruction 6).



Source: the author (2023).

Table 2 – Quantitative data of Lapinha cave photogrammetric reconstructions.

Reconstruction	File size	Processing time[30]	Area	Volume
Reconstruction 1	276 MB	11 minutes	324.08 m²	*
Reconstruction 2	148 MB	6 minutes	44.18 m²	11.34 m³
Reconstruction 3	258 MB	16 minutes	1177.10 m²	*
Reconstruction 4	375 MB	20 minutes	107.19 m²	*

Source: the author (2023).

* As the original mesh had too many holes, obtaining a watertight Poisson mesh was not possible and therefore, no volume information could be extracted.

[30] As expected, since photogrammetry is more computationally demanding than 3D reconstruction based on RGB-D data, it takes more time to process. In addition, the Photos Mode approach in the 3D Scanner App processes data in the cloud, not on the smartphone, so it is a much heavier technique than the LiDAR Mode.

4.1.2 Macumba cave

The Macumba cave was reconstructed using the iPhone LiDAR scanner approach. The time each reconstruction took to process is shown in Table 3, together with the measurements taken. In Figure 33, the models generated are displayed. 4 reconstructions were obtained and, just like the Lapinha cave reconstructions using the iPhone LiDAR method, processing time did not surpass 5 minutes. Only reconstruction 2 did not have its volume calculated, as the large holes in the original model caused by the limited range of the capturing device made it impossible for the MeshLab's Poisson Surface algorithm to estimate this parameter.

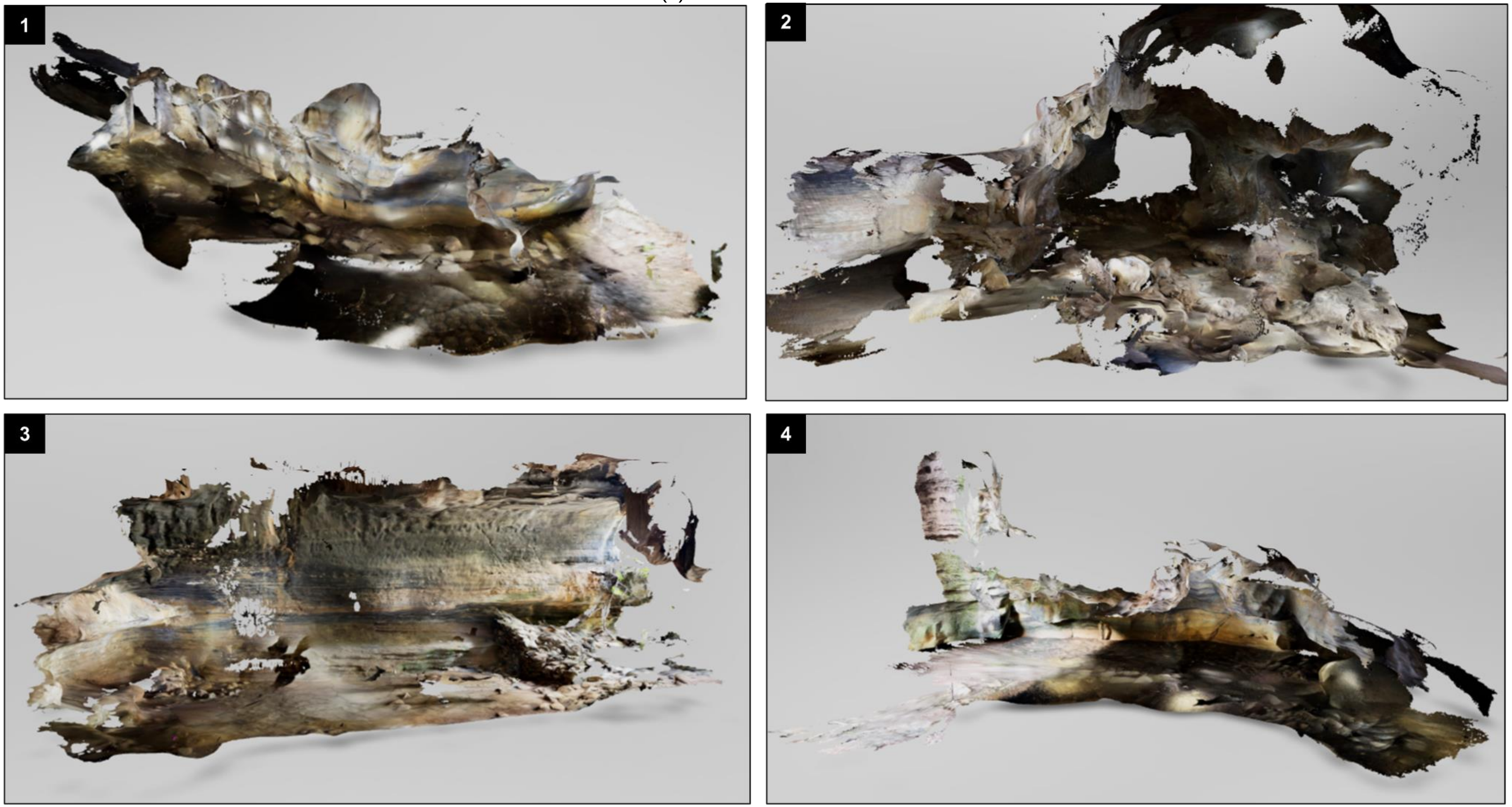
Table 3 – Quantitative data of iPhone's LiDAR Macumba cave reconstructions.

Reconstruction	File size	Processing time	Area	Volume
Reconstruction 1	509 MB	5 minutes	229.16 m^2	100.15 m^3
Reconstruction 2	352 MB	3 minutes	346.30 m^2	*
Reconstruction 3	580 MB	37 seconds	516.64 m^2	556.73 m^3
Reconstruction 4	412 MB	3 minutes	247.07 m^2	121.06 m^3

Source: the author (2023).

* As the original mesh had too many holes, obtaining a watertight Poisson mesh was not possible and therefore, no volume information could be extracted.

Figure 33 – 3D reconstructions of the Macumba cave using the iPhone's LiDAR. (1) Reconstruction 1; (2) Reconstruction 2; (3) Reconstruction 3; (4) Reconstruction 4.

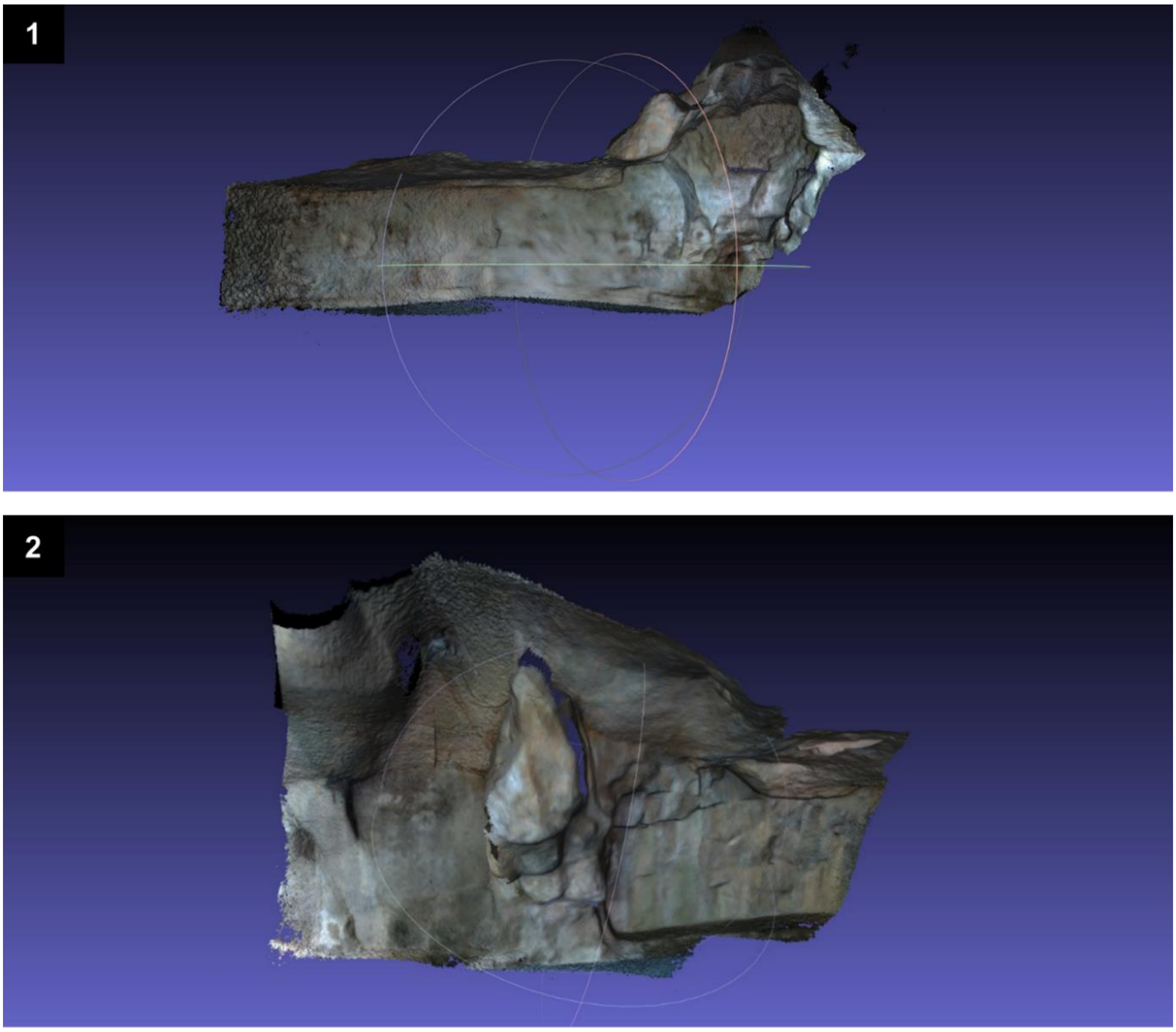


Source: the author (2023).

4.1.3 Lourdes grotto

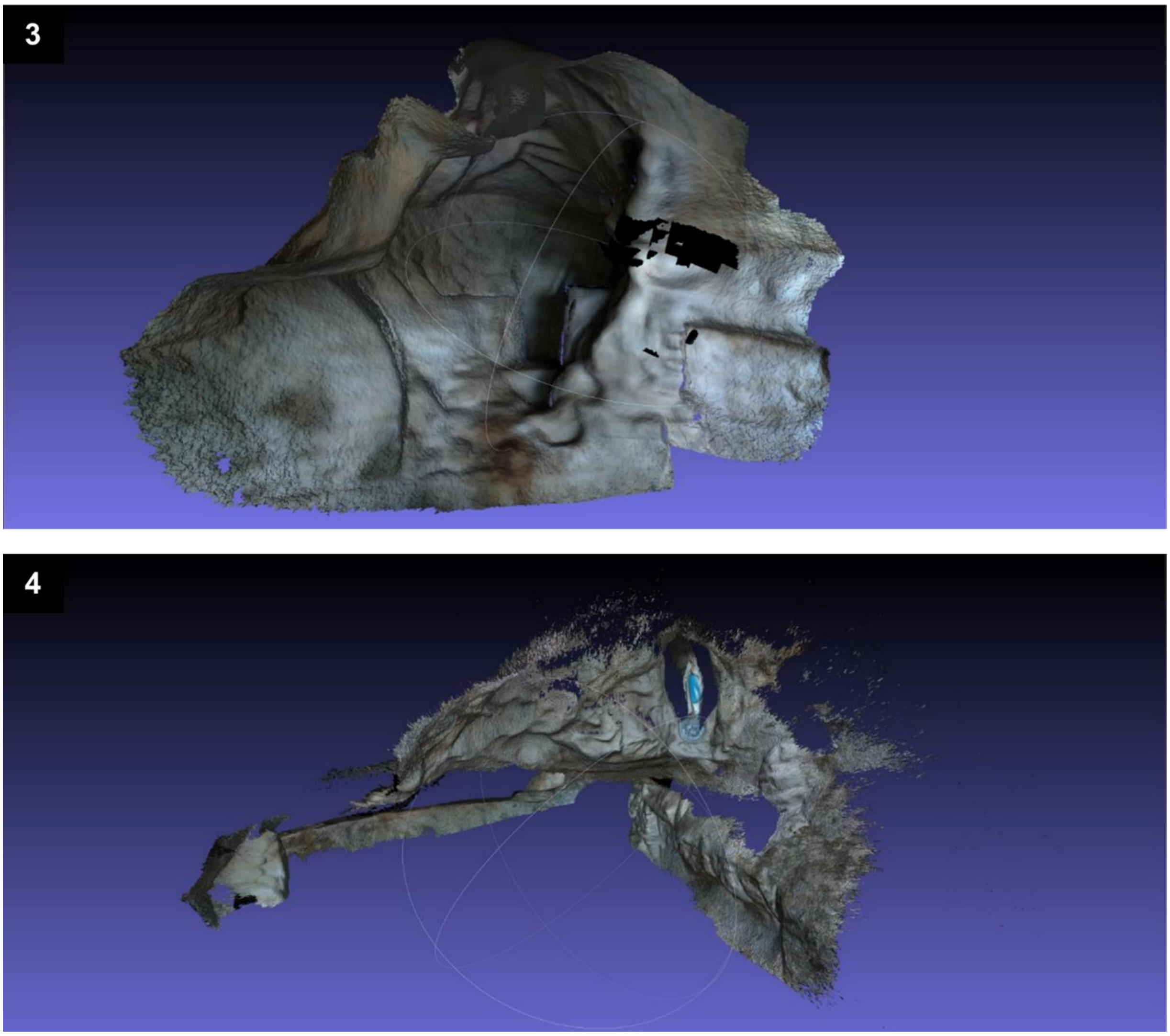
The Intel RealSense L515 camera and a Motorola Moto G30 smartphone were used to capture data of the Lourdes grotto in Recife. The results obtained after processing with Open3D are shown in Figure 34. Table 4 presents file size and processing times for each model. 4 reconstructions were generated, and processing took up to 25 minutes in one case. When executing the Poisson Surface Reconstruction for closing the mesh and estimating area and volume, a visibly inaccurate Poisson mesh was obtained, so it was decided not to proceed with the area and volume calculations, and consequently, no area and volume data is presented in Table 4. This was due to the small size of the reconstructions, as only small sections of the grotto were captured.

Figure 34 – Lourdes grotto reconstructions using Intel RealSense L515. (1) Reconstruction 1; (2) Reconstruction 2.



Source: the author (2023).

Figure 34 (continued) – Lourdes grotto reconstructions using Intel RealSense L515. (3) Reconstruction 3; (4) Reconstruction 4.



Source: the author (2023).

Table 4 – Quantitative data of RealSense L515 Lourdes grotto reconstructions.

Reconstruction	File size	Processing time
Reconstruction 1	382 MB	12 minutes
Reconstruction 2	195 MB	9 minutes
Reconstruction 3	239.9 MB	7 minutes
Reconstruction 4	800.7 MB	25 minutes

Source: the author (2023).

To better understand how the reconstruction alternatives compare to each other, a comparison of their usability and performance is presented in Section 4.2.

4.2 COMPARISON OF RECONSTRUCTION ALTERNATIVES

As described in Section 3.3, the proposed alternatives were compared according to: a) their ease of use regarding installations, data capturing, processing, visualization of results and export of the final model; and b) the time required to complete each stage in the reconstruction process.

The difficulty level to execute main functions was classified as 'Easy', 'Moderate' or 'Difficult' depending on the number of steps necessary to carry out those functions. 'Easy' involved clicking up to 5 times to complete the task; between 5 and 10 clicks, the activity was classified and 'Moderate'; above 15 clicks, the 'Difficult' class was assigned. For each solution, ease of use classification is shown in Chart 2.

Chart 2 – Usability of each proposed reconstruction alternative.

Ease of use	iPhone 13 Pro Max LiDAR	iPhone 13 Pro Max Photogrammetry	Intel RealSense L515 LiDAR
Hardware assemblage	Easy	Easy	Easy
Installation of software	Easy	Easy	Moderate
Data capture	Easy	Easy to Difficult*	Easy
Data processing	Easy	Easy	Difficult
Model exporting	Easy	Easy	Difficult
Data visualization	Easy	Easy	Easy
Area and volume calculation	Moderate	Moderate	Moderate

Source: the author (2023).

*Starting the capture process is an easy task; however, numerous clicks could be required if photos are taken manually.

The time required to complete each major activity is given in Chart 3. A Fast execution of the activity took up to 5 minutes. Between 5 and 15 minutes, the time required to carry out the activity was classified as Medium, and if the activity took more than 15 minutes to complete, the solution performance was considered Slow.

Chart 3 – Time-efficiency of the reconstruction solutions proposed.

Activity	iPhone 13 Pro Max LiDAR	iPhone 13 Pro Max Photogrammetry	Intel RealSense L515 LiDAR
Data capture	Fast	Slow	Fast
Processing	Fast	Medium	Slow
Exporting model	Fast	Fast	Fast
Area and volume extraction	Fast	Fast	NA
Visualization	Fast	Fast	Fast

Source: the author (2023).
NA: Not applicable as it was not possible to calculate area and volume of the obtained meshes with this approach.

4.3 RECONSTRUCTION PROCESS PROPOSAL

Considering the challenges encountered during the application of the methodological approach adopted (Section 3.2) and the obtained results, a complete reconstruction process is here proposed for each low-cost reconstruction technique presented.

4.3.1 iPhone LiDAR scanning

The first step in 3D reconstruction is the collection of data. The iPhone 13 Pro Max and the 3D Scanner App were used for that purpose. Planning the scan before starting the data capture is crucial so as not to capture the same areas many times. Because of that, starting in a corner is suggested. Before scanning, it is also important to carefully define the lighting system to be used. Diffuse, non-directional lights worked best when texturing the reconstruction, as the results in the Macumba cave showed.

The scanning is started in the 3D Scanner App main screen. The sensor should be moved in a slow, zigzag, up and down pattern during scanning. Additionally, adopting a 2-3 m distance from walls and other objects is recommended when possible (in some cases due to cave dimensions this may not be strictly followed). The 3D Scanner App shows a grid texture fill in the areas that have already been captured, helping to prevent the re-scanning of the same surfaces. In the potential presence of highly reflective objects inside the cave, scanning them must be avoided, as the algorithm may present reconstruction errors and the previously collected information in the same scan may be permanently damaged for later use.

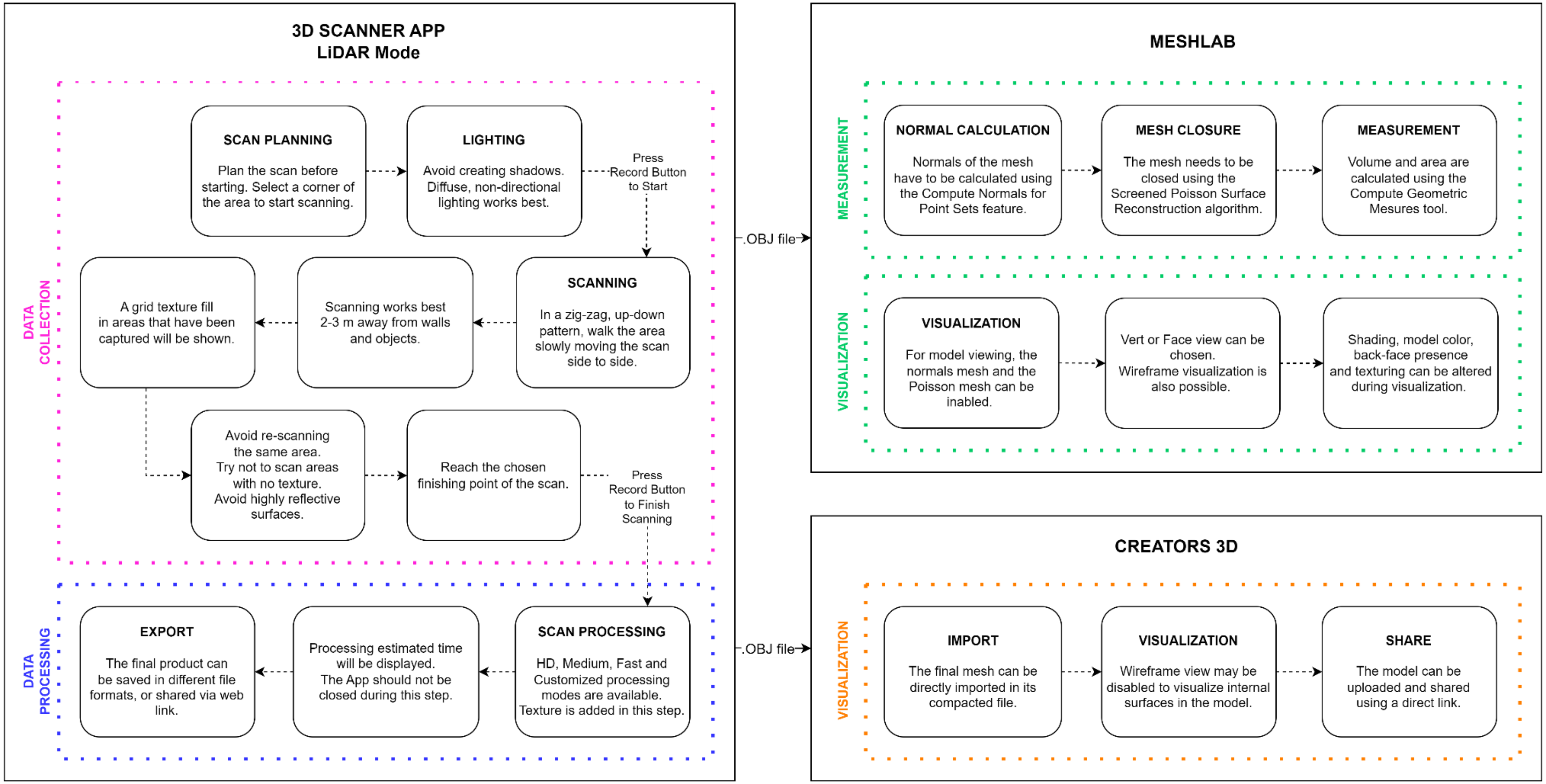
After completing the scanning step, data is processed in the 3D Scanner App as well. The HD processing option was applied in this work, but Medium, Fast and Custom processing modes are also available. During this step, the estimated processing time is displayed. The app should not be closed during that period. When the processing is concluded, the final reconstruction can be visualized within the app. The final product should then be saved in .OBJ format (web link sharing and other file formats are also available).

In order to estimate area and volume, the .OBJ file is then imported into MeshLab. Before geometric measurements, the user should compute vertices' normals using the Compute Normals for Point Sets feature, so that the Screened Poisson Surface Reconstruction algorithm can afterwards be used to create a closed-surface mesh (with no holes). All out of context bodies disconnected from the main mesh should be deleted before volume calculations. That way, it is possible to estimate area and volume using the Compute Geometric Measures feature.

If no measurements need to be estimated from the model, the .OBJ file can be directly visualized using Creators 3D. In case the file is compressed, it is not necessary to decompress it for import into the online tool. Some features like the Wireframe and Light Probe settings can be adjusted for a better visualization experience. The model can be uploaded and shared using a web link.

The step-by-step described above is presented in the summarized flowchart illustrated in Figure 35.

Figure 35 – iPhone 13 Pro Max LiDAR reconstruction workflow.



Source: the author (2023), based on the information available at www.3dscannerapp.com.

4.3.2 Photogrammetry with iPhone

Just like mentioned in Section 4.3.1, selecting a starting corner for the scan is suggested for photogrammetric reconstructions. The illumination system chosen should ideally be diffuse, and special attention should be put in not creating shadows.

Two alternatives can be followed for capturing photographs using the 3D Scanner App: the Auto Capture mode, which automatically captures images every 0.9 sec (although this timer can be increased), or the Manual Capture mode, which takes photos only when the user presses the shutter button. The former is recommended for small-size reconstructions, whilst the latter is a better option for medium to large dimension environments. Regardless of the capturing mode chosen, adjacent shots should have 70% or more overlap. In addition, a maximum of 250 photos should be captured. In case more shots are needed to complete the scanning of the whole environment, it is advised to take several small scans.

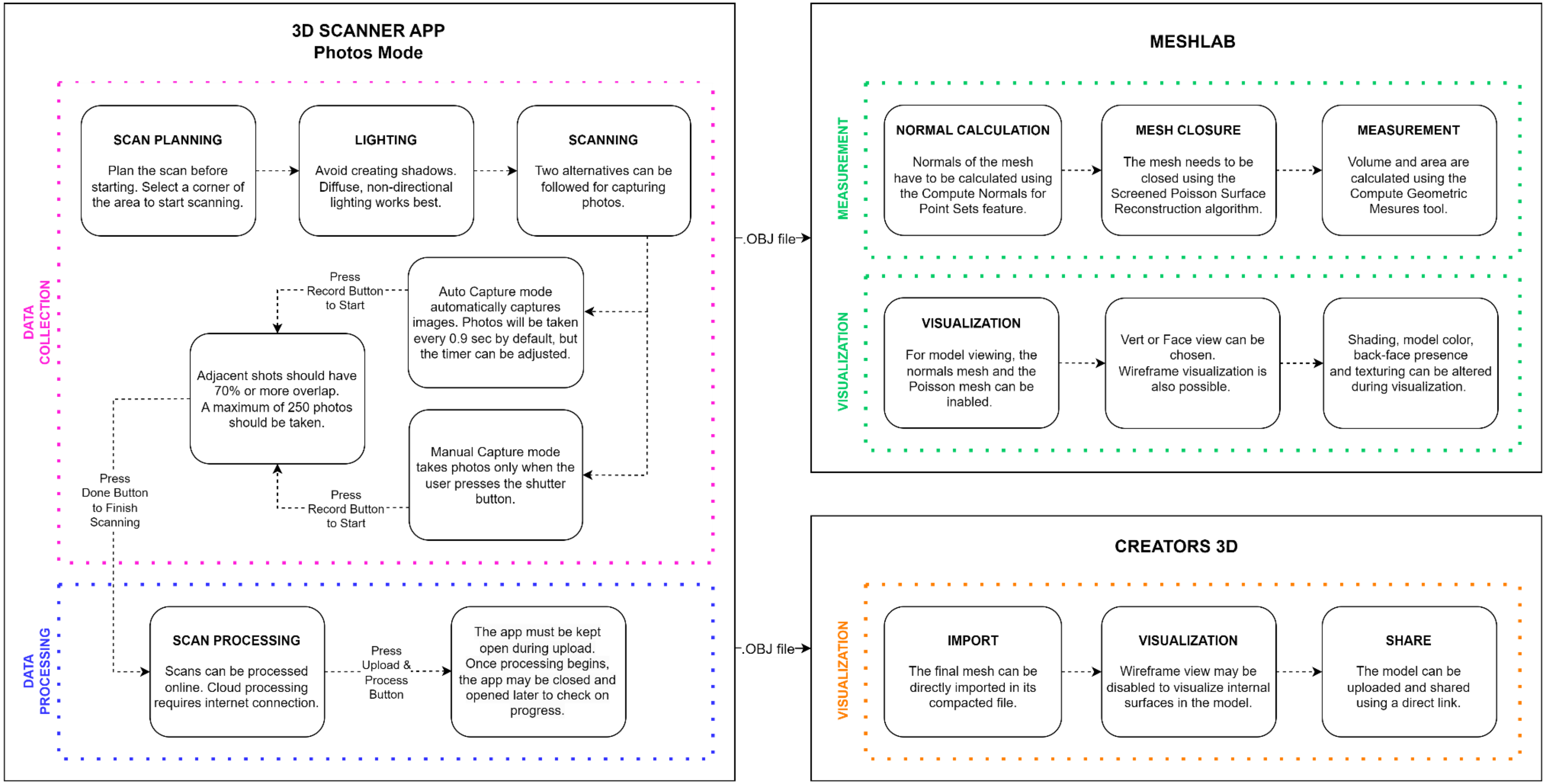
Once scanning is complete, data is processed in the 3D Scanner App to generate the final mesh. Cloud processing is suggested in this step, so internet connection is mandatory in this case. Photographs will initially be uploaded. In this stage, the app cannot be closed until the process is complete. After that, data processing starts. At this moment, the user may close the app. This task may take a few minutes to finish. When the processing is concluded, the final reconstruction can be visualized within the app. The final product should then be saved in .OBJ format (web link sharing and other file formats are also available).

In order to estimate area and volume, the .OBJ file is then imported into MeshLab. Before geometric measurements, the user should compute vertices' normals using the Compute Normals for Point Sets feature, so that the Screened Poisson Surface Reconstruction algorithm can afterwards be used to create a closed-surface mesh (with no holes). All out of context bodies disconnected from the main mesh should be deleted before volume calculations. That way, it is possible to estimate area and volume using the Compute Geometric Measures feature.

If no measurements need to be estimated from the model, the .OBJ file can be directly visualized using Creators 3D. In case the file is compressed, it is not necessary to decompress it for import into the online tool. Some features like the Wireframe and Light Probe settings can be adjusted for a better visualization experience. The model can be uploaded and shared using a web link.

The pipeline described for photogrammetric reconstructions is shown in Figure 36.

Figure 36 – Photogrammetry with the iPhone workflow.



Source: the author (2023), based on the information available at www.3dscannerapp.com.

4.3.3 Intel RealSense L515 + Android scanning

Differently to the previously described methods, to use the Intel RealSense L515, the camera has to be coupled to an Android Smartphone via USB type-C connection. Data is collected through the RS Camera App and before starting the scans, the 'No Ambient Light' and 'Low Ambient Light' settings should be activated. To define which lighting tools to use, it should be considered that Halogen and some LED light sources can reduce L515 performance. Too much light in the environment may result in a depth map with many holes. On the contrary, too dark surfaces may reduce depth range. When scanning the environment, walking at a medium pace is ideal, as both too fast and too slow captures can prejudice data capture. Depth measurement works best on rough surfaces with diffuse reflection: highly reflective surfaces can cause the laser light not to be reflected back into the receiver for detection. In addition, it should be considered that during activities inside the cave, placing the camera in a protective case with no air flow should be avoided as the camera only withstands operations at up to 30°C.

When the scanning is completed, a .BAG extension file is saved in the smartphone. This is the file used for data processing. Prior to running the Open3D library and generating the 3D mesh, a Python environment needs to be installed/launched in the user's PC. NVIDIA CUDA toolkit was the one used in the present study to optimize the process using GPU. The processing stage consists of executing the code lines available at GitHub[31] and described in the RealSense with Open3D tutorial[32]. Once completed, the final product is available in .PLY format to be exported for visualization and measurement.

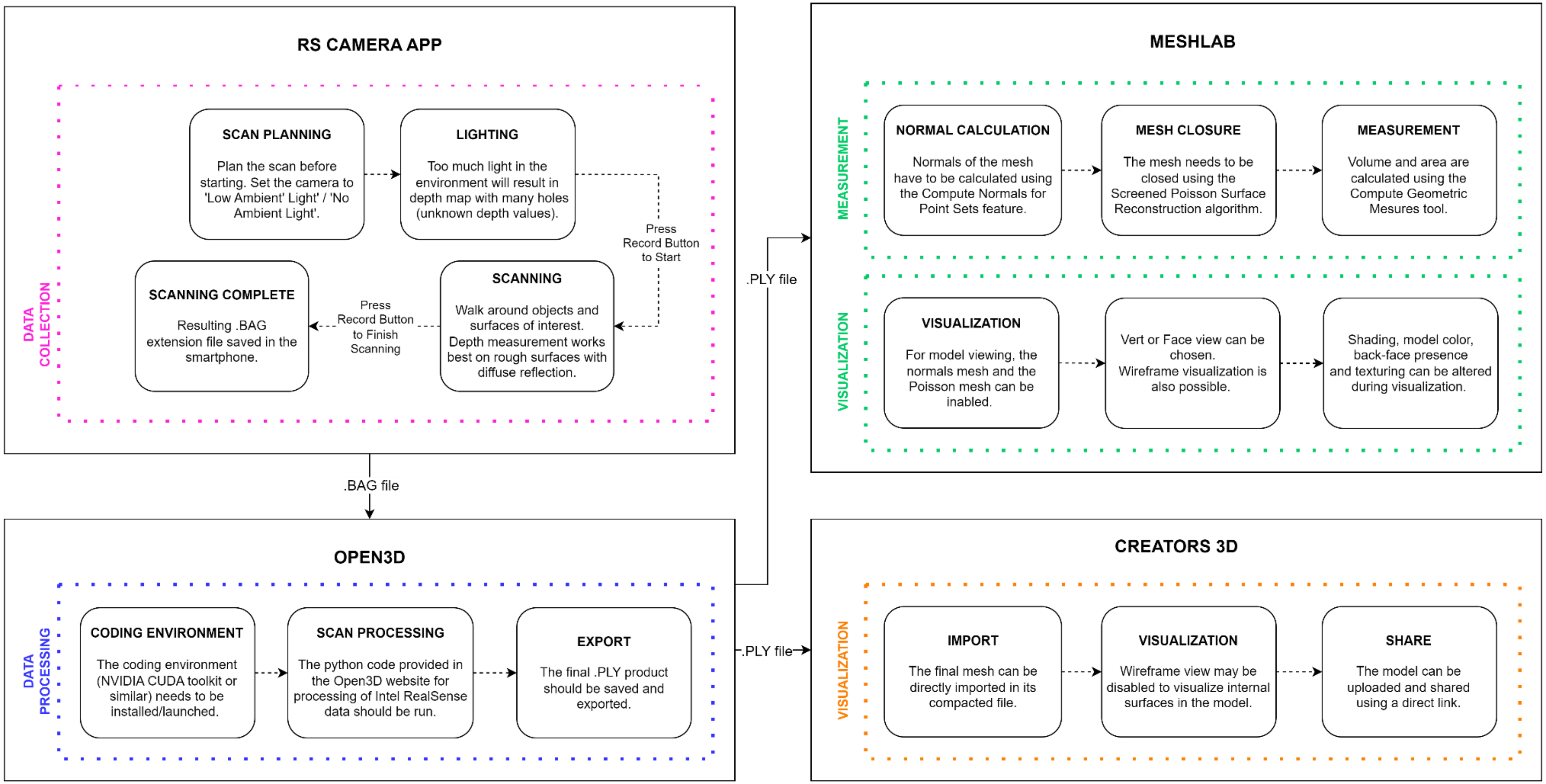
In order to estimate area and volume, the .OBJ file is then imported into MeshLab. Before geometric measurements, the user should compute vertices' normals using the Compute Normals for Point Sets feature, so that the Screened Poisson Surface Reconstruction algorithm can afterwards be used to create a closed-surface mesh (with no holes). All out of context bodies disconnected from the main mesh should be deleted before volume calculations. That way, it is possible to estimate area and volume using the Compute Geometric Measures feature.

[31] https://github.com/isl-org/Open3D/tree/master/examples/python/reconstruction_system
[32] https://www.open3d.org/docs/release/tutorial/sensor/realsense.html

If no measurements need to be estimated from the model, the .OBJ file can be directly visualized using Creators 3D. In case the file is compressed, it is not necessary to decompress it for import into the online tool. Some features like the Wireframe and Light Probe settings can be adjusted for a better visualization experience. The model can be uploaded and shared using a web link.

The workflow proposed to carry out cave reconstructions using the Intel RealSense L515 camera coupled to an Android device technique is presented in Figure 37.

Figure 37 – Workflow for 3D reconstructions using Intel RealSense L515.



Source: the author (2023), based on Intel RealSense L515 user guide available at https://support.intelrealsense.com.

As can be seen from the workflows presented, some minor steps like scan planning and definition of lighting system and major reconstruction stages like measurement and visualization apply to the three reconstruction alternatives. However, some particularities exist for each reconstruction process as well. In the following chapter, the presented results and application processes will be discussed to further understand the advantages and disadvantages of each reconstruction alternative.

5 DISCUSSION

5.1 ASSESSMENT OF RESULTS

Overall, the results presented in Chapter 4 had an acceptable quality. The three approaches proposed in this dissertation proved to be capable of performing well in speleological contexts. Flowcharts implemented and shown in Section 5 concisely show the step by step to carry out reconstructions with each solution, which will allow any potential user to successfully model their cave of interest, independently of their computational knowledge. However, some challenges arose during field activities and should be considered for future reconstructions.

5.1.1 iPhone 13 Pro Max

Regarding LiDAR scanning with iPhone, the maximum range is limited (up to 5 meters) and made it impossible to capture the cave's roof and other high features, both in the Lapinha and the Macumba caves. This created incomplete, holey meshes that were impossible to close using MeshLab and therefore, no volume measures could be obtained in those cases. Also, for vast surface areas, taking very large scans is not suggested by the app's developers as they may not process well; and indeed, some large scans captured in the field made the app stop working and information was lost. Additionally, for model texturing in the Macumba cave, it was necessary to use portable lamps. The 500-lumen headlamp shown in Figure 27 turned out to be a better source of lighting than the manual flashlight, as its diffused light did not saturate the camera. The manual flashlight, on the other hand, left white, saturated circles imprinted on the final models.

Concerning the photogrammetric approach applied, shaky photos had a big influence on texture. As mentioned in Chapter 3, the automatic capture of the 3D Scanner App was used, which took one picture every 0.9 secs. This high frequency required fast movements of the camera, which generated blurred photos in some cases. Manual capture might be a better option in that sense. Regarding model texturing, the results achieved through photogrammetry appear to be of greater quality than coloring in the LiDAR reconstructions. However, a maximum of 250 photos, as suggested in the app's user guide, is not enough for reconstructions of medium to big size environments, considering that the photos taken should have an overlap of at least 70%. In the case of the presented reconstructions, taking a limited number of photos led to defective meshes with many missing parts, which ended up impeding volume measurements. Consequently, in order to adopt the suggested quantity of photos and obtain quality reconstructions, it is necessary to generate many small, separate models to map a medium-size cave and join them afterwards.

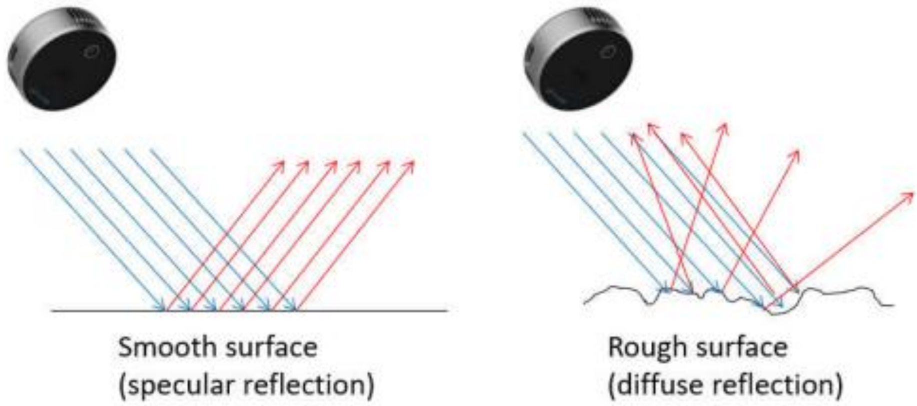
In summary, LiDAR capturing proved to be much faster and easier than 3D Scanner ‘Photos’ mode, making it a better alternative for cave contexts. However, both capturing methods resulted in final products with many holes. The consequence of that is missing information. Quantitative information extracted from those meshes might be inaccurate, as the missing parts have to be inferred to obtain area and volume data, for example. And, indeed, models of the same cave rooms obtained both with LiDAR and photogrammetry gave divergent geometric results.

To avoid large holey areas in the final meshes obtained with the LiDAR sensor, a possible solution would be using a selfie stick to capture information in more distant areas of the cave. That way, the distance between the iPhone to the surface to be mapped would be shortened, compensating the limited distance range of the device. In the case of models obtained with photogrammetry and considering the 250 photos limit, it is recommended not to use this technique for large areas. Instead, the photogrammetric approach should only be adopted for the reconstruction of reduced sections or small features within the cave. High quality reconstructions could be achieved like that, as a good photo overlapping would be attained.

5.1.2 Intel RealSense L515

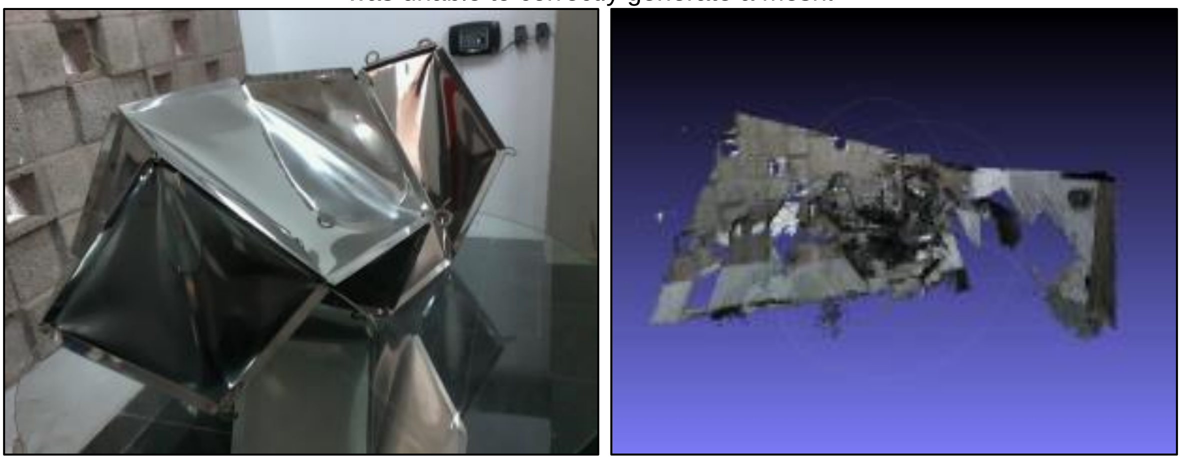
With respect to Intel RealSense L515 LiDAR scans, reflection can be an issue: as stated in the camera’s user guide, depth measurements work best on rough surfaces, as most of the reflected laser light will be received by the camera. On highly reflective objects and surfaces, the laser light may not get reflected back into the receiver for detection, and no depth value will be registered in those cases (Figure 38 and Figure 39). Although no highly reflective surfaces were mapped in the Lourdes grotto, this limitation should be taken into account when modeling other types of caves, as calcite and dolomite, the most common constituting cave minerals, can have vitreous to resinous luster and this could interfere in the performance of the camera.

Figure 38 – Reflection of laser light off smooth and rough surfaces.



Source: Intel RealSense Lidar Camera L515 User Guide (2020, p. 18).

Figure 39 – Reflective surface issues. (Left) Highly reflective object with smooth surface reconstructed during testing with Intel RealSense L515. (Right) Reconstruction results. The reconstruction algorithm was unable to correctly generate a mesh.



Source: the author (2023).

In addition, the 9-m maximum range of the camera depends on the reflectivity of the target, and darker objects may reduce the effective range of the device as they absorb most of the laser light.

Regarding the area and volume estimations, it should be noted that the generated models resulted in visibly inaccurate meshes when the Poisson Reconstruction Surface algorithm was executed in MeshLab, so no area and volume calculations were obtained. In future reconstructions, this stage of the process should be tested carefully.

Another negative point for the Intel RealSense scanner is that, according to its manufacturers, it should not be operated in wet conditions and/or in dusty environments. This might be an impediment for some speleological applications.

Moreover, the production of this camera was discontinued by Intel in 2021, which is a discouraging factor for its usage.

On the whole, based on the assessment presented and the comparisons described in Section 5.3, reconstructions using LiDAR technology showed a greater potential for cave modeling than photogrammetry. Between the two LiDAR solutions adopted, the one involving the iPhone 13 Pro Max scanner had the best time performance and usability, as its whole reconstruction process is less laborious than with the Intel RealSense camera. A good texturing quality was achieved with both the iPhone's LiDAR and with the photogrammetric approach using the iPhone. Texturing of good resolution could allow detailed visualization of stratifications and sedimentary structures, important features to understand the speleogenesis of the cave (De Waele et al., 2018).

5.1.3 Cost-Benefit Analysis

To further assess the proposed reconstruction alternatives, a cost-benefit analysis is here presented. For that purpose, the iPhone's LiDAR sensor and the Intel RealSense scanner are compared to the RIEGL VZ-400i, a well-known, high-end commercial terrestrial laser scanner that has been previously used in the modeling of caves (Hämmerle et al., 2014; Büyüksalih et al., 2020; Walters & Hajna, 2020). Photogrammetry was not included in the cost-benefit analysis, as it is less restricted by the capturing device and any digital camera can be used with that methodology.

Chart 4 summarizes the price of each of these sensors as well as their essential technical specifications for cave reconstructions. This information was obtained from RIEGL VZ-400i datasheet, Intel RealSense L515 datasheet and the iPhone 13 Pro Max technical description on Apple's website. As can be seen, the RIEGL VZ-400i can be used to map from small-sized caves to immense speleological environments due to its minimum and maximum distance ranges (Walters & Hajna, 2020). On the contrary, the iPhone LiDAR and the Intel RealSense scanner have both limited maximum distance ranges, making them more suitable for the reconstruction of small caves or small features within medium/large size caves. Additionally, the RIEGL scanner tolerates the widest temperature range during operation. On the other hand, the iPhone LiDAR sensor and the Intel RealSense scanner have a better tolerance to high humidity; the iPhone smartphone is, in fact, water resistant. The RIEGL sensor is the least portable tool of the three, with a weight 40 times greater than the iPhone 13 Pro Max and requires to be mounted on a tripod for scanning. This may represent a problem in hard-access caves or in narrow cave rooms. On the contrary, the iPhone LiDAR is integrated to the iPhone smartphone and the Intel RealSense camera can be coupled to a smartphone or tablet, making them both handheld devices.

In summary, to scan small caves or small details inside medium/large speleological environments, the iPhone LiDAR and the Intel RealSense camera are a cost-effective alternative, with a price that represents 1.36% and 2.17% of the total cost of the RIEGL equipment respectively. The iPhone’s LiDAR is recommended for caves with ceilings of 5 m high or less, while the Intel RealSense sensor can be used with larger caves (up to 9 m high). Photogrammetry is only recommended for detailed modeling of specific cave features, as the quantity of photos required to reconstruct whole environments is inviable when time and budget are limited.

Chart 4 – Cost-Benefit analysis. The RIEGL VZ-400i scanner, the iPhone 13 Pro Max and the Intel RealSense L515 LiDAR data capture devices are compared.

	RIEGL VZ-400i	iPhone 13 Pro Max	Intel RealSense L515
Cost (USD)	120,000[33]	1,600[34]	2,600[35]
Min range	1.5	-	0.25
Max range	800	5	9
Weight	9.7 kg	240 grams	95 grams
Dimensions	206 mm x 346 mm	160.8 mm x 78.1 mm x 7.65 mm	61 mm x 26 mm
Calibration	Yes	No	Yes
Color data	Yes	Yes (12MP RGB Camera)	Yes (2MP RGB Camera)
Sensors	Accelerometer, gyroscope, compass, barometer	Accelerometer, gyroscope, proximity, compass, barometer	Accelerometer and gyroscope
Power supply	Own battery	Own battery	Powered through USB to host platform
Operating Conditions	0-40°C / 80° humidity @ 31°C	0-35°C / 5% to 95% humidity	0-30°C / 90% humidity @ 40°C
Storage Conditions	-10°C to 50°C	-20°C to 45°C	0 to 50°C
Other	Cloud storage available	Integrated to iPhone smartphone	Requires host platform (i.e., smartphone)

Source: the author (2023).

[33] https://www.laserscanningforum.com
[34] https://www.iplace.com.br
[35] https://www.americanas.com.br

6 CONCLUSION

In this dissertation, affordable 3D reconstruction alternatives to model caves were studied. These solutions have a price of 1/10 or less of the cost of a top-quality, high-end LiDAR (which was estimated at 30,000 USD). The reconstruction pipeline followed with each of the proposed solutions was presented. The solutions and processes proposed included both the generation of 3D models of caves, as well as the extraction of their area and volume.

Three reconstruction approaches were proposed: laser scanning using the iPhone 13 Pro Max built-in LiDAR and the Intel RealSense L515 LiDAR camera, and photogrammetry using the iPhone 13 Pro Max. As the results obtained in this dissertation show, all three low-cost reconstruction techniques demonstrated to be capable of modeling small sections of caves with a satisfactory quality. The LiDAR technique using the iPhone 13 Pro Max smartphone showed to be the best amongst them, as it was the easiest alternative to use, with the fastest data capture and processing performance. Alternatively, the Intel RealSense LiDAR should be the preferred option if using an Android device is available instead. However, cave dimensions and what the model will be used for are important factors to determine which solution to use. Photogrammetry proved to be more powerful for texturing final products, but its use in large environments is not recommended as it implies capturing many small scans and their processing can be time consuming. A photogrammetric approach should be rather indicated for modeling small size speleological environments, or for detailed reconstructions of specific objects/features inside caves.

6.1 CONTRIBUTIONS

Although 3D cave modeling research is abundant in academic literature, the low-cost mobile laser scanning techniques proposed in this dissertation have not been deeply studied by the scientific community for 3D reconstructions in speleological contexts, meaning the presented reconstruction processes constitute a groundbreaking approach. Moreover, the fact that the iPhone 13 Pro Max is a relatively recently launched smartphone makes its study innovative.

No studies involving the 3D reconstruction of the Lapinha and Macumba caves and the Lourdes grotto were found during the development of this dissertation, so the results here presented are a contribution for future studies of these sites.

Overall, the proposed reconstruction alternative using the iPhone approaches has a cost of approximately 1,600 USD, while the Intel RealSense L515 alternative costs around 2,950 USD. These values represent, respectively, less than 11% and 20% of the 15,000 USD starting price for TLS scanners[36], and between 1.5% and 2.7% of the 110,000 USD cost of the RIEGL VZ-400i TLS Lidar Scanner[37] given as an example in Chapter 2.

In addition to the mentioned contributions, two conference papers were presented during the development of this research:

Chaves Fitzgerald, G., Ventura, V., Vasconcelos, G., Martins, V., Teixeira, J. M., Bernard, E., 2022. Reconstrução 3D de Baixo Custo Aplicada a Ambientes de Cavernas. Presented at the 7th Symposium on Environmental Management - 17th Brazilian Conference on Engineering and Environmental Geology (CBGE) held in Belo Horizonte, Brazil.

Teixeira, J. M., Pimentel, N., Barbier, E., Bernard, E., Teichrieb, V., Chaves, G., 2023. Low-Cost 3D Reconstruction of Caves. Presented at the 18th International Conference on Computer Vision Theory and Applications held in Lisbon, Portugal.

6.2 NEW RESEARCH OPPORTUNITIES

With the promising results obtained in this dissertation, new research opportunities arise. In the short term, it is intended to test the iPhone pipelines in a new cave with a more current iPhone model, the 14 Pro Max.

The proposed alternatives could also be tested in the same cave and compared to a reference model. Based on the conclusions presented here, the reference model should be the one captured with the iPhone LiDAR scanner. The mentioned comparison could be made quantitatively by selecting visible points in all models to understand their deviation from the reference point; or qualitatively and include an assessment of the fidelity of the model from visually comparing it with cave photographs, and the contrast between their quality.

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[36] https://www.geo-matching.com
[37] https://www.laserscanningforum.com

Furthermore, user feedback regarding the proposed reconstruction solutions and processes would be beneficial to understand their real applicability. That feedback could be used to facilitate decision making on which solution for 3D cave mapping to prioritize in future studies.

For TLS data capturing, scan targets are commonly used to support the scan registration process (Idrees & Pradhan, 2017). The implementation of such targets with mobile laser scanners could be helpful for future reconstructions to merge individual scans. Additionally, georeferencing the model would allow it to precisely locate the model in cartographic maps and integrate it with other information in Geographic Information Systems (GIS) to analyze wider spatial interactions (Gallay et al., 2015).

LiDAR scanners not only capture spatial data, but also intensity information. Exploring the uses of that information and how it can be helpful to better understand the cave's characteristics would add value to the generated models. As stated by Eitel et al. (2016), the intensity measurement by the scanner indicates the reflectance of a surface and consecutively, could be used to get spectral information about chemical surface properties and about the constituting rock, amongst other attributes.

3D models of caves could be useful for environmental impact monitoring in small caves where geotourism activities are developed. These models could be used for immersive Virtual Reality applications (Büyüksalih et al., 2020) in educational contexts. Additionally, 3D reconstructions could aid biologists studying cave fauna (like bats) and their relationship with cave dimensions and internal structure (Barros & Bernard, 2023). For all the mentioned purposes, the proposed low-cost reconstruction alternatives could be used.

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