Challenges and Results in the Exploration and Documentation of Unique Historical Underground Complexes

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Abstract

Historical mining adits represent an important part of cultural heritage, but their documentation often poses significant challenges due to limited accessibility, complex shapes, and harsh underground conditions. This paper compares traditional and modern surveying methods for underground spaces, focussing on the use of static and mobile laser scanning as well as low-cost solutions such as LiDAR sensors integrated in smartphones. Field tests conducted at selected sites in the Czech Republic evaluated the accuracy, time requirements, and suitability of each method for different types of adits. The results demonstrate that MLS technology offers an optimal balance between accuracy and efficiency, while even low-cost devices can provide basic data for quick preliminary mapping. The study provides recommendations for selecting the appropriate documentation methods according to site-specific conditions.

1. Introduction

1.1 Significance of Sites

Underground spaces are an integral part of the cultural heritage left in the landscape. Their beauty and uniqueness have captivated mankind for many years until today. Over time, mankind has not only exploited these natural underground spaces but has begun to create its own. Their motivation was to mine the precious resources hidden beneath the surface of the earth. The tools used for this mining, from today's perspective, can be considered very primitive, and the cutting of rock with them very difficult. Mining in these types of mines was conducted along a vein and the size of the passages was just right for one man. In the territory of the present-day Czech Republic, there are several localities where precious metals were mined during the Middle Ages. The most important locations include the area of Kutná Hora, the Jáchymov region, Jílové u Prahy, Kašperské Hory and the northern part of the Jeseníky Mountains. Many of these mines are not fully documented.

Exploring underground tunnels not only provides information about the significance of the site, but important artefacts can also be found in these spaces. Historic mines may have been filled in over time or may have been flooded or walled in. The information in them has thus been preserved. Enthusiasts are pushing for their return to the world. The aim is to make these mines accessible and to carefully document them. Since they usually lack funding and equipment, there is logical cooperation with the university and the National Heritage Office. Many of the archaeological finds are quite unique and will take time to be described and documented (Pavelka, Jr and Pacina, 2023).

1.2 Study Cases

1.2.1 Barbora Mine Adit

The area of the city neighbourhood of Kutná Hora was one of the most important Central European areas for silver mining. Mining has been carried out in this locality since the middle of the 13th century. It is estimated that before the Hussite Wars (the first half of the 15th century), an average of 2-3 tonnes of silver was extracted per year. In the 16th century, there was a significant decline in mining and the Jáchymov area became a more important centre (Holub 2018).

1.2.2 Johannes Mine Adit

This mine is in the Ore Mountains near the city of Jáchymov and was an important tin mine with other mines in the neighbourhood. Mining began here in the 16th century at the latest. Mining at this mine continued virtually uninterrupted until the 1870s. Today, it is a large underground complex under UNESCO protection, together with the Saxon part in neighbouring Germany.

1.2.3 Adit Mine 'U Pinců'

The adit mine is one of many typical adits in the city of Jáchymov. At the beginning of the 16th century, silver veins were found in the Jáchymov area, and the town became the second most populous town in the Czech Kingdom (Majer 1994). The origins of this mine date back to 1516, when there was a small fortress at the entrance to the adit and a mint nearby. The tunnel was originally about 60 m long.

1.2.4 Bohuliby Mine Adit

The first mining near the city Jílové u Prahy began in the 12th century, but it started to rise in the 13th century. At that time, this location was one of the most important in the Czech Kingdom in terms of gold mining. The Bohuliby Mine is neighbouring the more important Pepř Mine and they are interconnected (Morávek 2016).

2. Material and Methods

This paper deals with the issue of documentation of historical mines or general underground spaces. Various geological and speleological tools are used to map underground spaces. The most common are compass, bands, distance metres and total stations. Currently, laser scanners are widely used (Pavelka Jr. et al, 2023).

2.1 Characteristics of Historical Mines

2.1.1 Shape and Size of Adit Tunnels

Historical adits usually share one important characteristic: narrow cross-sections. When the adit or shaft was used mainly for ventilation, access, drainage, or exploration, its dimensions were kept very limited due to the labour-intensive nature of manual excavation and frequent backfilling.

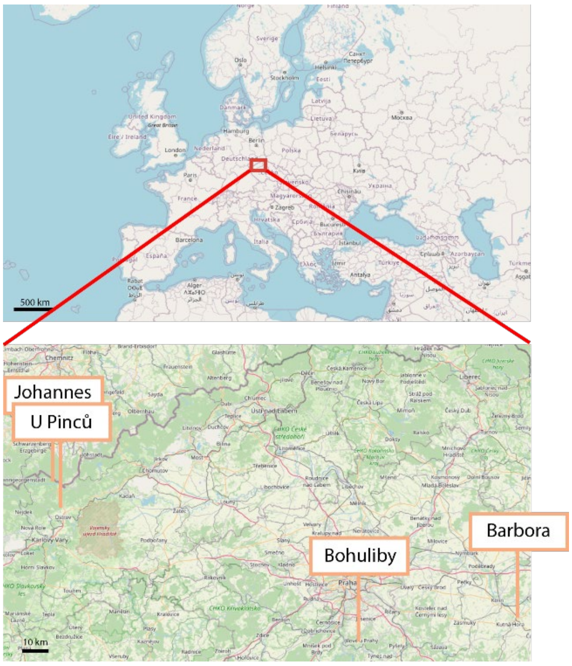

Figure 1. Location of study cases

Movement in these spaces is generally possible only in a crouched position and often requires crawling or moving on the hands and knees. This factor significantly limits the size and weight to survey equipment that can be deployed. Figure 2 shows a passage in the “U Pinců” adit where the clearance height is about 60 cm and the tunnel curves to the right.

Figure 2. Narrow passage in the tunnel ‘U Pinců’

In this respect, the challenge for adits is not only their size, but also their shape. Historical adits often lack straight sections; instead, the tunnels twist and turn in multiple directions. This characteristic significantly reduces the effectiveness of many standard surveying methods. Another difficulty that limits the use of certain devices is the presence of vertical shafts (Figure 3) and passages. In these parts, movement is possible only with ladders or rope access. This becomes especially restrictive if the adit needs to be connected to the outside, and the survey must seamlessly continue through different levels.

Figure 3. Entrance to Barbora mine

2.1.2 Adit Environment

As already mentioned, historical adits were often abandoned and over time became flooded or filled with debris. The first long-term task is, therefore, to reopen and make these adits accessible again. Only after at least partial clearance can more extensive documentation of the structure be carried out. Even after cleaning, it is necessary to expect high humidity, flowing water, partially flooded sections, and above all pervasive mud. These environmental conditions require special attention, especially when using electronic survey equipment.

2.2 Traditional measurement methods

2.2.1 Manual Instruments

Manual instruments represent the most traditional and widely used surveying method in underground environments, particularly in caves and old adits (Worthington, 1997). The basic setup includes a measuring tape, compass, and clinometer, commonly used together in the so-called "tape-compass-clinometer survey" (Ballesteros et al., 2013).
The main advantages of manual instruments are their low cost, easy portability, and independence from batteries or sensitive electronics, which is a major benefit in demanding underground environments. On the other hand, their disadvantages include lower accuracy and greater time requirements. Errors in estimating azimuth or inclination can accumulate, resulting in deviations over longer survey sections.

2.2.2 Total Stations / Theodolites

Measuring distances and angles with a total station in underground spaces is one of the fundamental tasks of engineering and specialised geodesy. A total station combines the functions of a theodolite and an electronic distance metre. In the documentation of underground areas, total stations are often used to establish a control network, which provides reference points for subsequent measurements. When configured and measured correctly, such a network can achieve millimetre accuracy (Urban and Jiřikovský, 2015; Sanmiquel et al., 2020).
During surveying with a total station, a selective point measurement method is usually applied, where individual target points are intentionally chosen. Modern instruments allow for precise measurement using a prism or remote distance

measurement (RDM) when slightly lower accuracy is acceptable or access is limited (Luo et al., 2016).
As shown in Figure 3, using a total station requires sufficient space for setting up the instrument and for operator movement. This method is labour intensive and time consuming. Stabilising the measured points is recommended, and additional tools may be needed. For example, a stable plumb line when transferring points through a vertical shaft.

Figure 4.: Positioning the point field using the theodolite

2.3 Modern Measurement Methods

2.3.1 Terrestrial Laser Scanning

Rapid spatial data acquisition has seen significant growth in geodesy and cultural heritage documentation in the past two decades. Terrestrial Laser Scanners (TLS), can capture millions to billions of points in a short time, faithfully recording the shape and structure of surfaces. This type of scanner is used in underground spaces, such as historical adits and caves, primarily for detailed documentation and the creation of highly accurate 3D models (Giordan et al., 2021).
The measurement principle is based on emitting a laser beam that reflects off an object. The device measures the return time or the phase shift to determine the distance. Modern TLS instruments combine this with precise angle measurement, achieving spatial accuracy on the order of millimetres to centimetres. A major advantage in underground conditions is that the scanner can operate in complete darkness and generate data without external lighting (Van Genechten et al., 2008).
Today, there is a wide variety of static scanners that differ in size and accuracy. Many require a similar space and tripod setup as a total station, while more compact models can fit almost anywhere. A minor drawback is that these devices often record points only beyond a certain minimum distance. For example, the Leica BLK360 (Figure 5) has a minimum measurable distance of 0.6 metres.

Figure 5. Measurement with TLS Leica BLK360

2.3.2 Mobile Laser Scanning

Mobile laser scanning is an alternative method to capture 3D environments using LiDAR technology. A recent trend is the use of handheld mobile scanners based on the SLAM principle. This technology uses data from an inertial navigation unit (INS) to determine the approximate position of the scanner and refines this trajectory in real time using the measured points, allowing an accurate reconstruction of the scanned environment. Significant technological advancements have brought the accuracy of mobile scanners close to that of static systems, and in many cases they even surpass it (Štroner et al., 2025). Newer models, such as the Faro Orbis (Figure 6b), make it easy to link measurements to existing reference control networks within an adit and can also perform rapid static scanning when higher point density or detail quality is required, which is ideal for larger underground areas (Di Stefano et al., 2021).
Scanning in motion offers one major advantage: complete data coverage without shadowed areas. The scanner continuously captures everything in its surroundings while moving, and to increase accuracy, it is recommended to close the scan trajectory back at the starting point. This ensures that even complex wall shapes are recorded with minimal gaps. With handheld scanners, the operator is the carrier of the device (Figure 6a), which greatly facilitates movement in confined underground spaces, provides high flexibility in vertical sections, and makes it easy to capture protrusions and recesses. Processing software for MLS often includes the option to set a mask around the device, enabling recording of points very close to the scanner.

(a) (b)

Figure 6. MLS measuring a) Barbora mine, b) Johannes adit

2.3.3 Low-cost Solutions

With the growing demand to document underground spaces, caves, and adits, low-cost solutions that enable basic spatial documentation on a limited budget are becoming increasingly common. This category includes modified hobby-grade devices, open-source software tools, and improvised surveying setups.

A typical example is the DIY mobile LiDAR systems that use affordable laser rangefinders such as the LIDAR-Lite or Slamtec RPLIDAR. These sensors are often combined with inexpensive IMU modules and small computers like the Raspberry Pi or Arduino. Although their precision does not match that of professional TLS or MLS systems, they provide basic spatial data sufficient for orientation maps and preliminary documentation (Redovniković et al., 2024).
In recent years, one of the most affordable low-cost solutions for rapid interior and underground documentation has become the iPhone Pro equipped with a LiDAR sensor (Figure 7). This Time-of-Flight (ToF) LiDAR scans the surroundings up to approximately 5 metres and generates a sparsely sampled point cloud that is immediately visualised in the application.

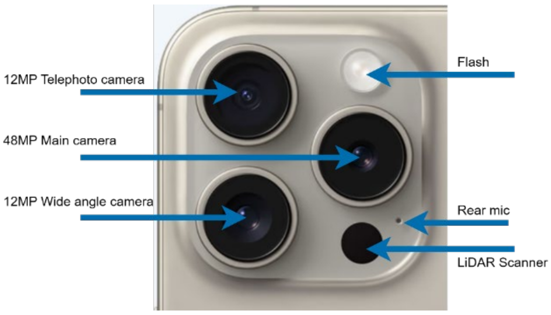

Figure 7. iPhone 15 Pro sensors

The main advantage of the mobile LiDAR integrated on the iPhone is its high mobility and ease of use. It does not require special hardware, complex calibration, or elaborate setup. With commercial applications such as SiteScape, Polycam, or Pix4D, users can quickly capture a spatial model of small adits or portals (Figure 7), which is ideal for rapid surveys. Since this approach combines photogrammetry with LiDAR scans, sufficient lighting of the area is necessary.

Figure 8. Portal scanning with iPhone 15 Pro

2.4 Comparative Field Test at 'U Pinců' Adit

To demonstrate and compare the practical use of different surveying methods in underground conditions, a test was conducted in the historical 'U Pinců' adit. This site was selected due to its variable tunnel width and typical challenges, such as limited space and irregular shape. Due to the narrow dimensions of the corridor, it was not possible to use the total station method here.

The adit consists of two parts. The first third comprises sections with a width of up to 3 metres, where Ground Control Points (GCPs) were placed to link the individual measurements. The second part consists of a narrow passage typical of historical adits, where specific points were marked for control measurements of the tunnel widths.

1. Manual method

The basic profile widths of the tunnel were measured using a handheld laser distance meter HDM-90G. Each width was measured twice, and the final value is the average of these measurements.

2. Terrestrial Laser Scanning

For surveying the adit spaces, a Leica BLK360 scanner was used. This device stands out for its compact size and its ability to measure and register point clouds without the need for reference spheres. The specified accuracy of the scanner is 6 mm at 10 metres.
During measurement, it is essential to ensure significant overlap between individual scan stations. Otherwise, it becomes difficult to align the scans, and the resulting point cloud will contain large gaps. The measurement was performed in a single direction.

3. Mobile Laser Scanning
4. For mobile data acquisition, the Faro Orbis system was used, which has a manufacturer-specified accuracy of 5 mm. Due to the length and shape of the test section of the adit, the survey could be completed within a single closed loop.

When moving within the narrow adit, it is essential to maintain a steady walking speed and keep the device as close as possible to the centreline of the tunnel to minimise trajectory deviations. To improve the quality of the point cloud texture, the scanner was equipped with a 360° light source that provided uniform illumination of the dark environment and enhanced the visual appearance of the colour texture.

5. iPhone LiDAR.
6. To verify the potential of a low-cost solution, the built-in LiDAR sensor of an iPhone was used. Scanning was carried out using the Pix4D application, which allows immediate data capture and subsequent processing in desktop software. Due to the limited range of the sensor and its sensitivity to lighting conditions, the tunnel had to be properly illuminated using a 360° light source.

The scanning captures data only in the forward direction because the phone's cameras do not provide full 360° coverage. Therefore, the operator held the phone at an oblique angle toward the tunnel walls and moved smoothly along the tunnel perimeter to record the key structural elements of the adit.

3. Results

3.1 Selection of a Suitable Surveying Method

The survey requirements are crucial when selecting an appropriate method. Based on the experience gained from surveying historical adits in this project, the methods were evaluated according to several key criteria:

1. **Absolute accuracy** - Indicates how faithfully the method captures the overall shape and position of the entire adit in space, that is, how closely the final model matches reality.

2. **Relative accuracy** - Describes how precisely the individual parts of the adit are captured, such as tunnel width, profile height or proportions on a smaller scale within the whole.
3. **Time efficiency** - Describes the amount of time required for field measurement and subsequent data processing. It depends on the speed of data collection, handling of the equipment, and operator workload.
4. **Tunnel shape** - Indicates how easy or difficult it is to survey tunnels with curves, bends, branches, or irregular alignments, where straight sections are absent.
5. **Tunnel size** - Expresses the suitability of the method for use in differently sized spaces. Considers whether the equipment can be operated even in narrow or low profiles with limited room for movement.
6. **Environmental robustness** - Describes the resistance of the technique and method to challenging underground conditions, such as moisture and mud.
7. **Capturing hard-to-reach areas** - Evaluates the method's ability to capture distant or poorly accessible features, such as high ceilings, shafts, deep pits, or side cavities that cannot be surveyed up close.
8. **3D documentation** - Defines the level of detail and quality of the spatial record provided by the method, including point cloud density, texturing capability, and completeness of the captured environment.

Figure 9 shows the comparative evaluation of these criteria in a simple diagram. From this the suitability of each method for use in historical underground spaces can be seen. A score of 0 means 'unsuitable' and a score of 5 means 'highly suitable'. Based on the results, the MLS method can be considered the most suitable. It is important to note, however, that these are general results and that each criterion depends on the specific device used.

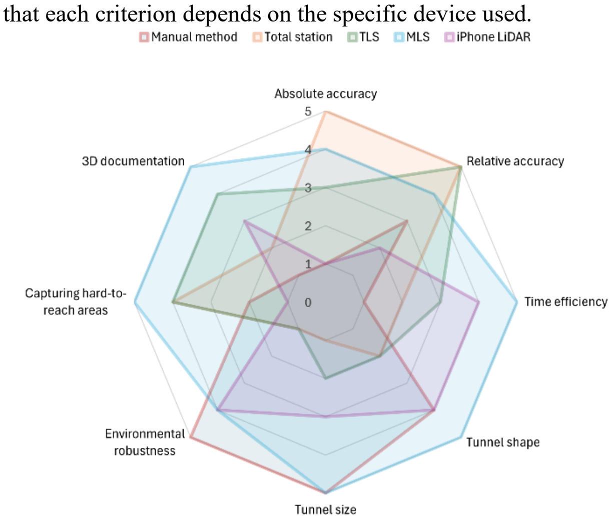

Figure 9. Evaluation of the suitability of the method for measuring underground spaces

3.2 Accuracy and Time Efficiency

Since it was not possible to survey the adit using a total station, the MLS method was chosen as the reference measurement. Table 1 shows the numerical values of the differences between the individual methods. RMSE 2D compares the deviation in the horizontal cross section, while RMSE 3D represents the deviation calculated from the coordinates of marked check points. Figure 9 illustrates the deviation in the horizontal cross section of the adit at 25 metres from the entrance to the narrow section.

Device (Method)	RMSE 2D	RMSE 3D	Time of measurement
Faro Orbis	-	-	8 min
Leica BLK360	13 cm	14 cm	70 min
iPhone LiDAR	5 cm	23 cm	15 min
HDM-90G	1 cm	-	20 min

Table 1. Accuracy and Time Requirements of Individual Surveying Methods, case study "U Pincû"

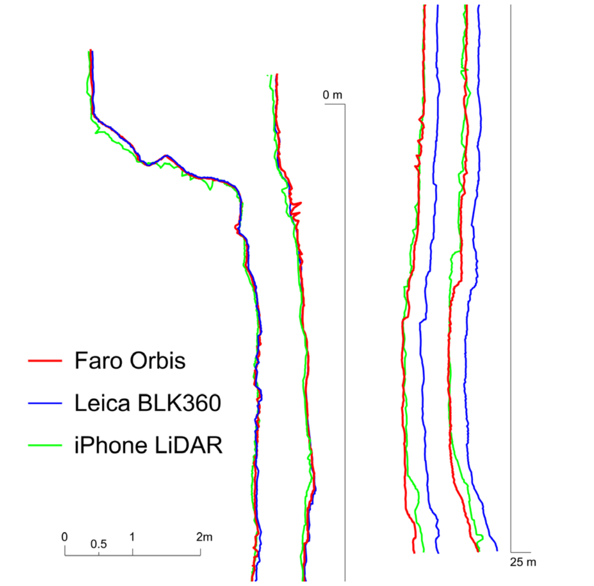

Figure 10. Comparison of methods on the cross-sectional profile of the 'U Pincû' adit

3.3 Quality of 3D outputs

The resulting quality of the point clouds captured by each method is presented in Figure 10-11. For each method, a 4.5-meter-long longitudinal section and a cross section are shown. These examples illustrate the differences in point cloud density, the level of detail of fine features, and the texture quality of the scanned space.

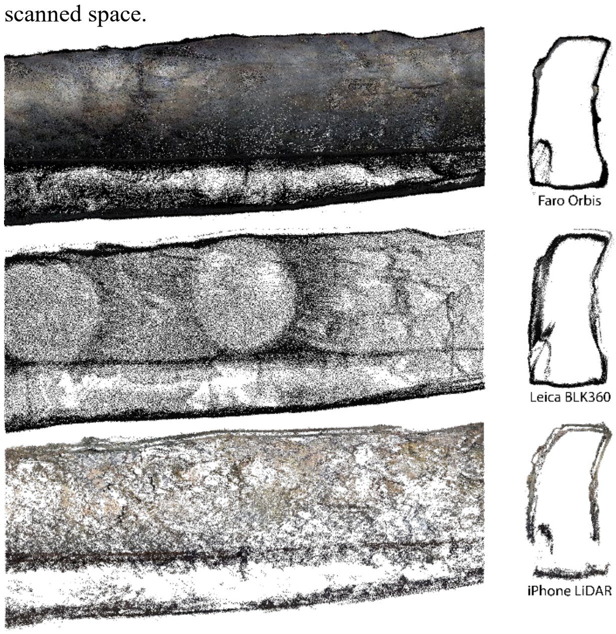

Figure 11. Comparison of measured point clouds of the 'U Pincû' adit

https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-103-2025

To demonstrate the potential of mobile mapping, a polygonal model (3D mesh) was also generated from the data captured by the iPhone LiDAR sensor. This model is created automatically by combining depth data from the LiDAR with photographs from the built-in camera, resulting in a textured surface that enhances the clarity and realism of the representation. An example of this textured model is shown in Figure 12.

Figure 12. Textured 3D mesh of the ‘U Pincŭ’ adit generated from iPhone LiDAR data using Pix4D

Figure 13 shows (via QR code) the fly-through of the textured point cloud of the ‘U Pincŭ’ case study, captured using the MLS method.

Figure 13 – QR code providing access to the video: Fly-through of the “U Pincŭ” point cloud

4. Conclusion

This article presented the main challenges and practical experiences with the exploration and documentation of unique historical mining adits in the Czech Republic. The diversity of the underground environment and the associated measurement difficulties were demonstrated at several selected sites, such as the Barbora, Johannes, Bohuliby, and 'U Pincŭ' adits.

The comparative field test clearly showed that the mobile laser scanning (MLS) method currently represents the best compromise between measurement accuracy, time and practicality in narrow, irregular, and difficult to access underground spaces. Although absolute accuracy is slightly lower than surveing with total station, the flexibility and speed of MLS makes it the most effective tool for large-scale subsurface documentation. Low-cost solutions, such as the LiDAR sensor integrated in the iPhone, have also shown promising results and can be used for rapid orientation, although their range and point density are limited.

Based on the obtained results, it can be concluded that the combination of modern laser scanning methods with appropriately set processing procedures allows the creation of detailed 3D models even under demanding underground conditions. These models make a significant contribution to the protection and study of the historical mining heritage and at the same time enable conservation planning, the creation of virtual tours, and popularisation among the public.

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