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Evaluation of the Geometric Accuracy of LiDAR and Camera Sensors in Narrow Underground Structures

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Abstract

Accurate 3D mapping of narrow underground structures is critical for tunnel inspection, mining, and subsurface exploration applications. This study evaluates the geometric accuracy of different LiDAR and camera-based sensors in confined environments (Erdstall facilities). We compare the performance of a high-precision terrestrial LiDAR scanner (Leica BLK360), a smartphone LiDAR system (iPhone 15 Pro Max), and an RGB-depth sensor-based device (Lenovo Phab 2 Pro with Google Tango technology). The field experiments and evaluation are based on the quality of the point cloud, the spatial consistency, and the measurement deviations. The handling of the measuring devices used and the measurement duration are also considered. The results indicate that, while both sensors have unique strengths, LiDAR demonstrates superior performance in capturing detailed measurements and achieving higher point density, particularly in challenging lighting conditions. In contrast, camera sensors excel in texture and color fidelity, providing rich visual information that aids interpretation. However, the handheld device has significant advantages in handling and measurement duration and is far superior to the terrestrial scanners in these narrow underground structures.

Introduction

Surveying Erdstall facilities provides valuable data for scientific studies on historical settlements, lifestyles, and practices of past societies. This data can also help to identify patterns and trends in the distribution of mounds. Overall, surveying Erdstall facilities helps to preserve their cultural heritage, expand our understanding of the past, and make history accessible for future generations. In this study, we evaluate the geometric accuracy of LiDAR and camera sensors in the challenging environment of narrow underground structures. The accuracy and reliability of these sensors are critical for applications such as autonomous navigation, structural health monitoring, and geological surveying. We conducted a series of experiments in various underground settings, including tunnels and mines, to assess the performance of these sensors under constrained conditions. The study compares the point clouds and images obtained from LiDAR and camera systems with ground truth data derived from high-precision total station measurements. Key metrics such as spatial resolution, error rates, and data completeness were analyzed. Our results indicate that LiDAR sensors generally offer higher spatial accuracy and robustness to low-light conditions, but camera sensors provide valuable complementary data, especially in texture-rich environments. Integrating both sensor types through sensor fusion techniques shows promise in enhancing the overall geometric accuracy and reliability of mapping and navigation tasks in narrow underground structures. This research highlights the importance of choosing appropriate sensor technologies and fusion strategies to achieve optimal performance in subterranean applications.

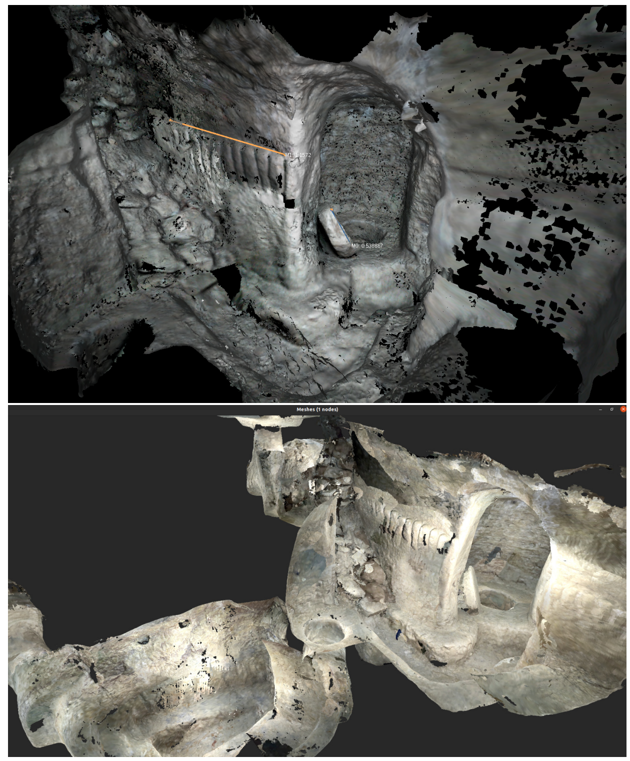

Figure 1. *Confined spaces and crawlways (vertical and horizontal holes) characterize such Erdstall facilities. Due to the lack of an air shaft, a suction system would supply the rooms with fresh air to inspect and measure the facility. The two images show details in room 5, with the upper image showing the 3D mapping from the Lenovo Phab2 Pro and the lower image showing the color-enhanced display and denser point cloud from the iPhone 15 Pro Max.*

This study aims to evaluate and quantify the geometric accuracy of LiDAR and camera sensors when used in narrow underground structures, such as tunnels, mines, and Erdstall facilities, see Figure 1. Its goal is to determine how effectively these sensors can capture and represent the complex geometries of such environments. The insights gained from this study are intended to guide the selection and integration of sensor technologies for applications that require precise spatial data, such as autonomous navigation, structural health monitoring, and geological surveying in subterranean settings. Accurately mapping and navigating narrow underground structures is a significant challenge due to these environments' constrained and often harsh conditions. Traditional surveying methods are time-consuming and may not provide the necessary spatial resolution. LiDAR and camera sensors offer potential solutions, but their performance can be affected by factors such as low lighting, occlusions, and the intricate geometries of underground spaces. There is a need to systematically evaluate the geometric accuracy of these sensors to determine their suitability and limitations for use in narrow underground structures. This study seeks to address this gap by comparing the accuracy of LiDAR and camera sensors against high-precision ground truth data and exploring the benefits of sensor fusion techniques to enhance mapping and navigation in these challenging conditions.

Related Work

High-precision laser scanning devices such as Terrestrial Laser Scanning (TLS) or Mobile Laser Scanning (MLS), RGB-D cameras, and photogrammetric techniques (Closed-range and Structure from Motion (SfM)) are commonly employed to create detailed 3D models with a dense set of 3D points:

- Terrestrial Laser Scanning (TLS): Terrestrial laser scanning involves using a stationary laser scanner to capture detailed 3D point clouds. The scanner emits laser beams in multiple directions, and the reflected signals are used to calculate the distances to surfaces, creating a dense set of 3D points.
- Mobile Laser Scanning (MLS): Mobile laser scanning systems are mounted on vehicles or platforms, allowing for the rapid collection of 3D point cloud data as they move through the Erdstall passages. This technique is beneficial for capturing data in confined spaces where setting up a stationary scanner might be challenging.
- Close-Range Photogrammetry: Close-range photogrammetry involves capturing high-resolution photographs of the Erdstall from different angles. Specialized software then analyzes the overlapping images, identifies common points, and triangulates their positions to generate a 3D model.
- Structure from Motion (SfM): Structure from Motion is a photogrammetric technique that reconstructs 3D structures from overlapping images. By analyzing the relative positions and orientations of the photos, the software can generate a 3D point cloud and textured mesh of such facilities.
- Unmanned Aerial Vehicle (UAV) or Unmanned Aerial Systems (UAS) Photogrammetry: Drones equipped with high-resolution cameras can capture aerial imagery of Erdstall sites. UAV photogrammetry involves processing these images to create accurate 3D models. This technique is beneficial for mapping Erdstalls from above and capturing the landscape context.
- Multispectral Imaging: Besides capturing visible light, multispectral imaging involves recording information in multiple wavelength bands, including the infrared. This can be useful for revealing details not visible to the naked eye and enhancing the accuracy of 3D reconstructions.

Various archaeology, geosciences, and robotics studies have explored the mapping of underground structures, including Erdstall facilities, using 3D LiDAR scanning [10]. While Erdstall tunnels remain a relatively under-researched topic in this context, similar methodologies have been successfully applied to other underground environments, such as caves, mines, and historical tunnels.

Early research on underground LiDAR mapping primarily focused on terrestrial laser scanning (TLS). Studies such as those by Böhm [1] demonstrated the efficacy of static LiDAR scanners in capturing high-resolution 3D models of confined underground spaces. Their work highlighted the precision of TLS in heritage documentation and its capability to produce detailed point clouds for structural analysis.

More recently, mobile LiDAR-based approaches have gained traction. Handheld and backpack-mounted mobile mapping systems, such as the GeoSLAM ZEB series, have been widely used for cave and tunnel documentation. These systems employ Simultaneous Localization and Mapping (SLAM) algorithms to facilitate real-time data acquisition in GPS-denied environments [13]. They are particularly suitable for Erdstall tunnels, which often feature narrow and winding passages.

3D mapping creates digital representations of indoor and outdoor environments, such as buildings, offices, warehouses, or homes. Traditionally, mapping required specialized equipment such as laser scanners, total stations, or complex photogrammetry setups. However, advancements in mobile technology, mainly Apple's LiDAR-equipped iPhones, have made it easier and more accessible for users to capture detailed 3D maps of indoor spaces [5], [2]. With the introduction of LiDAR sensors in iPhone Pro models (starting with the iPhone 12 Pro), Apple has significantly improved the ability to scan and understand the surroundings. The combination of LiDAR, high-resolution cameras, motion sensors, and Apple's ARKit framework enables users to perform accurate mapping using just a smartphone in indoor and outdoor applications [12], [8], [9].

[11] et al. have developed a comparison of the accuracy and precision of the generated data with the iPhone 13 Pro camera and the LiDAR sensor to the UAS photogrammetric model of the historical site of the Giza pyramids. Several factors influencing accuracy, including sensor resolution, environmental conditions, and the geometric complexity of the structures, were analyzed. The findings highlight the importance of selecting the appropriate sensor based on the specific requirements of underground surveying tasks. A first field experiment in the Erdstall structure

in Unterstetten was performed [4]. This study contributes to the ongoing discourse on sensor integration in geospatial applications and offers insight for practitioners aiming to improve the accuracy of their data collection in constrained environments. Future research should focus on optimizing LiDAR-based SLAM for narrow underground networks and developing robotic solutions tailored to the constraints of Erdstall facilities.

Methodology

Erdstall tunnels are an important aspect of historical architecture, often challenging to study due to their narrow and winding nature. Traditional measurement techniques have limitations in confined spaces, creating a need for advanced technologies such as LiDAR and sophisticated camera systems. This study compares the accuracy of geometric data collected by the Lenovo Phab 2 Pro, a consumer-grade smartphone with a depth sensor, the iPhone 15 Pro Max with its advanced camera capabilities and built-in LiDAR, and the professional-grade Leica BLK360. Four measuring methods have been used to survey the Erdstall in Unterstetten. Speleological surveying is performed immediately on the first ascent and provides initial impressions and experience. However, photogrammetry was characterized by taking numerous photographs and creating a precise three-dimensional model of objects or environments. The 3D LiDAR scanners used generate very dense point clouds of the surroundings. The evaluation was conducted on selected Erdstalls in Unterstetten/Austria, known for their unique architectural features and historical relevance.

Speleological surveying

Speleological surveying refers to surveying caves and underground structures by specially trained speleologists or cave explorers. These surveys accurately document the geometry, extent, and characteristics of caves and underground structures. Unlike traditional surveying techniques performed by professional surveyors or geodesists, cavers often use specialized techniques and tools suited to the challenges of underground environments. These include, for example:

- Passage drawings: Cavers often draw hand-made maps and diagrams of cave passages to document the structure and progression of the caves. These drawings usually contain essential information such as distances, directions, height differences, and prominent features.
- Survey points: Cavers often use unique markers or stationing points to take measurements in caves. These can be markers, such as paint stains or markers, metal pins, or bolts inserted into the rock. Polygon lines usually do surveying.
- Measurement tapes, compasses, and clinometers: Simple tools such as measuring tapes, compasses, and clinometers are used to measure distances, directions, and inclinations in caves.
- Digital surveying tools: In modern caving, digital surveying tools such as laser distance meters are also used to take precise measurements in caves and create detailed maps.

Open source 3D SLAM

We used in some experiments the open source software RTAB-Map (Real-Time Appearance-Based Mapping) [6] open-source software, which is a SLAM (Simultaneous Localization and Mapping) algorithm that constructs a globally consistent 3D map using graph-based optimization, loop closure detection, and multisession option [7]. RTAB-Map primarily relies on graph-based SLAM with loop closure detection and integrates visual, RGB-D, and LiDAR SLAM techniques; see 1. It is highly modular and can work with different sensor inputs for real-time 3D mapping and localization.

This method is used for the Lenovo Phab2 Pro and iPhone 15 Pro Max, handheld devices that create precise three-dimensional models of objects or environments using images, see Figure 2. This technique uses the principle of triangulation to make an accurate 3D model from a collection of 2D images. Here is a basic explanation of the process that was performed.

Feature Detection and Tracking: Characteristic points or features in the images, such as corners or edges, are identified and tracked to determine their movement between images. This is typically done using feature detection methods such as the Harris corner detector or scale-

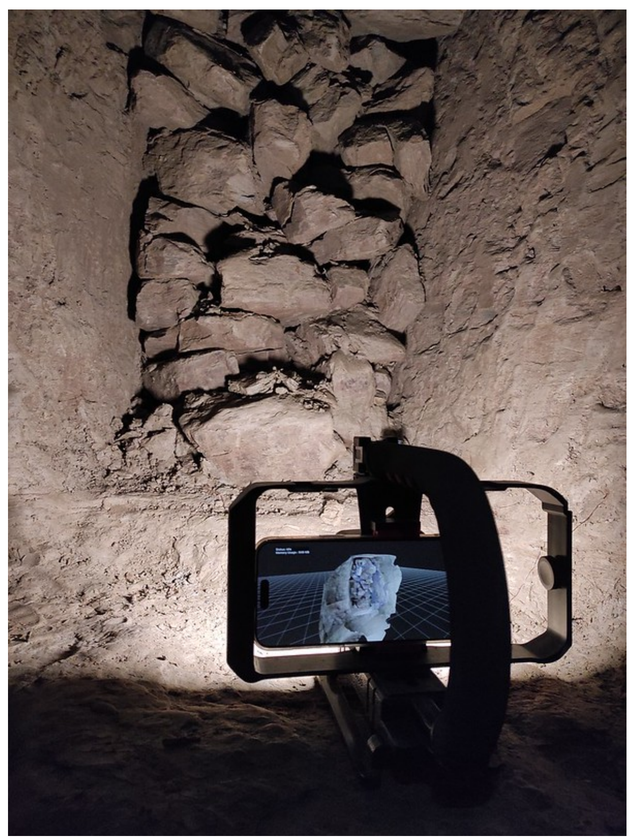

Figure 2. *Hand-held 3D sensor system during live 3D mapping of the construction shaft in room 2.*

SLAM techniques used in RTAB-Map

SLAM Type	RTAB-Map Implementation	Equations
Graph-Based SLAM	Pose graph optimization (g2o, GTSAM)	$\mathbf{x}^* = \arg\min_{\mathbf{x}} \sum_{(i,j)\in C} \|f(x_i,x_j) - z_{ij}\|^2_{\Omega_{ij}}$
Visual SLAM	ORB, SIFT, SURF-based feature tracking	$I_x dx + I_y dy + I_t = 0$
RGB-D SLAM	Depth-based 3D reconstruction	$\mathbf{P}_w = R \cdot dK^{-1} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} + t$
LiDAR SLAM	ICP for scan matching (optional)	$E(R,t) = \sum_{i=1}^{N} \|p'_i - (Rp_i + t)\|^2$
Loop Closure	Bag-of-Words (BoW) + Bayesian Filtering	$P(L_t\|Z_t) = \frac{P(Z_t\|L_t)P(L_{t-1})}{P(Z_t)}$

invariant feature transform (SIFT). Given an image $I(x,y)$, a corner is detected at locations where the second-moment matrix

$$M = \sum_{(x,y)\in W} w(x,y) \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix} \tag{1}$$

has large eigenvalues, where I_x and I_y are the image gradients in the x and y directions, respectively, and $w(x,y)$ is a weighting function.

Optical Flow and Motion Estimation: Based on the tracked features and their movement between images, algorithms such as optical flow or feature matching are applied to estimate the system's movement. Given two consecutive frames, the displacement $d = (dx, dy)$ of a feature point can be estimated using the optical flow constraint equation:

$$I_x dx + I_y dy + I_t = 0 \tag{2}$$

where I_t is the temporal image gradient. Using multiple features and robust estimation techniques, the camera motion is recovered, and a point cloud is generated as densely as possible based on the spatial positions of the points.

Point Cloud Representation: The point cloud represents the object's surface or environment by a cloud of points in three-dimensional space. Mathematically, the point cloud can be represented as

$$P = \{p_i = (x_i, y_i, z_i) \mid i = 1, 2, \dots, N\} \tag{3}$$

where (x_i, y_i, z_i) are the Cartesian coordinates of each point in space.

Camera Projection Model: The software then calculates the three-dimensional structure based on the relative positions of these features in the images. This is typically done using structure-from-motion (SfM) or stereo-vision techniques, where the 3D points are reconstructed through triangulation. Given a calibrated camera model, a 3D point $P = (X, Y, Z)$ is projected onto an image plane using the camera projection equation:

$$s \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = K [R \mid t] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{4}$$

where (u, v) are the 2D image coordinates, K is the intrinsic camera matrix, R is the rotation matrix, t is the translation vector, and s is a scale factor. Using multiple views and corresponding feature points, the 3D coordinates of each point can be estimated.

The key mathematical components for the SLAM algorithms in RTAB-Map are:

Bayesian Loop Closure Detection: RTAB-Map detects loop closures using a Bayesian probability estimation. The probability of a loop closure at time t given past observations is computed as:

$$P(L_t|Z_t) = \frac{P(Z_t|L_t)P(L_{t-1})}{P(Z_t)} \tag{5}$$

where:

- $P(L_t|Z_t)$ is the updated probability of a loop closure at time t.
- $P(Z_t|L_t)$ is the likelihood of the current observation Z_t given that a loop closure exists.
- $P(L_{t-1})$ is the prior probability from the previous step.
- $P(Z_t)$ is a normalizing factor.

Graph Optimization and Pose Estimation: The SLAM back-end optimizes the sensor's trajectory using graph-based optimization. The backend uses nonlinear graph optimization techniques such as g2o (General Graph Optimization) or GTSAM (Georgia Tech Smoothing and Mapping) to minimize errors in the pose graph. The pose graph consists of nodes representing sensor poses x_t and edges representing spatial constraints. The optimization minimizes the error function:

$$\mathbf{x}^* = \arg\min_{\mathbf{x}} \sum_{(i,j)\in C} \|f(x_i, x_j) - z_{ij}\|^2_{\Omega_{ij}} \tag{6}$$

where:

- $\mathbf{x}^*$ is the optimized trajectory.
- $f(x_i, x_j)$ is the predicted relative transformation between poses x_i and x_j.
- z_{ij} is the observed transformation.
- Ω_{ij} is the information matrix that weights the constraint.

Memory Management and Global Map Update: RTAB-Map employs a memory management strategy to balance accuracy and computational efficiency. The system defines a memory function $M(t)$ that activates or deactivates past nodes in the graph:

$$M(t) = \begin{cases} 1, & \text{if node is active in the working memory} \\ 0, & \text{if node is transferred to long-term memory} \end{cases} \quad (7)$$

This allows real-time operation by dynamically pruning older nodes while maintaining a globally consistent map.

3D Model Reconstruction: The point cloud is then converted into a 3D model by interpolating surfaces between the points. This process can be performed using methods such as Poisson Surface Reconstruction, which solves the screened Poisson equation:

$$\nabla \cdot \mathbf{J} = \rho \quad (8)$$

where $\mathbf{J}$ represents the vector field of normal constraints, and ρ is the indicator function defining the surface.

RTAB-Map is a robust SLAM framework that integrates feature tracking, loop closure detection, and graph-based optimization to construct a dense 3D map in real-time. Using a combination of probabilistic models and pose graph optimization, it efficiently manages memory while maintaining global consistency.

Professional 3D LiDAR Scanning

The Leica BLK360 is a high-precision LiDAR scanner designed for professional 3D scanning, surveying, and spatial mapping, see Figure 3. It is widely used in architecture, engineering, construction (AEC), heritage preservation, and geospatial analysis due to its high accuracy, portability, and ease of use. The Leica BLK360 utilizes LiDAR (Light Detection and Ranging) technology to capture highly accurate 3D point clouds of environments, see Figure 4. It features:

- High-Resolution LiDAR Sensor: Achieves an accuracy of approximately ±6 mm at 10 meters, making it suitable for precise measurements.
- 360° Scanning Capability: Captures a full spherical scan of its surroundings in just a few minutes.
- HDR Imaging: Integrates high-quality color images with point cloud data for photorealistic reconstructions.
- Compact and Lightweight Design: Weighing around 1 kg, it is highly portable compared to traditional terrestrial laser scanners.

Figure 3. High-precision terrestrial LiDAR scanner: Leica BLK360 mounted on a tripod and equipped with additional lighting (left); Positioning the LiDAR above the crawlway to measure it as accurately as possible (right).

Figure 4. Above ground and underground surveying of Erdstall environment by LiDAR BLK360.

Experimental Results

The cave explorers' survey of the Unterstetten Erdstall in 1998 documents its condition. The plan also shows structures inside the complex, such as crawlways, steps, landings, seating niches, and the bench. The experienced cave and sinkhole explorers also noticed the construction shaft; however, as Figure 5 shows, they assumed a round shape. However, the 3D survey in [3] revealed an elliptical shape, approximately 1.8 m long and 1.2 m wide. The geometric accuracy of 3D scanning and spatial mapping varies significantly between the Lenovo Phab 2 Pro, iPhone 15 Pro Max, and Leica BLK360, as they are designed for different purposes and utilize different sensing technologies.

The Leica BLK360 is a professional-grade LiDAR scanner for high-precision surveying and 3D reconstruc-

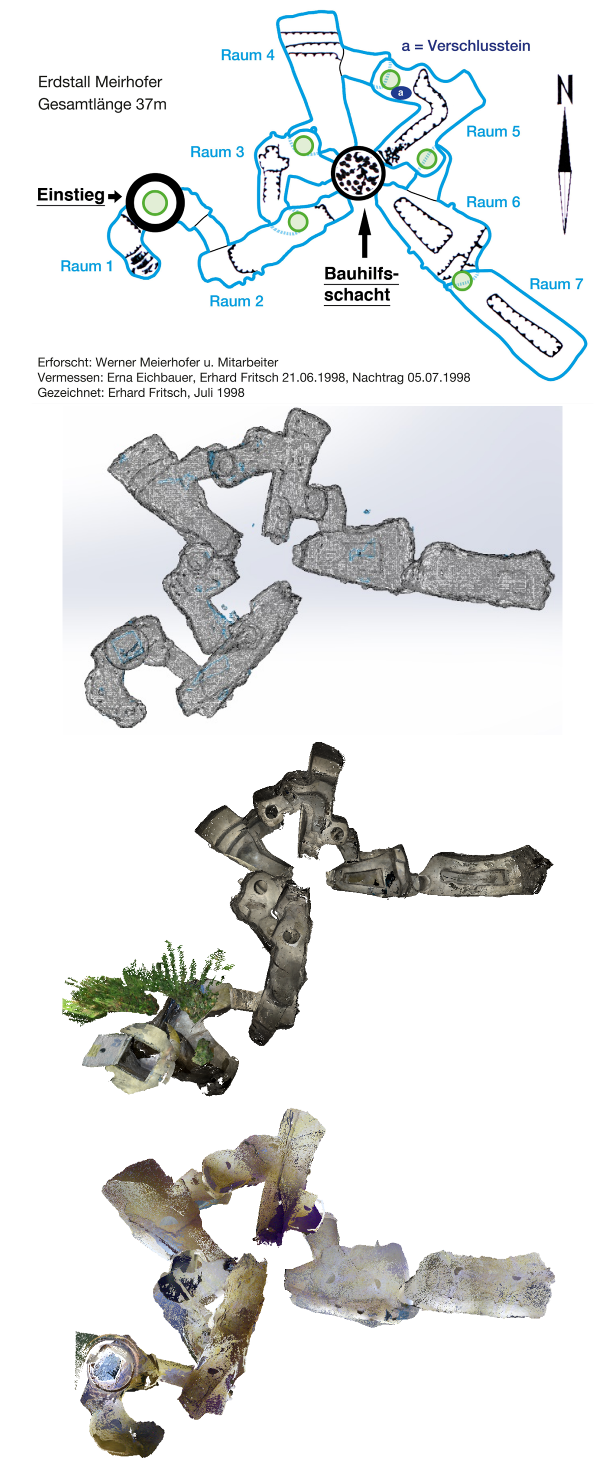

Figure 5. Comparison of the two measuring methods: (from top to bottom) speleologist survey original plan (photo: Erhard Fritsch, 1998); 3D survey using photogrammetry with Lenovo Phab2 Pro; 3D survey using with iPhone 15 Pro Max and top view with Leica BLK360.

tion. It achieves an accuracy of approximately ±6 mm at 10 meters, making it the most precise among the three. Its high-resolution LiDAR sensor, HDR imaging, and ad-

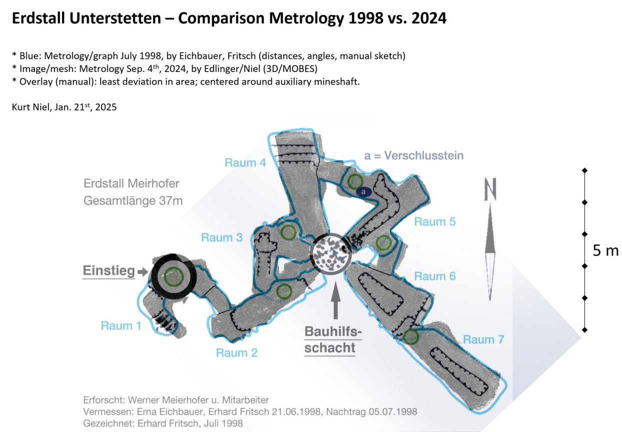

Figure 6. Overlay of the two measurements: Speleological surveying and 3D mapping with iPhone 15 Pro Max.

vanced point cloud processing ensure exceptional detail and reliability, making it ideal for architecture, construction, and geospatial analysis applications.

The iPhone 15 Pro Max incorporates Apple's LiDAR scanner, designed primarily for AR applications, object scanning, and depth sensing. While it provides millimeter to centimeter-level accuracy, it lacks the range and precision of dedicated LiDAR scanners. The iPhone's computational photography, AI-driven depth estimation, and sensor fusion enhance detail, but errors can occur in large-scale 3D reconstructions due to its limited sensor range and resolution. It is suitable for consumer-grade 3D scanning, indoor mapping, and augmented reality applications but falls short for high-precision surveying.

The Lenovo Phab 2 Pro, introduced as one of the first smartphones with Google Tango technology, features a Time-of-Flight (ToF) depth sensor and RGB camera for 3D mapping. However, its geometric accuracy is the lowest among the three, typically in the centimeter range, making it less reliable for precise measurements. While innovative at its time, the depth data is noisy and less refined, leading to errors in object reconstruction and mapping. Table 2 compares the performance of LiDAR and camera sensors integrated into devices like the Lenovo Phab2 Pro, iPhone 15 Pro Max, and Leica BLK360 for mapping and navigation in narrow underground structures.

In conclusion, the Leica BLK360 is the most accurate and suited for professional 3D scanning, the iPhone 15 Pro Max provides moderate accuracy for AR and general-purpose scanning, and the Lenovo Phab 2 Pro has the lowest geometric accuracy, making it less effective for precise 3D mapping.

Comparison of the measurement methods in selected rooms

The Erdstall of Unterstetten is a remarkable example of these underground structures in Austria and Europe. These Erdstalls are small, often labyrinthine passages and chambers whose purpose and origin are still mysterious. The Unterstetten Erdstall has typical features and unique

Comparison of LiDAR and Camera Sensors in Narrow Underground Structures

Criteria	LiDAR (Lenovo Phab2 Pro)	LiDAR + Camera (iPhone 15 Pro Max)	High-Precision LiDAR (Leica BLK360)
Sensor Type	Time-of-Flight (ToF) LiDAR	Advanced ToF LiDAR + Pro Camera Array	High-Precision Laser Scanner
Resolution	Low to moderate (spatial accuracy ±3-5 cm)	Moderate (LiDAR ±3 cm, camera resolution 48 MP)	High (accuracy ±1 mm)
Field of View (FOV)	70°	120° (camera) + 90° (LiDAR)	360° panoramic LiDAR view
Range	Up to 4-5 meters in low-light environments	Up to 5 meters (LiDAR) and high camera clarity for visuals	Up to 60 meters (optimal for large spaces, adjustable range)
Performance in Low Light	Effective but struggles with fine texture mapping	Effective with LiDAR; cameras use Night Mode for visuals	Optimal due to LiDAR accuracy and low-light compensation
Portability	Compact; handheld mobile device	Compact; handheld mobile device	Bulky; portable with tripod or mount
Battery Life	4 hours for scanning tasks	6 hours for combined use	8 hours (depending on scanning intensity)
Processing Speed	Moderate; relies on mobile hardware	Fast; optimized with Apple A17 Pro chip	High; dedicated processing unit for real-time 3D mapping
Data Output	Basic point clouds, 2D scans	High-resolution 3D maps, photo-realistic visuals	Detailed point clouds, photogrammetry-quality 3D models
Use Case Suitability	Small-scale, casual mapping, and navigation	Mid-scale mapping with rich visuals for better context	Professional-grade mapping, documentation, and analysis
Cost	Low ($700 at release)	Moderate ($1,500)	High ($25,000)
Durability in Harsh Conditions	Limited resistance to dust and moisture	Moderate resistance (waterproof rating IP68)	Robust; designed for harsh environments
Geometric Accuracy	++	+++	+++
Texture Accuracy	++	+++	+++
Density	+	++	+++
Color	+	+++	+++
Measure Time	++	+++	-
Handling	+++	+++	-

Figure 7. *Measurement of the horizontal crawlway using the conventional measuring method (roll meter) (width: 43.6 cm, height: 34.5 cm) and the door frame (width: 60.7 cm).*

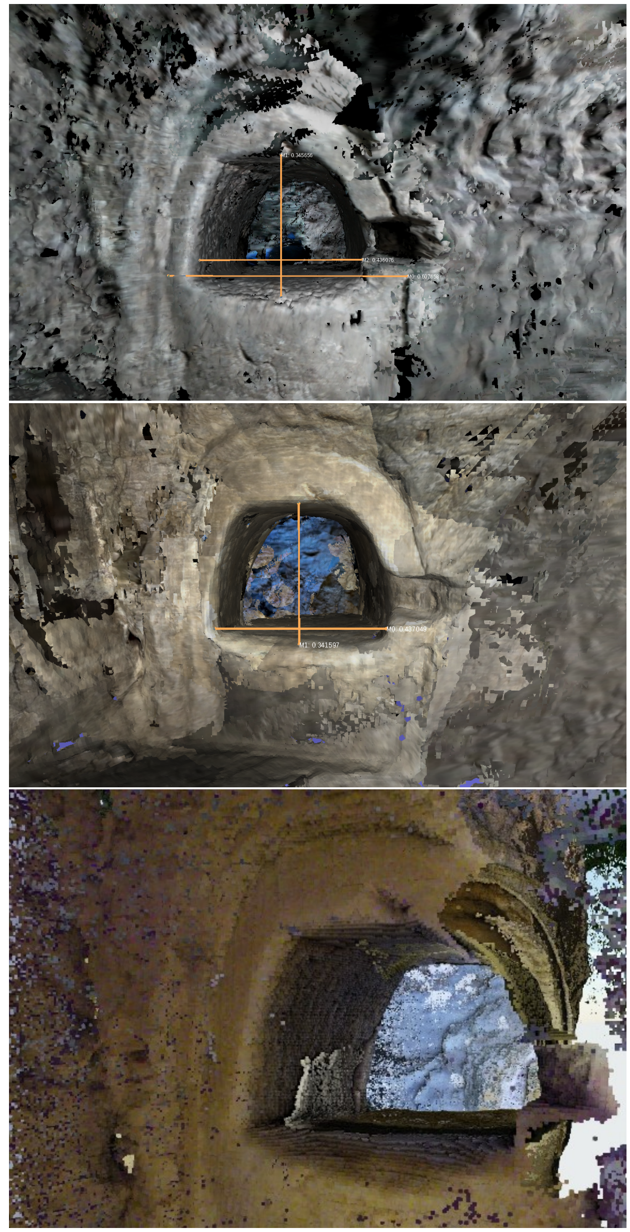

Figure 8. *Measurement of horizontal crawlway with digital measurement method: 1. Lenovo Phab2; 2. iPhone 15 Pro Max; Leica BLK360.*

characteristics that make it a prime example of this type of structure. It is 37 m long and completely preserved from the original entrance to the final chamber. There is a central construction shaft from which five chambers lead(ed) away at different levels. The following figures show the horizontal slip measured using the manual speleologist's measurement using a rolling measure and the 3D measurement using photogrammetry. The statistics show that the horizontal slip is 34.5 cm high and 43.6 cm wide, and the door frame is just under 60.7 cm wide. Based on the two measurements, we were able to confirm that the accuracy of the 3D measurement using photogrammetry could be verified with a maximum deviation of 1 cm.

Another interesting comparison of the two measurement methods was carried out on the vertical crawlway between spaces 5 and 6. The figures show that the 3D measurement method used has the potential to generate accurate 3D surface models. Both measurements show that this crawlway has a diameter of 40 cm.

The iPhone 15's camera sensor significantly outperforms the Lenovo Phab 2 Pro in texture reproduction, color fidelity, and detailed reconstruction; see Figure 8 and 9. With a 48 MP sensor and advanced computational photography (Deep Fusion, Smart HDR 5, and the Photonic Engine), the iPhone 15 delivers sharper details, more accurate colors, and improved low-light performance. In contrast, the Phab 2 Pro, featuring a 16 MP sensor and early Google Tango AR technology, was designed for spatial mapping rather than high-quality imaging. While the Phab 2 Pro's depth-sensing technology was innovative, its RGB camera resolution, dynamic range, and image processing are inferior to the modern AI-powered enhancements of the iPhone 15 Pro Max.

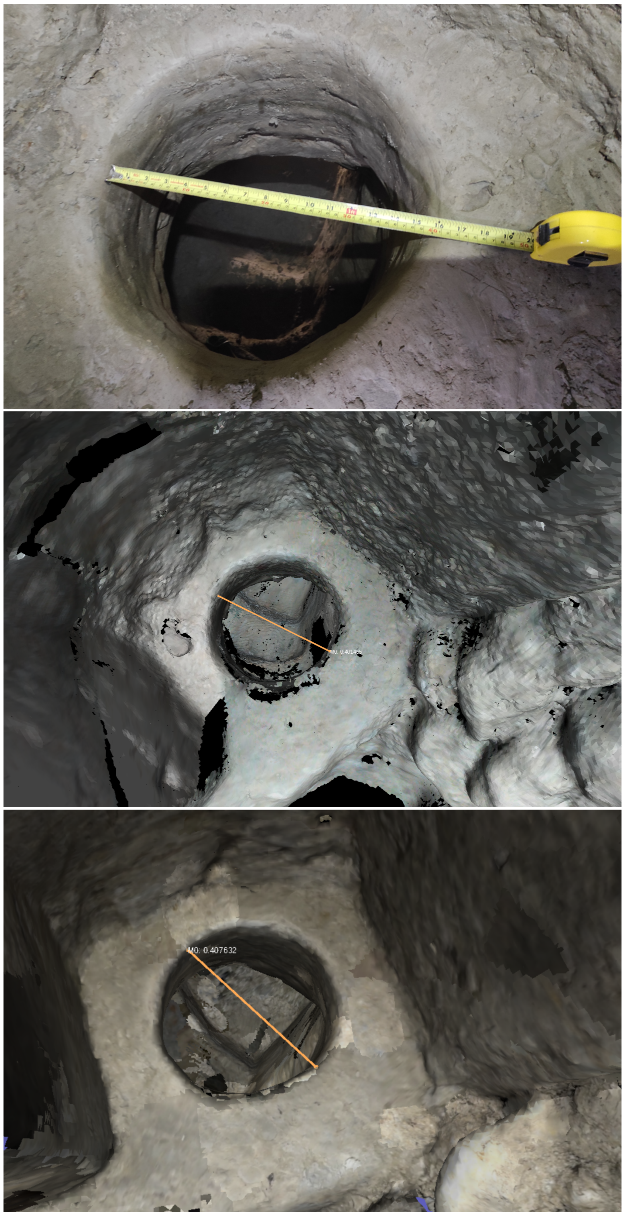

Figure 9. *Comparison of the three measurement methods for vertical crawlway (diameter: 40.1 cm) between rooms 5 and 6. The measurement methods: 1. Speleological surveying; 2. Lenovo Phab2; 3. iPhone 15 Pro Max.*

Conclusion and Future Work

This study evaluated the geometric accuracy, texture quality, point cloud density, color fidelity, measurement time, and handling of three different 3D scanning systems: Leica BLK360 (high-precision terrestrial LiDAR), iPhone 15 Pro Max (smartphone LiDAR) and Lenovo Phab 2 Pro (RGB depth sensor with Google Tango technology) for mapping narrow underground structures, specifically Erdstall facilities. These ancient, confined tunnels present unique challenges for 3D documentation, including low visibility, irregular surfaces, and restricted maneuverability. Due to its high-resolution LiDAR and HDR images, the Leica BLK360 delivered the highest geometric accuracy (±6 mm at 10 meters), dense and precise point clouds, and excellent texture and color reproduction. However, its longer measurement time, tripod setup, and limited mobility made it less practical for scanning extremely tight passages in Erdstall structures. Despite these limitations, it remains the most reliable tool for detailed and precise documentation of underground heritage sites. The iPhone 15 Pro Max, equipped with a mobile-grade LiDAR sensor, offered a faster and more flexible scanning process, making it well-suited for rapid documentation of narrow, hard-to-reach sections. However, its lower point cloud density, increased depth estimation errors, and reduced color fidelity limited its ability to capture fine surface details. However, it balanced usability and efficiency, making it a viable option for preliminary mapping and quick assessments of Erdstall facilities. The Lenovo Phab 2 Pro, which features Google Tango's RGB depth sensor and ToF, exhibited the lowest accuracy, sparse and noisy depth data, and suboptimal texture quality. Although its measurement time was short and handling was intuitive, its significant deviations and poor depth resolution make it unsuitable for detailed archaeological or geospatial documentation. It is an example of early mobile 3D scanning technology, highlighting recent advancements in smartphone-based LiDAR systems. This research underscores the importance of selecting and integrating appropriate sensor technologies to optimize performance in the challenging contexts of narrow underground structures such as Erdstall facilities. Future research directions are proposed to explore hybrid systems that combine the strengths of LiDAR and camera sensors in a compact, portable device.

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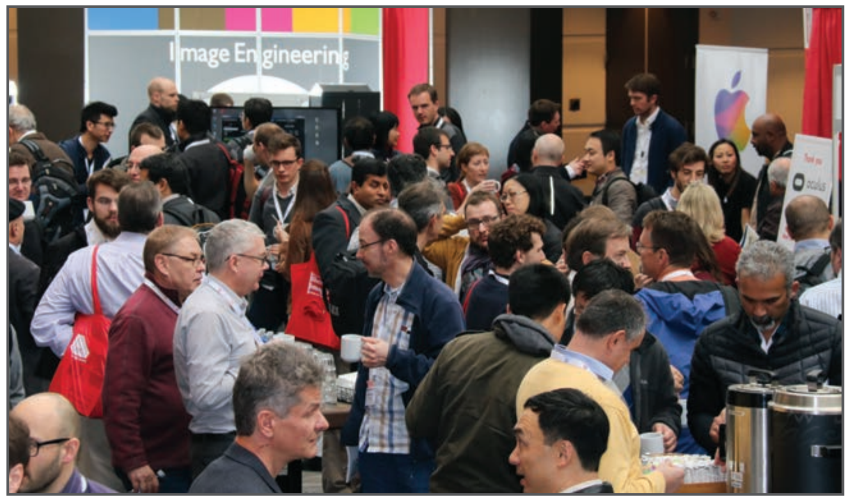

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