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Mobile 3D Mapping of Erdstall Facilities

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Abstract

The 3D mapping of Erdstall facilities presents unique challenges due to their underground and confined nature. This research explores the application of mobile mapping systems to overcome these challenges and acquire accurate spatial data within Erdstall passages. Using a handheld device that combines an RGB camera with depth sensor and motion tracking technology, we address the difficulties associated with limited access, uneven surfaces, low light conditions, and complex geometries inherent to Erdstalls. The research contributes to the understanding of Erdstall architectures, spatial relationships, and historical contexts. By evaluating the effectiveness of mobile mapping technologies in Erdstalls, this study contributes valuable insights to the broader field of archaeological mapping in challenging environments. The results demonstrate the potential of mobile 3D mapping as a powerful tool for documenting and preserving underground heritage sites while providing a foundation for further interdisciplinary studies and initiatives.

Introduction

An Erdstall is an underground infrastructure or tunnel system, often dug in sandy or loose soil. These structures are found in various parts of the world and often have an elongated shape with low ceilings. Burrows are usually relatively small and can only be traversed by one person at a time. The exact purpose of Erdstall is not clearly understood and there are various theories about their use. Some researchers believe that they were used as hiding places in warlike times, while others suspect that they served ritual or religious purposes. There are also theories that suggest that Erdstalls were used as storage sites or places for certain craft activities. Mounds are often difficult to date as there is limited archaeological evidence to determine their age.

Erdstalls can be found in Bavaria, Upper Austria, Lower Austria, and occasionally in Styria and Burgenland [12]. Similar facilities are also known in the Czech Republic, Slovakia and Hungary. Comparable underground facilities can also be found in France, England and Spain. One such Erdstall can also be found in the municipality of Tollet, see Figure 1, which dates back approx. 800 years based on the radiocarbon method. The aim of this paper is to survey such facilities to better understand and visualize the construction of the tunnels and shafts for the Erdstall researchers. 3D reconstruction and real-time 3D mapping is major research in scene understanding for autonomous robot and sensor systems. Furthermore, the study explores the benefits of mobile 3D mapping for archaeological documentation, research, and public engagement. We discuss

Figure 1. *Confined spaces and connecting holes characterize such facilities. Due to the lack of an air shaft, a suction system would be used to supply the rooms with fresh air in order to carry out the inspection and measurement of the facility.*

the potential of virtual exploration through 3D models, allowing researchers and the public to interact with Erdstalls without physical intrusion. The research contributes to the understanding of Erdstall architectures, spatial relationships, and historical contexts.

Related Work

The 3D mapping of Erdstall facilities, or underground infrastructure, serves several purposes, depending on the context and goals of the mapping project in the municipality of Tollet, see Figure 2. The goals for the 3D measurement of such facilities are very diverse and could bring the following potentials for mankind:

- Archaeological Research: Erdstalls are often associated with historical periods, and 3D mapping can aid archaeologists in studying these structures. Mapping helps document the layout, dimensions, and features of Erdstalls, providing valuable insights into the historical and cultural contexts in which they were created.

- Research and Exploration: Mapping Erdstalls can support ongoing research and exploration efforts to discover new passages or connections between existing ones. This can lead to a better understanding of the extent of Erdstall networks and their distribution in different geographical areas.
- Environmental Monitoring: 3D mapping may also be employed for monitoring the surrounding environment of Erdstalls. This can include assessing potential risks such as soil erosion, water ingress, or other environmental factors that could affect the stability and preservation of these underground structures.
- Understanding Function and Use: The purpose of Erdstalls is not fully understood, and 3D mapping can aid in unraveling their function and use. Analyzing the structure, dimensions, and interconnectedness of Erdstalls can provide clues about their intended purpose, whether it be for shelter, storage, ritualistic activities, or other functions.
- Preservation: Mapping Erdstalls can contribute to their preservation by creating detailed records of these underground structures. Preservation efforts may involve monitoring the condition of Erdstalls over time, identifying areas of deterioration, and implementing strategies to protect and conserve these historical sites.
- Cultural Heritage Documentation: Erdstalls are part of cultural heritage, and 3D mapping helps document and preserve this heritage for future generations. Detailed maps and models can be valuable resources for educational purposes and public awareness campaigns about the historical significance of Erdstalls.
- Tourism and Public Engagement: In some cases, 3D maps and virtual reconstructions of Erdstalls can be used for tourism and public engagement. Virtual tours with Augmented Reality (AR) solutions or exhibits allow people to explore these underground structures without physically entering them, contributing to public awareness and appreciation of cultural history.

Overall, 3D mapping of Erdstall facilities serves as a valuable tool for researchers, preservationists, and cultural heritage enthusiasts, helping to unlock the mysteries of these underground passages and contribute to the broader understanding of historical and cultural landscapes [12]. For the creation of environment 3D maps by autonomous robots or handheld devices, there are basically a large number of projects and devices on the market. However, only a small part of them is suitable for indoor or underground use, since absolute position sensors such as GPS cannot be used. The main challenge here is that the geometry of the map can easily start drifting on long straight lines or confined spaces. In addition, high-resolution distance sensors are of great importance, especially for 3D mapping. In recent years, many new products have been introduced to the market, especially in the field of LiDAR-based distance measurement. For example, LiDAR systems with up to 128 layers can be purchased from the manufacturers Velodyne, Ouster, Leddartech, or Livox at an acceptable price. For online 3D mapping different algorithms such as the LOAM [17], Google carthographer [6] or RTABMap [8], [7] are tested on mobile robot platforms. Most of the developed SLAM approaches are either visual or LiDAR-based and that makes it difficult to compare each algorithm [10]. A comprehensive overview of significant types of mapping algorithms and their limitations is presented in [2] and [14]. The focus of this result is to have robust real-time 3D mapping and situational awareness that can be evaluated and combined with visual feature detection. 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.

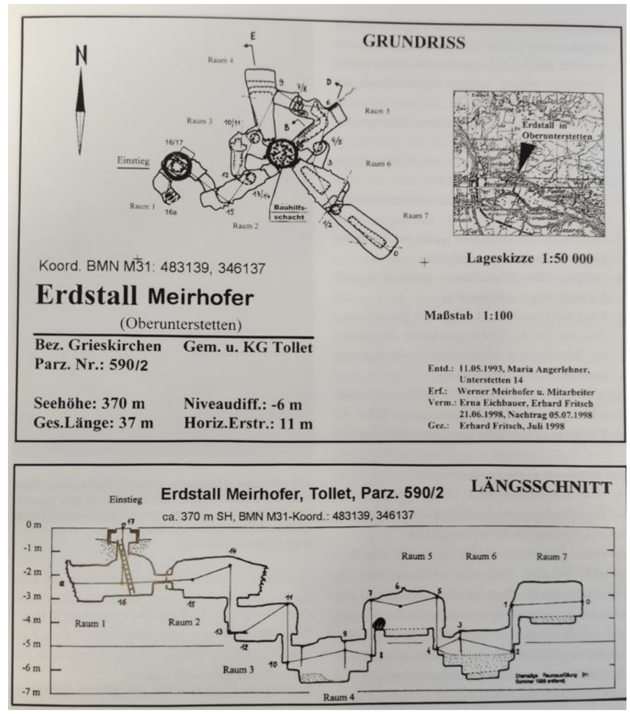

Figure 2. Existing 2D map with side and top view of the Erdstall in the municipality of Tollet: From this central auxiliary construction shaft, seven small chambers were built at different levels and connected to each other by small corridors [12].

These techniques are often used in combination to achieve the best results. Comprehensive research results on 3D mapping of larger caves and underground facilities using TLS, PLS or SfM techniques are listed in [5]. 3D mapping of caves with mobile handheld devices, e.g. with 2D LiDAR [18], 3D LiDAR [3] or iPhone [1] give a comparative study between commercial handheld mobile off-the-shelf and in-house solutions. Research in large-scale exploration of cave environments with UAVs can be found in [13], [16], [15] or [4]. The choice of method depends on factors such as the size and accessibility of the Erdstall, the desired level of detail, and the specific goals of the research project. A mobile handheld camera, see Figure 3 with a depth sensor was chosen for the first field tests and measurements of the Erdstall in Tollet, as access to such facilities is very narrow (< 40 cm) and difficult.

Implemented Method

Mapping Challenges in Confided Spaces

Mapping narrow environments in 3D poses several challenges due to the constraints imposed by the confined spaces. Some of the key problems include:

- 1. Limited Line of Sight: Narrow environments often have limited visibility, making it difficult for sensors to capture comprehensive data. This can result in incomplete or inaccurate mapping due to occluded areas that are not directly visible from the sensor's perspective.
- 2. Sensor Limitations: The sensors commonly used for 3D mapping, such as LiDAR (Light Detection and Ranging), stereo cameras or depth cameras, may struggle to operate optimally in tight spaces. The narrow confines can restrict the field of view, reducing the ability to capture data from all angles.
- 3. Reflection and Interference: In confined spaces, the sensors may encounter issues related to reflections and interference. Surfaces in close proximity can bounce signals back to the sensor, leading to noise and inaccuracies in the generated 3D map.
- 4. Complex Geometry: Narrow environments often have intricate and complex geometry, such as sharp turns, tight corners, or irregular surfaces. Traditional mapping algorithms may face difficulties in accurately representing and navigating through such intricate spaces.
- 5. Localization Challenges: Precise localization within narrow environments can be challenging. Traditional methods like GPS may not be effective in these spaces, and relying solely on onboard sensors for localization may lead to cumulative errors over time.
- 6. Data Fusion: Integrating data from multiple sensors to create a cohesive 3D map can be challenging in narrow spaces. Ensuring consistency and accuracy in the fusion process becomes crucial for generating reliable maps.
- 7. Computational Demands: Processing and analyzing the data collected in real time can be computationally demanding. In narrow environments where quick and accurate responses are often required, the computational load can be a significant challenge.
- 8. Dynamic Environments: If the narrow space is subject to frequent changes, such as moving objects or varying lighting conditions, mapping becomes more challenging. Adapting to dynamic environments in real time requires robust algorithms and sensor capabilities.

Researchers and engineers are actively working on addressing these challenges through advancements in sensor technology, mapping algorithms, and localization techniques. Customized solutions and approaches are often needed to overcome the specific difficulties posed by mapping in narrow environments.

Hardware Approach

A compact sensor and exposure unit were put together for the field test, allowing the user to climb through the very narrow spaces and connecting corridors, see Figure 3.

Project Tango [11] was an initiative by Google aimed at creating a platform for advanced augmented reality (AR) and computer vision applications. The project, which focuses on the development of mobile devices with advanced sensors and the ability to understand and interact with the 3D space around them, was announced in 2014. The Project Tango contains key features for measuring Erdstalls:

- Depth Sensing: Project Tango devices were equipped with depth-sensing cameras, often using technology like structured light or time-of-flight to capture detailed depth information about the environment.
- Motion Tracking: Advanced motion tracking sensors, such as accelerometers and gyroscopes, were integrated into Project Tango devices. These sensors allowed the device to track its movement and orientation in real-time.
- 3D Mapping: With depth sensing and area learning capabilities, Project Tango devices could create 3D maps of their surroundings. This was particularly useful for applications like indoor navigation, gaming, and virtual furniture placement.
- Learning Environment: Project Tango devices had the ability to learn and understand the physical space they were in. This was achieved through a combination of sensor data and computer vision algorithms, allowing the device to recognize and remember key features in the environment.

The hardware that embodied the Project Tango concept was released in the form of developer kits and a few

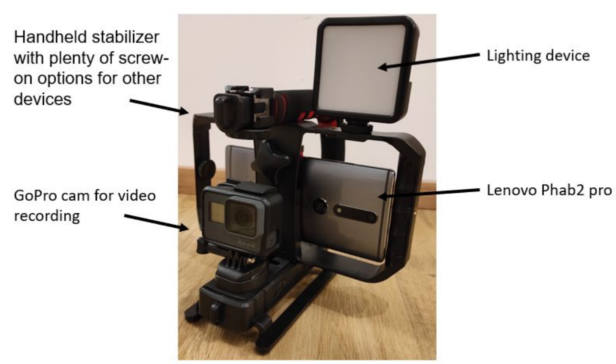

Figure 3. *Handheld mobile 3D mapping device (Lenovo Phab2 pro), lighting device and GoPro cam for video recording.*

consumer devices, such as the used device of Lenovo Phab 2 Pro. In 2017, Google announced the discontinuation of Project Tango, shifting its focus to ARCore, a platform that uses more standard smartphone cameras to achieve augmented reality experiences. ARCore is designed to be more accessible to a wider range of devices without the need for specialized depth-sensing hardware.

3D Mapping Approach

For the first field test we used the open-source RTAB-Map algorithm on Google's Project Tango. RTAB-Map (Real-Time Appearance-Based Mapping) is an open-source simultaneous localization and mapping (SLAM) library for robot mapping and navigation. It is designed to create 3D maps of an environment in real-time while the handheld device is exploring it. RTAB-Map was primarily developed for robotic applications, but it can also be used in various scenarios where 3D mapping is required, such as augmented reality and virtual reality.

The key features of RTAB-Map include:

- Simultaneous Localization and Mapping (SLAM): RTAB-Map performs SLAM, which is the process of a robot or a handheld device mapping its environment while simultaneously keeping track of its own position within that environment.
- Appearance-Based Mapping: RTAB-Map uses visual information to build maps. It relies on visual features and appearance-based techniques, including keyframe-based mapping, loop closure detection, and visual odometry.
- Loop Closure Detection: One of the critical functionalities of RTAB-Map is its ability to detect loop closures, which are instances where the robot revisits a location it has been to before. This helps in improving the accuracy of the map by correcting drift that might have occurred during the exploration.
- RGB-D (Color and Depth) Sensing: RTAB-Map supports RGB-D sensors, which provide both color and depth information. This type of sensor, like the Microsoft Kinect or Intel RealSense cameras, allows for more detailed and accurate mapping.
- Graph-Based Representation: The 3D map created by RTAB-Map is represented as a graph, where nodes correspond to keyframes and edges represent spatial constraints. This graph structure aids in efficient mapping and localization.
- Integration with Robot Operating System (ROS): RTAB-Map is commonly used in conjunction with the Robot Operating System (ROS), a flexible framework for writing robot software. This integration makes it easier to incorporate RTAB-Map into robotic systems.

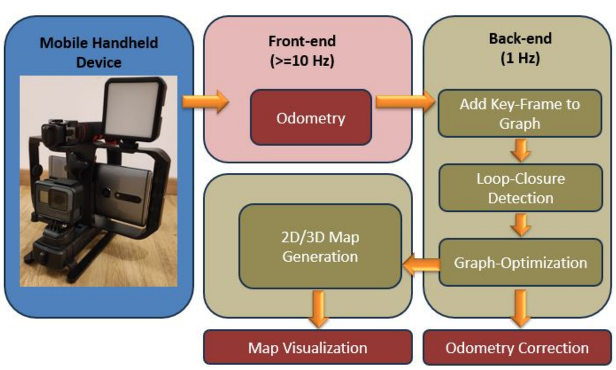

Figure 4. *Overview of RTAB-Map: Real-Time Appearance-Based Mapping with an handheld device.*

Researchers and developers use RTAB-Map in a variety of applications, including mobile robot navigation, robotic exploration, and mapping of indoor environments. Its real-time capabilities and focus on appearance-based mapping make it suitable for scenarios where visual information is crucial for accurate mapping and localization.

Experimental Results

Due to the special characteristics of these underground structures, the 3D measurement of Erdstalls involves a number of challenges. Erdstalls are often narrow and cramped, making it difficult for conventional measurement equipment to reach and traverse the passages. This limitation can hinder the collection of comprehensive data, especially in confined spaces. The following figures show the used measurement system and the use of markers, which have made the measurement process more stable, especially when localizing the system and merging all point clouds.

Due to the insufficient RAM memory of 3GB LPDDR3 of the mobile device the procedure for the acquisition was planned in such a way that each room and each intermediate corridor was scanned and saved separately. At the end, the individual data packages were fused together in the software RTAB-Map, and various filters were applied and visualized as 3D point-cloud and 3D-mesh in the open-source Meshlab software, see Figure 5.

Figure 5. *Map-Generation as 3D point cloud (top) and 3D mesh (bottom).*

RTAB-Map with multi-session [9] was used for the merging process of multiple maps. We have processed consecutively 12 input databases that contain data taken from the handheld device during 12 mapping sessions. Erdstalls are often narrow and cramped, making it difficult for conventional measurement equipment, see Figure 1. Therefore, during the evaluation of the system, one run was carried out with and one without additional marker installation. Seven static ARUCO Markers were installed in the underground facility. A Marker detection was enabled and added as landmarks for graph optimization. We used a 5x5 100 dictionary for our field test with a marker length of 20cm, see Figure 8.

The evaluation and comparison of the two runs in Figure 6 has shown that the measurement error accumulates when measuring without markers and that an increasing error occurs when measuring the connection paths. Each measurement was started in the last room and each room and connecting path was measured individually. The Figure 6 shows that the measurement error for rooms 1 and 2 in particular is up to 1.2m, see Figure 7. This can be attributed to the fact that the connecting path between

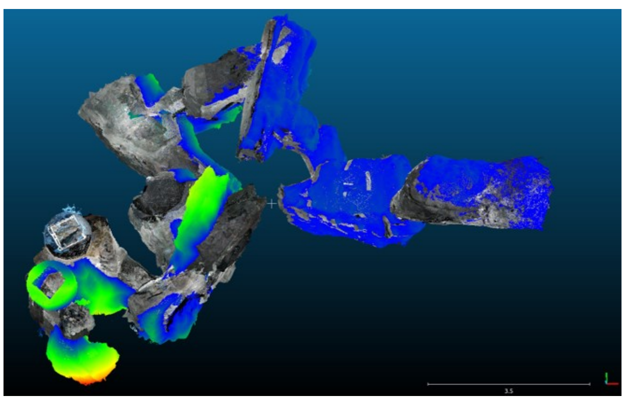

Figure 6. *Comparison of 3D point cloud reconstruction with and without marker detection.*

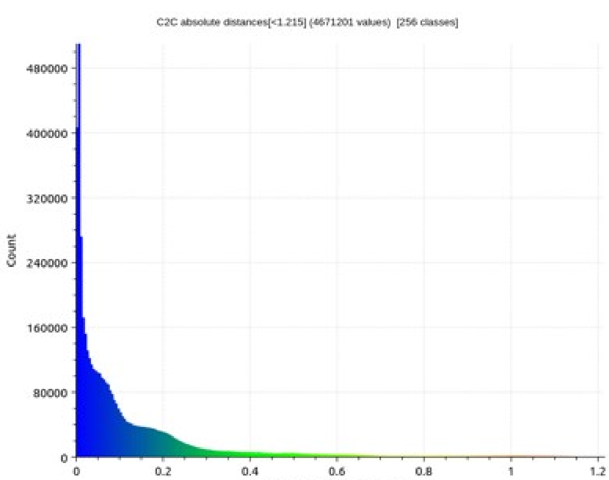

Figure 7. *Evaluation of tracking accuracy [m] with and without marker detection with the open source project CloudCompare.*

Figure 8. *ARUCO marker detection for an improved localization and loop closure detection.*

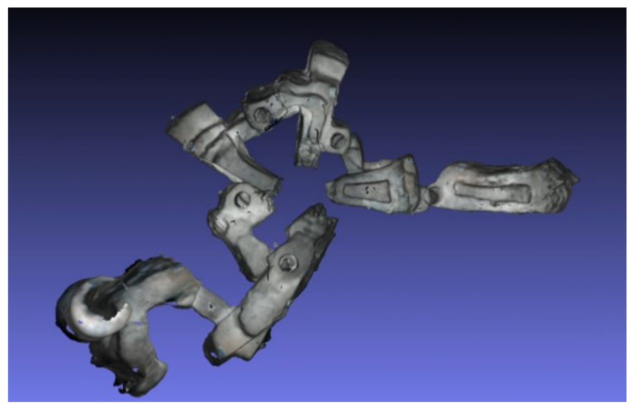

Figure 9. *Top view of the Erdstall and merging of multiple maps.*

the two rooms has a diameter of only approx. 40 cm and is the only one that runs horizontally. A final top view of the Erdstall is presented in Figure 9.

Conclusion and Future Work

Our mobile mapping approach aims to enhance the efficiency and accuracy of data acquisition while minimizing the impact on these archaeological sites. We discuss the integration of simultaneous localization and mapping (SLAM) algorithms to navigate through tight spaces, leveraging mobile platforms equipped with advanced sensors to capture detailed 3D point clouds of Erdstall interiors. We also address the preservation concerns associated with introducing mobile mapping systems into these historical structures. Furthermore, the study explores the benefits of mobile 3D mapping for archaeological documentation, research, and public engagement. We discuss the potential of virtual exploration through 3D models, allowing researchers and the public to interact with Erdstalls without physical intrusion. The measurement data obtained was subsequently used to generate an accurate 3D reconstruction and thus gain further insights and procedures for surveying such facilities. A further work is to evaluate the recorded data with a high precise LiDAR/Camera measurement device.

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Josef Weichenberger is a luminary in the field of underground tunnel research. Originally from Linz-Ebelsberg, Josef works in the Upper Austrian Provincial Archives and has been studying these man-made and natural underground structures for 45 years.

[1] http://www.erdstallforschung.at/