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UAV LiDAR flight planning for high precision rockfall monitoring in alpine environments: first strategies and preliminary results on Mt. Hochvogel

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Key words: laser scanning, point clouds, deformation analysis, geomonitoring, natural hazards

SUMMARY

This paper outlines a practical workflow for surveying alpine regions that are susceptible to rockfalls using UAV LiDAR (unmanned aerial vehicle-based light detection and ranging). The primary goal is to capture the area of interest as comprehensively as possible while ensuring high geometric resolution and accuracy. The generated point clouds are utilized to detect deformations with high precision, capable of measuring changes within a few centimeters. The resulting findings contribute to alpine monitoring and thus also to future hazard prevention measures to protect people and nature. In this study, we apply our workflow to the rockfall on Mt. Hochvogel, located at the border between Germany and Austria.

Firstly, this study introduces a new flight planning approach that considers the specifications of SLAM-based laser scanners. This method allows for a particularly close flight to the object of interest, which makes it possible to capture a usable point cloud for our application. Secondly, we evaluate the quality of the point cloud obtained through UAV LiDAR by comparing it with tachymetric measurements like targets, as well as with a point cloud collected via Terrestrial Laser Scanning (TLS) from an earlier period. The analysis of those specific data sets demonstrates that UAV LiDAR in this configuration achieves an accuracy of less than two centimeters relative to the reference measurements, confirming its suitability for rockfall monitoring. Our strategy regarding UAV LiDAR demonstrates the enormous potential of this combined system, which we intend to expand and deepen in our future research.

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1. INTRODUCTION

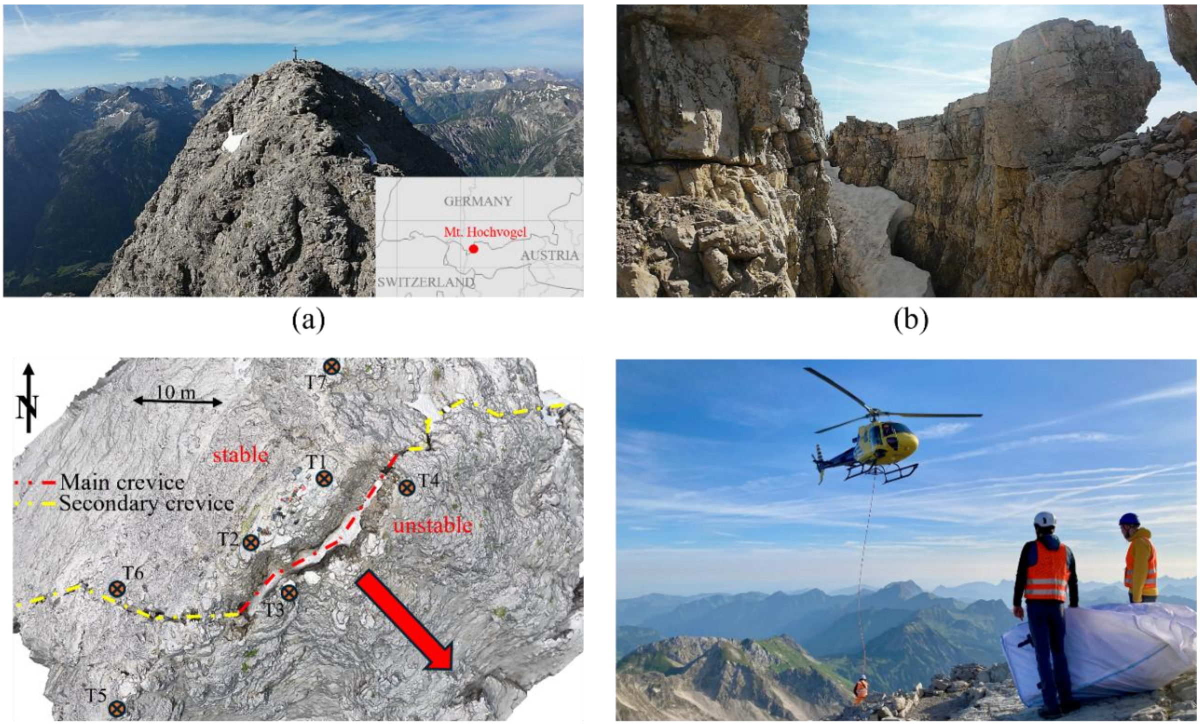
Climate change is leading to an increase in extreme events, such as landslides and rockfalls, which gained global media attention in Switzerland's Valais canton in 2025. These events are classified as alpine natural hazards. The decline of permafrost due to rising temperatures and the more frequent occurrence of extreme weather events are considered the primary causes of the rise in these alpine natural hazards (Huggel et al., 2012). Apart from this, the Alps are generally subject to gravity-induced changes (Krautblatter et al., 2013).

A significant example of an at-risk alpine area is Mt. Hochvogel, a 2,592-meter-high mountain located in the Allgäu Alps, Germany, near the Austrian border (see Fig. 1a). The summit of Mt. Hochvogel features a crack approximately 30 meters long and up to six meters wide, which widens by about three centimeters each year (see Figs. 1b and c). This crack divides the mountain summit into a stable side and an unstable side (see Fig. 1c). In the event of a rockslide, up to 260,000 cubic meters of rock could fall in extreme cases (Leinauer et al., 2020).

For this reason, extensive geodetic, geological, and geophysical monitoring has been conducted on Mt. Hochvogel for many years, utilizing a variety of methods. The primary aim of this monitoring is to provide a comprehensive and precise description of slow rock movements on mountain slopes. This presents a significant challenge for sensor technology, as it requires reliable detection of surface deformations, which can be as small as a few centimeters per year. As part of this developed monitoring strategy, several epoch-wise geodetic measurements are performed in the snow-free period between June and September each year, with a helicopter flying all equipment (instruments and people) up the summit (see Fig. 1d).

As a solution for geodetic monitoring, a geodetic network with fixed measuring points has been established on Mt. Hochvogel over the years. This network has been expanded to include black-and-white targets as ground control points (GCP) for Unmanned Aerial Vehicle (UAV) flights (see Fig. 1c). In addition to traditional tachymetric network measurements, a patch-based approach has been developed. This method allows features extracted from terrestrial laser scanning (TLS) point clouds to be integrated into existing geodetic deformation analyses (Raffl and Holst, 2024). Small deformations in the centimeter range can also be identified using terrestrial photogrammetric point clouds at Mt. Hochvogel (Lucks et al., 2024). The terrain at Mt. Hochvogel is generally steep and consists of loose scree, which makes terrestrial surveying difficult and dangerous. Consequently, all those solutions mentioned focus on the main crevice, although several secondary crevices have formed in the comparatively large area that has yet to be surveyed (see Fig. 1c).

By bringing in UAV LiDAR (Light Detection and Ranging) technology as further technology for high-precision rockfall monitoring on Mt. Hochvogel, we now aim to address this challenge by combining the benefits of laser scanning with the capabilities of UAVs. Laser scanning allows for the fast, comprehensive, and accurate capture of the environment, while UAVs enable quick and extensive scanning of the entire mountain peak from various angles, including steep slopes and overhangs. Given that minor rock movements can occur at any time and in any location, current advancements in this technology should allow for the collection of data on volume, speed, and direction across the entire mountain peak.



(a) (b) (c) (d)

Fig. 1. Visualization of the area under investigation – Mt. Hochvogel in the Allgäu Alps, Germany: (a) Photograph showing the summit from the northeast. (b) UAV photograph of the main crevasse. (c) The mesh model provides an overview of the local conditions with stable and unstable sides, and rock movement is indicated by the red arrow. (d) Photograph illustrating the complex conditions in alpine regions.

Although there already exist various studies on rockfall monitoring using UAVs, we see a lack of knowledge and solutions for using UAV LiDAR for high-precision monitoring in rough alpine surroundings. Thus, our studies cover the following scientific research questions:

- What is the systematic approach to flight planning and the implementation of UAV LiDAR in alpine regions?
- Is UAV LiDAR technology suitable for monitoring rockfalls in alpine areas with an accuracy of a few centimeters?
- What insights can be obtained from the initial flights to enhance the quality of future missions?

Section 2 will give an overview of existing studies of UAVs for rockfall monitoring, Section 3 deals with our measurement concept concerning equipment, flight planning, and its execution on Mt. Hochvogel. In Section 4, we will present the results obtained from UAV LiDAR data and provide a qualitative and a quantitative analysis based on both pointwise and point-cloud-level comparisons with reference data. Section 5 concludes the study.

2. UAVS FOR ROCKFALL MONITORING

The use of UAVs combined with surveying sensors for monitoring rockfalls is well established in various fields (Eichel et al., 2020). Most research has focused on photogrammetric sensors due to their lightweight digital cameras, proven workflows, large coverage area, and high practicality. Hence, with UAV photogrammetry, studies have already shown the potential to detect rockfalls within the centimeter range (e.g., Cirillo et al., 2024). Nowadays, technological advancements have made drones increasingly powerful, resulting in longer flight times and greater operational ranges. The payload capacity has also been enhanced, allowing for the mounting of heavier sensors such as laser scanners.

UAV LiDAR has been successfully utilized for monitoring structures like bridges (Gaspari et al., 2022). Additionally, a framework has been developed for flight planning of UAVs in relation to Building Information Modeling (BIM) (Song et al., 2022). Flight planning with the geometry of a grid for area coverage by laser scanning is also described (Eltner et al., 2022). UAV LiDAR is also applied in mapping coastal areas (Lin et al., 2019). Furthermore, the advantages of integrating UAV LiDAR into rural regions for detecting landslides have been demonstrated (Choi et al., 2023).

Notably, the literature about UAV LiDAR in rockfall monitoring remains scant. For instance, research has demonstrated that point clouds generated by both UAV photogrammetry and UAV LiDAR can be utilized to estimate parameters for rockfall trajectory simulations (Žsabota et al., 2023). Additionally, data collected by UAV LiDAR can be integrated with data from terrestrial laser scans to leverage the strengths of both methods in identifying rockfalls (Fu et al., 2022). Moreover, comparative studies have been conducted on UAV LiDAR, TLS, and low-cost LiDAR modules (Hellmy et al., 2024).

While previous research has primarily focused on UAV LiDAR products, there is a lack of sophisticated flight planning for complex environments such as alpine regions with big height differences, where flight parameters must be continuously adapted to the topography to achieve highly accurate results. Moreover, there are considerable risks, such as the potential loss of the measurement system due to crashes. Operating UAVs at altitudes near 2,600 meters above sea level presents both logistical and meteorological challenges. Therefore, the current approach concerning flight planning must be expanded in this regard. Our work focuses on designing a UAV flight plan aimed at achieving high precision and quality assurance for detecting small deformations in geodetic monitoring measurements. A well-structured flight plan significantly influences the quality of the measurement outcomes.

3. MEASUREMENT CONCEPT FOR HIGH-PRECISION ROCKFALL MONITORING USING UAV LIDAR

First, this section outlines the equipment used in our study (Section 3.1). Afterwards, we describe our new approach for flight planning concept concerning UAV LiDAR (Section 3.2). Finally, we will explain how the UAV flight on Mt. Hochvogel was carried out (Section 3.3).

3.1 Technical Equipment

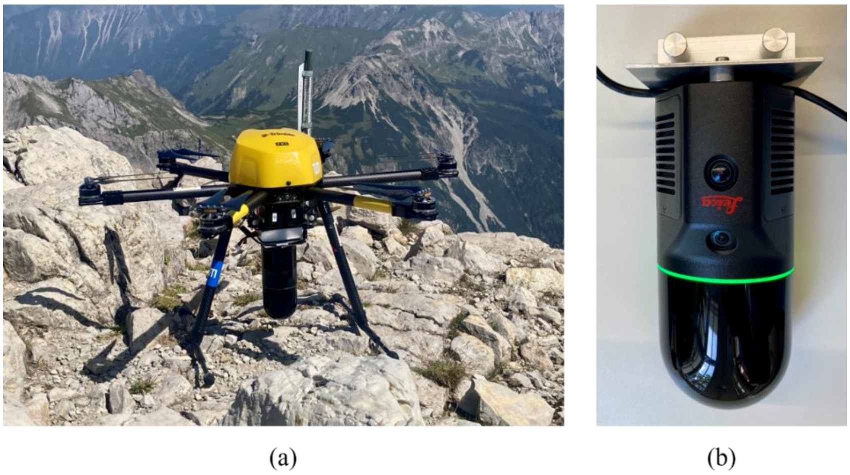

(a) (b)

Fig. 2. (a) Photograph of the Trimble ZX5 UAV in the configuration used. (b) Photograph of the Leica BLK ARC scanning module used with a specially designed mounting bracket.

The UAV utilized in this study is a Trimble ZX5 hexacopter (see Fig. 2a). This drone falls under the Open A3 category as per the Implementing Regulation (EU) 2019/947 for drones. It has a take-off weight of five kilograms with the specified configuration. Under normal conditions – meaning no wind and a standard atmosphere – the flight time is approximately 20 minutes (Trimble Navigation Limited, 2015). The UAV can be operated manually, or its flight path can be programmed using *GroundStation* planning software by MULTIROTOR, enabling the ZX5 to fly a specified trajectory automatically. Flight navigation is accomplished through a combination of GNSS (Global Navigation Satellite System) and IMU (Inertial Measurement Unit). The UAV is powered by two lithium polymer batteries, each rated at 14.4 volts and 9,000 milliampere hours, connected in parallel. It can operate at wind speeds of up to 10 meters per second.

Originally designed for photogrammetric flights, the drone serves as a carrier platform for surveying sensors. To mount a laser scanner underneath the drone, a rigid adapter was specially designed and constructed as a gimbal (see Fig. 2b). The Leica BLK ARC is employed as the laser scanner; it is an autonomous, mobile module optimized for close-range mobile laser scanning, operating effectively within a range of 0.5 to 20 meters. It provides point cloud accuracy, achieving one centimeter precision and a point measurement rate of 420,000 points per second. The scanning process utilizes SLAM (Simultaneous Localization and Mapping) technology. For this purpose, the BLK ARC features a 360-degree viewing system equipped with three 4.8-megapixel cameras. Scans can be triggered manually via a tablet connected through Wi-Fi, which also allows for a live view of the generated point cloud for visual inspection.

The scanner is powered by a lithium polymer battery with a voltage of 14.4 volts and a capacity of 1,600 milliampere hours. This lightweight battery ensures sufficient scanning duration to cover the entire flight. The total weight of the scanner, including the battery and suspension, is approximately one kilogram. The interaction between the UAV and the laser scanner, along with the flight parameters, has been tested in various flight tests.

3.2 Flight planning

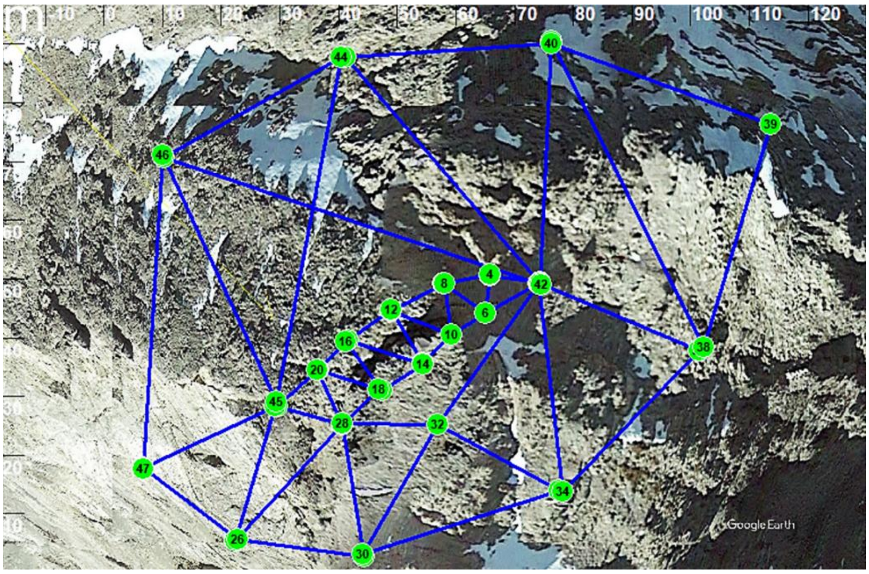


Fig. 3. Example 2D representation of the flight trajectory at Mt. Hochvogel as a network geometry. The numbering of the nodes refers to the flight commands. Nodes can be flown multiple times.

Flight planning is the initial step in any UAV operation and involves selecting the flight trajectory and parameters. These choices depend on factors such as the area of interest (AOI) being surveyed, the sensors being used, and external conditions like wind and light. Corrections to the flight plan will only become evident after evaluating the measurement results. Thus, careful flight planning tailored to the specific sensor technology and application is crucial for achieving high-quality measurement outcomes. Therefore, thorough flight planning is essential.

When it comes to flight planning, there are specific requirements and considerations for using LiDAR modules. For instance, the SLAM-based scanning process of the Leica BLK ARC necessitates loop closures in the point cloud at regular intervals. This allows for the calculation and correction of the laser scanner's trajectory. Additionally, the SLAM algorithm needs to be uninterrupted while navigating complex mountain terrains, ensuring adherence to the specified range and making SLAM-friendly adjustments in perspective. Hence, conventional flight planning, which typically uses parallel flight paths for photogrammetric flights, has limited effectiveness. Consequently, we propose a novel approach to flight planning that utilizes triangular meshing of nodes aligned with the geometry of geodetic networks (see Fig. 3).

This network geometry offers several advantages:

- The nodes create regular loop closures without covering the edges redundantly. This leads to more efficient use of flight time.
- A waiting time can be assigned to each node. During this time, the UAV maintains its position to simulate a static 360-degree scan. This increases the resolution in these specific areas in the resulting point cloud.
- The overlap of the flight paths is designed to conform to the mountain's geometry, resulting in greater overlap towards the summit, where areas of interest are located, and less overlap at the edges. The meshing can be adjusted to any desired tightness based on the AOI or objects like targets. The result is a higher point density that is needed for high-precision monitoring and improved SLAM results.
- The network can be expanded or linked as needed, allowing for multiple flights with battery changes.
- Each node can be assigned to a separate altitude following the mountain’s geometry. In photogrammetric flights, this feature typically occurs only at the end of a flight path, because the nodes are not located in the center of AOI.

Regarding flight altitude, the accuracy and resolution of the laser scan improve as the distance to the AOI decreases. If the distance to the surface needs to remain constant, the flight altitude must be continuously adjusted, especially in mountainous regions. The chosen flight altitude is a balance between accuracy, resolution, coverage, and acceptable risk. The flight altitude is one of the most critical parameters in flight planning (cf. Sofonia et al., 2019). In our application, flight altitude is set to five meters above ground level (AGL) at each waypoint.

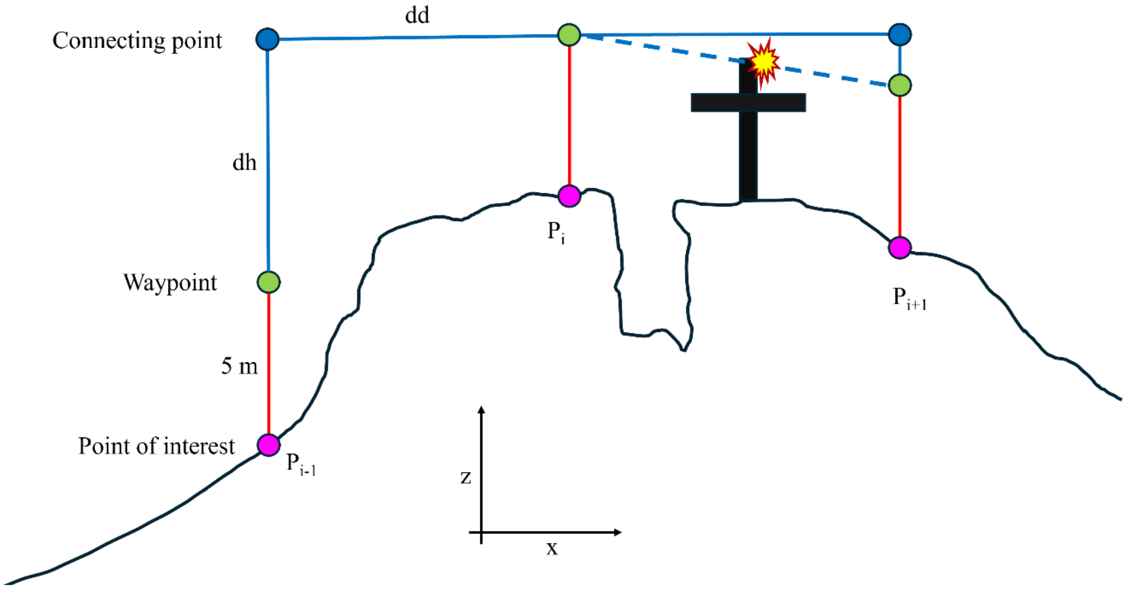


Fig. 4. Schematic representation of the side view of the flight trajectory with characteristic points and the problem of unadjusted altitudes.

The network geometry consists of waypoints (nodes) defined by the 3D coordinates of points of interest (POI) within the AOI, plus the chosen flight altitude of 5 m AGL (see Fig. 4). If the flight altitude is too high, important details may not be captured. On the other hand, if the altitude is too low, it will increase the flight time needed to cover the AOI. Additionally, the irregular shape of natural features can lead to crashes and a potential total loss of the aircraft. This risk is heightened by the fact that flying diagonally between waypoints poses significant hazards due to natural obstacles.

Therefore, the flight path is divided into a horizontal component (dd) and a vertical component (dh). The connection refers to a point that is determined based on the coordinates of the POI. It is crucial to consider whether P_{i+1} is situated at a higher or lower altitude than P_i. If P_{i+1} has a lower altitude, the UAV first travels the horizontal distance before it can descend vertically to reach the necessary height. Conversely, if the target point is at a higher altitude, the UAV must ascend directly. By selecting a smaller distance (dd), the natural geometry of the mountain can be approximated more accurately.

A program was developed for flight planning that calculates the trajectory based on the entered flight parameters. It outputs corresponding commands with coordinates, which are then sent to the UAV. If critical distances to the surface are not maintained, warnings are generated. As with closed geometric leveling, the height difference between the start and end points must be zero.

Initially, flight planning is carried out in *CloudCompare*, utilizing a basic 3D model of Mt. Hochvogel, created from earlier photogrammetric images. In this step, a list of the POI is manually compiled within the model following a geodetic network geometry. For vertical rock faces, virtual grid points outside the AOI can also be selected and added to the point cloud. Once the point list is created, it is transferred to the program along with the defined flight parameters, which can be found in Table 1.

Table 1: Selected flight parameters for flying over Mt. Hochvogel.

Parameter	**Value**
Height AGL	5 m
Speed hz	2 m/s
Speed v	1 m/s
Waiting time	5 s
Catch radius	1 m

The parameters for the flight include altitude, horizontal and vertical flight speeds, a waiting time at each waypoint, and a catch radius that serves as a tolerance measure around each waypoint. The vertical flight speed is set to half of the horizontal speed because the UAV’s downdraft, known as downwash, can cause instability during descent. This distinction emphasizes the separation of the trajectory into horizontal and vertical components.

At the conclusion of the program, an interactive 3D representation of the trajectory and the surrounding mountain is generated. This visualization helps verify the flight path and the effectiveness of collision avoidance measures (see Fig. 5).

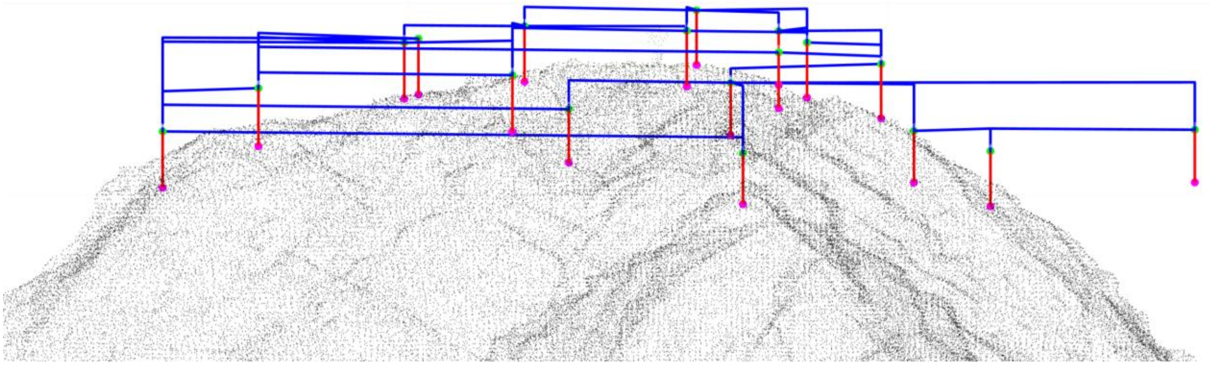


Fig. 5. 3D view of the flight trajectory at Mt. Hochvogel for visual inspection

3.3 Performing UAV flight

The UAV flight took place in June 2025. Before starting the automatic flight, wind speed was measured using an anemometer to ensure flight safety. The average wind speed was about 3 meters per second. Visibility was sufficient with sunny weather conditions and scattered clouds with a high base.

A significant operational limitation of the UAV system is that negative altitude values cannot be interpreted. Consequently, the starting point must be set at the lowest point of the mission because its height is inertially set to 0 m. In alpine terrain, this can complicate the maintenance of line-of-sight (LOS) contact with the pilot, who is positioned at the summit for an optimal overview. Additionally, the absence of flat surfaces poses challenges for takeoff and landing, which places high demands on the pilot's flying skills. These natural conditions increase the risk associated with conducting UAV flights in such terrain (see Fig. 6).

The pilot continuously monitored telemetry data, such as battery levels, on the remote-control unit. Maintaining a safe distance from nearby mountaineers was always a top priority. An assistant helped the pilot by remotely controlling the laser scanner via a tablet and monitoring the point cloud captured in real-time.

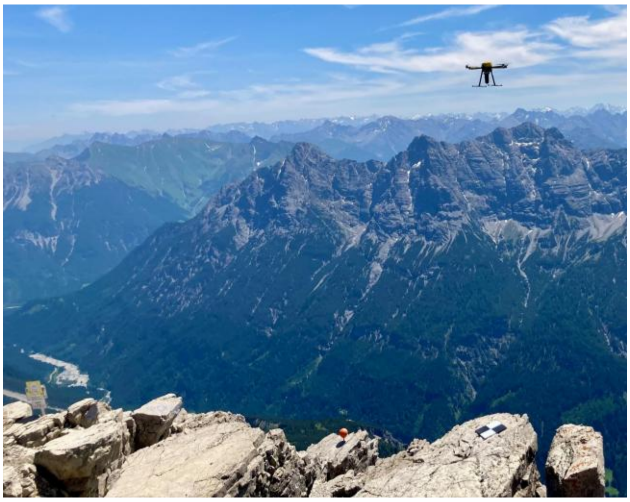


Fig. 6. Photograph of the UAV flight over Mt. Hochvogel with a target.

4. PRELIMINARY RESULTS AND EVALUATIONS OF MAPPED POINT CLOUDS

This section presents a qualitative analysis of the measured point cloud (Section 4.1) and a quantitative analysis (Section 4.2). For the latter one, we compare the results with coordinates measured by a total station (TPS) and point clouds mapped by TLS.

4.1 Qualitative analysis of point cloud

The point cloud represented in Fig. 7 displays the measurement results from the UAV flight over Mt. Hochvogel. It captures the entire mountain peak, including both the main and secondary crevasses, as well as the stable and unstable sides. The coloring is based on the cameras integrated into the scanning module; however, some areas lack RGB information due to the scan housing casting shadows, resulting in those regions appearing black. Nevertheless, detailed 3D analysis reveals a consistent point density, indicating that there are no irregularities, particularly in the main crevasse, and a high level of detail (cf. Quantitative analysis, Section 4.2). This assessment indicates that the flight parameters and trajectory have led to a high-quality result.

Nevertheless, as future enhancements of the flight planning, the point density could be further increased by reducing the horizontal flight speed. In addition to that, the steeper the terrain, the more intermediate waypoints must be chosen in order not to interrupt the SLAM algorithm. To enhance resolution, especially in the target areas for future measurements, it may be beneficial to conduct terrestrial scans of these targets before the UAV flight.

Additionally, it seems to be advisable to divide the network into smaller sub-missions during the flight planning process. In the future, instead of conducting a single flight, multiple flights could be performed by changing the battery, which would increase both the size and accuracy of the point cloud. There is always a trade-off between coverage and accuracy.

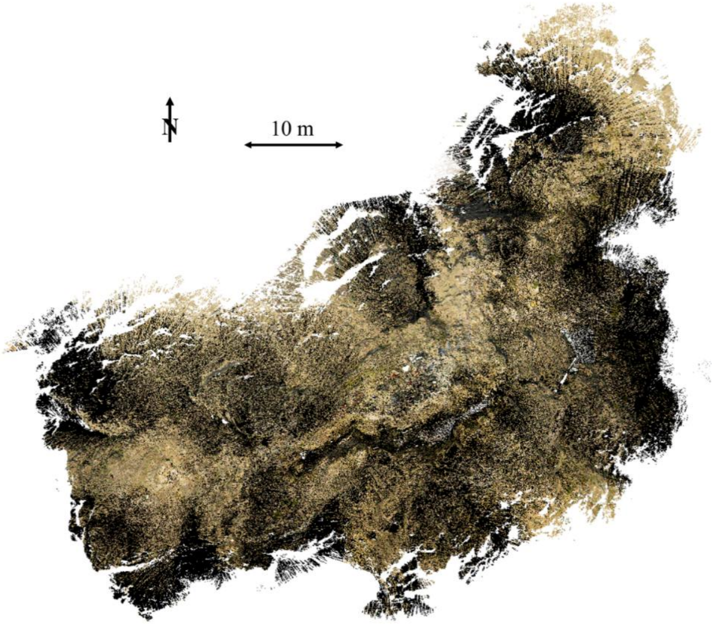


Fig. 7. Point cloud of the mountain peak captured by UAV LiDAR.

4.2 Quantitative analysis of point cloud comparison

Section 4.2.1 deals with a comparison between the UAV LiDAR point cloud and tachymetrically measured targets in the same epoch. Section 4.2.2 presents a point cloud comparison between UAV LiDAR 2025 and TLS 2023 of the mountain's summit.

4.2.1 Total station measurements from 2025

The following comparison serves as a local check for point accuracy. At the summit, black-and-white targets measuring 25 by 25 centimeters were deployed before the flight. To ensure stable and repeatable positioning for multiple flights, the targets were secured using threads embedded in the ground and were integrated tachymetrically into the existing geodetic network. The mounted targets function as checkpoints. The absolute differences in the x, y, and z coordinates, along with the Euclidean distance, are presented in Table 2. Due to the insufficient resolution of the UAV point cloud for automatic target detection using standard software, the centers of the targets were selected manually. For all four points around the main crevice, the Euclidean distance is less than two centimeters. This quantitative assessment indicates a high local point accuracy of the UAV LiDAR point cloud.

Table 2: Comparison of the coordinates of the checkpoints between UAV LiDAR and tachymetric surveying.

	dx (m)	**dy (m)**	**dz (m)**	**ds (m)**
Target 1	0.004	0.009	0.007	0.012
Target 2	0.004	0.004	0.013	0.014
Target 3	0.009	0.013	0.009	0.018
Target 4	0.012	0.008	0.012	0.018
Mean	**0.007**	**0.009**	**0.010**	**0.016**

4.2.2 Terrestrial Laser Scanning from 2023

Figure 8 presents a comparison of the point clouds generated by UAV LiDAR in 2025 and TLS in 2023 as a reference, analyzed using the M3C2 algorithm (Lague et al., 2013). The TLS point cloud was captured with a Leica RTC 360 laser scanner. The M3C2 algorithm has already been employed in a previous study to assess the consistency of the same data set and photogrammetric point clouds (Raffl et al., 2025). The UAV LiDAR point cloud and the TLS point cloud are roughly aligned using manually selected identical points. For fine registration, the Piecewise-ICP is employed (Yang and Holst, 2025). The stable area of Mt. Hochvogel is utilized for this purpose; it is manually extracted from both point clouds and down sampled to a resolution of three centimeters. The transformation matrix is then applied to the target point cloud.

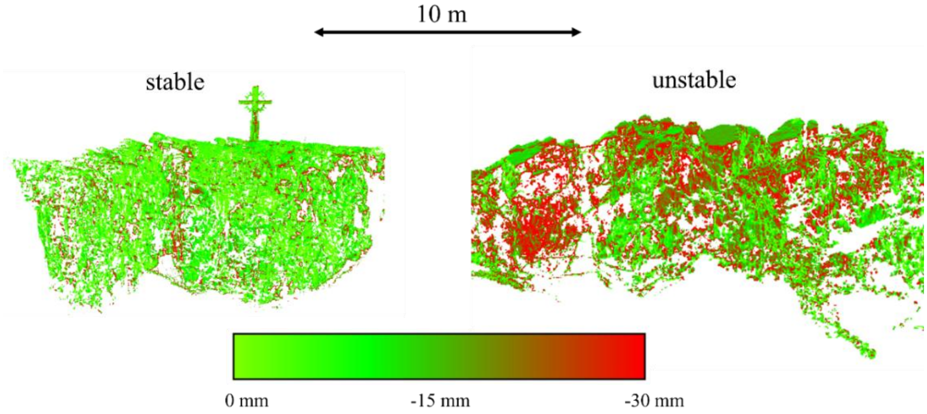


Fig. 8. Illustration of the M3C2 distances between UAV LiDAR 2025 and TLS 2023 on the stable side (left) and the unstable side (right) of the summit.

The M3C2 distances range from 0 mm to -30 mm. In the stable area, a largely uniform color pattern is observed, except for some crumbling stones. The mean value of the M3C2 distances is 6 mm here. This suggests a high level of consistency between the two point clouds mapped by different sensors. A conclusion is that the geometry of the UAV LiDAR point cloud accurately reflects the mountain's summit, which is an important aspect for precise rockfall monitoring.

In the unstable area, the values show greater variability. Selected boulders show a deformation of approximately -30 mm. This deformation falls within the expected range of rock movement over a two-year period, even if movements up to 60 mm are detected. Since the M3C2 algorithm does not use displacement but difference vectors, the deformations are often too small because in-plane deformations are underestimated (Holst et al., 2017).

Finally, both point clouds are compared using selected parameters (see Table 3): The TLS point cloud consists of approximately 500 million points, which is accompanied by a high level of detail due to the point density. While the point density of the UAV lidar point cloud is also sufficient, it could still be larger to capture more details. A big advantage of the UAV LiDAR point cloud is that it offers extensive coverage with a quick recording time due to its mobile laser scanning capabilities. Therefore, approximately the same number of points per second is recorded in both methods.

Table 3: Comparison of parameters between UAV LiDAR 2025 and TLS 2023.

Parameter	**UAV LiDAR 2025**	**TLS 2023**
Scan mode	mobile	static
Number of points	70,222,035	538,898,230
Area	6,742.8 m^2	1,472.4 m^2
Scan duration	15 minutes	120 minutes
Points per m² / point density	Approx. 10,415	Approx. 366,100
Points per second	Approx. 78,000	Approx. 75,000
Seconds per m²	Approx. 0.1	Approx. 4.9

5. CONCLUSION

The approach described in this paper focuses on flight planning for UAV LiDAR operations in alpine regions, specifically using Mt. Hochvogel as a case study. A methodical approach to flight planning was developed that takes all specifications of the SLAM-based laser scanning module into account. This flight planning was successfully implemented, and a reliable dataset was generated. An established flight plan can be repeated from one measurement campaign to the next, resulting in reproducible measurement results. This allows for inter-epoch comparisons between UAV LiDAR point clouds.

A complete point cloud of the mountain peak was generated from the measurement, which exhibited sufficient geometric resolution for the intended applications. Based on the derived analyses, we can conclude that UAV LiDAR is well-suited for high-precision rockfall monitoring. Our approach demonstrated accuracy in the range of less than two centimeters.

Thus, based on the given preliminary results, we postulate that UAV LiDAR is an efficient technique for surveying large areas of mountain peaks in a short amount of time and with manageable equipment. This underscores the potential of UAV LiDAR for deformation measurement in the future, especially as advancements in technology continue to enhance power and reduce the weight of laser scanners and UAVs. Current constraints include the reliance on manual target designation and reduced flight time at high altitudes. Furthermore, refining SLAM behavior in steep terrain is still a challenge.

In future work, based on the outcomes, we will try to further optimize flight planning regarding the resolution and size of the area. In addition to that, we will develop more extensive methods for precise geodetic deformation analysis. By fusing multiple data sets from various sources and times, it would be possible to create a digital twin of the mountain peak, which can be continuously updated.

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