A MEASUREMENT SYSTEM FOR MAPPING SNOW DISTRIBUTION CHANGES IN AN AVALANCHE RELEASE ZONE

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ABSTRACT: Since people have been living in mountain regions, they are threatened by the danger of snow avalanches. Critical situations may require the closure of traffic routes or the evacuation of settlements as temporary risk mitigation measures. However, the decision-making experts currently have only limited data to base their decision on. A crucial parameter influencing the avalanche situation is the accumulation of wind drifted snow, and the resulting variation of the snow depth and stability across a slope. Herein, we propose a ground-based measurement system which will enable quasi permanent monitoring of the snow depth distribution in avalanche release areas with high spatial and temporal resolution. The system comprises Livox low-cost LiDAR sensors, photo cameras, as well as meteorologic instruments. The setup is designed to operate autonomously, capturing snow depth variations in an avalanche release zone close to the ski resort Jakobshorn in Davos, Switzerland. Using first test datasets, we analyze the specific strengths and weaknesses of the low-cost LiDAR sensors. Drone-based photogrammetry serves as reference for validation. The developed sensor system will serve to build up a snow depth database, which is used in a further step as an input for developing models predicting the snow depth distribution based on meteorological and terrain parameters. All information shall finally be provided to practitioners in a scenario-based platform to aid their decision-making process of traffic route safety measures.

KEYWORDS: LiDAR, Monitoring, Snow Depth, Road Safety, Avalanches

1. INTRODUCTION

Snow avalanches endanger people and infrastructure in mountainous regions. Following the concept of integral avalanche protection different intervention strategies have been deployed (Wilhelm et al., 2000). With a combination of active, passive, permanent and temporary measures permanent settlement in endangered regions have become safer. Active measures include artificial avalanche releases as a short term intervention and avalanche defence structures, prominently recognisable in mountainous areas, as permanent installations. Another permanent but passive measure is the zoning of land with hazard indication maps. The protection of roads and other traffic lines is often achieved by passive and temporary measures, meaning their complete (but temporary) closure in critical situations. This can be very drastic, for example in the winter of 2018 the road and train line to the tourist destination Zermatt in Switzerland had to be closed for several days (Bründl et al., 2019), locking in thousands of tourists and locals.

The decision whether and when to close a road is usually taken by a committee of local experts. Their decision is based on the avalanche bulletin, the weather forecast, data from automated meteorological stations and most importantly, personal experience. However, quantitative and up-to-date information about the actual local avalanche situation is mostly unavailable. One crucial parameter is the distribution of the snow depth across a slope, especially in potential avalanche release areas. Fresh snow gets redistributed by wind, and the resulting local accumulations can increase the danger level of avalanches significantly (Schweizer et al., 2003).

The local distribution of snow heights is highly variable in space and time, especially if there are strong winds during and after snowfall. Therefore, it is necessary to aim for a monitoring with high spatial (small decimeter level) as well as temporal (sub-daily) resolution to gain a better understanding of the local scale processes connecting wind drifted snow and avalanche releases.

There are different approaches to measure snow

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depth and its spatial variations. Snow depth measurements are traditionally done manually by reading the snow height from fixed installed or mobile poles. Attempts of automatic measurements are made by monitoring snow poles using time-lapse photogrammetry and image processing to automatically determine the snow height (Dong & Menzel, 2017; Garvelmann et al., 2013; Kopp et al., 2019). This gives a timeline of the snow depth, but only at a specific point. Other photogrammetric approaches like multi-view photogrammetry or structure from motion allow deriving 3D models and detecting the spatial variations of surface changes. Photogrammetry, in this context, uses either ground-based (Filhol et al., 2019; Liu et al., 2021; Mallalieu et al., 2017), airborne (Bühler et al., 2015; Bührle et al., 2023) or satellite-based (Marti et al., 2016; Shaw et al., 2020) cameras. However, the quality of 3D reconstruction strongly depends on the light conditions. Difficulties arise with homogeneous fresh snow or diffuse light, when there are no distinct features recognizable at the snow surface (Bühler et al., 2016; Bühler et al., 2017). Another commonly used technique is LiDAR (Light Detection and Ranging), which also uses sensors both ground-based (Adams et al., 2013; Deems et al., 2015; Schön et al., 2015) and airborne (Jacobs et al., 2021; Painter et al., 2016). The advantage of LiDAR sensors is that they are less dependent on the ambient light, but there are specific system requirements for the measurement of snow and ice (Deems et al., 2013).

There are different considerations for the usage of sensors either ground-based or airborne. Airborne approaches usually lead to a better spatial coverage, and need, according to the acquisition height, less time to cover larger areas. However, the ground resolution deteriorates with increasing acquisition height and the chances that the visibility of the ground is interrupted by fog or clouds increase. Other challenges, especially when flying close to the ground with a UAV, are the wind conditions, strongly influencing the feasibility of a controlled flight. Airborne acquisitions with an airplane often have high expenses per acquisition, impairing the feasibility of multiple measurements to gain a high temporal resolution. Fixed installed sensors on the ground have the disadvantage of less spatial coverage, due to occlusions and shadowing. When operated autonomously, a high temporal resolution can be achieved and the feasibility of acquisitions is less dependent on weather conditions.

In this paper we introduce a ground-based monitoring system, designed to acquire high spatial and temporal resolution snow depth data in an avalanche release area, over several winter seasons. Detailed information of snow depth variations is essential for practitioners that work in winter road safety management, but not yet available for their daily usage. Furthermore, the expected dataset enables further advances in snow depth modelling, avalanche formation research and avalanche simulations.

In section 2 we introduce the anticipated study site in Davos, Switzerland. Section 3 gives detailed information about the concept, the selected sensors and the planned measurement stations. Afterwards, we show first test data of the LiDAR sensors in section 4, followed by a conclusion and an outlook in section 5.

2. ANTICIPATED STUDY SITE

The study area is located in the Dischma valley, a high alpine mountain valley, branching from the Davos Landwasser valley, in the southeast of Switzerland. The valley is permanently inhabited, and in past winters the road had to be closed several times due to avalanche danger, for example in 2018, 2019 and 2021. There are multiple avalanche tracks along the valley that have the potential to reach infrastructure at the valley bottom. We will conduct our study at the "Wildi" avalanche, which is depicted in Figure 1 with its outline from 2019, where it reached the Dischma road. To monitor its release area we will set up the instruments in the slope, close to the ridge. Figure 2 shows the region of interest from the view of station 1.

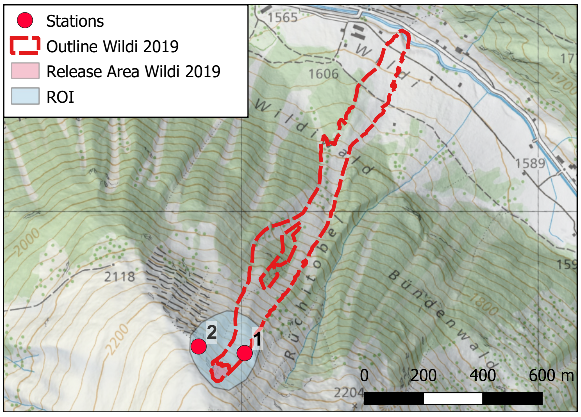

Figure 1: Overview of the study area with the locations of the measurement stations, the outlines of the release area and the track of the Wildi avalanche from 2019 and the region of interest (ROI), which will be monitored, background map source: map.geo.admin.ch

Figure 2: Picture of the study site, the region of interest is colored in light blue, below right is an artist's visualization of station 1.

3. MONITORING SYSTEM

3.1 Overall concept

To measure the snow height distribution with high spatial and temporal resolution we propose a ground-based station design, containing a LiDAR sensor, a photo camera, as well as meteorological instruments. The latter include sensors to measure the wind speed and direction, humidity, and the temperature of air, snow surface and snowpack. All sensors (except the temperature sensors within the snowpack) are mounted on a pole, high enough to be above the snow cover during winter. The temperature sensors for the snowpack are mounted on shorter poles at various heights, such that they are covered by snow for most of the winter season. The expected snow heights are retrieved from earlier acquisitions of the area using airborne photogrammetry (Bührle et al., 2023).

3.2 Sensors

The main instrument for the measurement of the snow heights is the LiDAR sensor. The most important specifications for the LiDAR sensor for this project are the detection range and the wavelength. To be able to completely cover the targeted avalanche release area, the sensor needs to measure distances of up to 200 m. The reflectance of snow is different for different optical wavelengths and grain sizes (Wiscombe & Warren, 1980). Deems et al., 2013 made a thorough review on LiDAR measurements of snow and determined wavelengths around 905 nm or 1064 nm, to have the best properties regarding spectral reflectance and penetration into the snow surface.

There is a sensor, optimized for the measurement of snow and ice, namely the Riegl VZ-6000, which is used for example for large scale glacier monitoring, in Greenland (LeWinter et al., 2014) or Austria (Voordendag et al., 2021). In our measurement system we cannot use it as a component because its operation is not eye safe and our measurement site is next to a popular skiing resort. We instead plan to use a Riegl VZ-6000 sensor at a later stage of the research to provide reference data for specific experiments or tests. There is no other scanners optimized for this kind of application which we could use, therefore we were searching for options in other domains, looking for low cost solutions. A market analysis showed that many automotive- or industrial-grade LiDAR sensors use a wavelength between 865 and 905 nm. Further criteria were the ability to measure distances up to 200 m, and a field of view of at least 70 degrees horizontally and 20 degrees vertically. Table 1 shows a selection of currently available LiDAR sensors, meeting the criteria mentioned above.

Instrument	Wavelength [nm]	Max. range [m]	FoV (HxV)
Hesai Pandar128	905	200	360° x 40°
Livox Avia	905	450	70.4° x 77.2°
Ouster OS2 (Rev7)	865	350	360° x 22.5°
Quanenergy M8 Prime Ultra	905	200	360° x 20°
Velodyne Alpha Prime	903	300	360° x 40°

Table 1: Overview of some currently available LiDAR sensors with selected specifications regarding the wavelength, maximum range and Field of View (FoV)

We selected the Livox Avia LiDAR sensor because it is the only sensor, meeting the basic requirements, that has the capability of operating with a non-repetitve scanning pattern. All other sensors listed above, are multi-beam LiDAR sensors where the channel distribution is fixed, resulting in a repeated line pattern. In a kinematic use case, for which the sensors were primarily designed, the movement of the scanner allows a high spatial resolution perpendicular to the scanlines. In our case, the LiDAR sensor will be mounted statically, which would lead to not closable gaps between the static scan lines. The Risley prism-based non-repetitive pattern (Vuthea & Toshiyoshi, 2018) of the Livox Avia sensor has the advantage to achieve an increase of spatial resolution when increasing scanning times (see Figure 3).

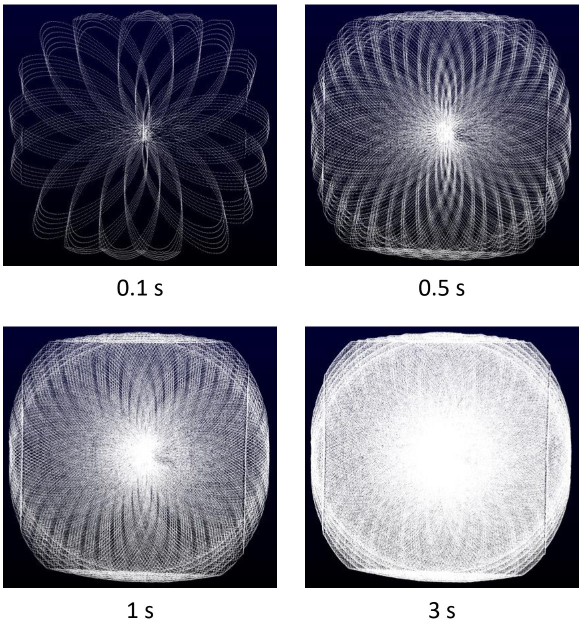

Figure 3: The Risley prism-based non-repetitive scanning pattern of the Livox Avia sensor, after different scan durations. (The flattened part in the upper and lower area is due to the limited size of the scanned wall.)

According to the specifications the maximum detection range of the Livox Avia sensor is 450 m, in testing conditions with 80% reflectivity of the target and 0 klx ambient light. With an ambient light of 100 klx and a target reflectivity of only 10 % the manufacturer still indicate a detection range of 190 m. The precisions of range and angles are specified with 2 cm and 0.05°, respectively. The emitted beam diverges with 0.28° vertically and 0.03° horizontally.

In addition to the LiDAR sensor we will use a photo camera for monitoring the snow heights in the region of interest. With the calculation of the transformation between the camera and the LiDAR sensor we can project the color information from the image onto the LiDAR point cloud and in the other direction project the 3D LiDAR points onto the image for spatial reference. With the LiDAR-camera fusion, we can combine the respective strengths of the systems and generate a more complete data set. We selected a Canon EOS R7 32 megapixel photo camera with an RF-S lens with 18-45 mm focal length. The zoom lens allows to optimally configure the camera settings on site, to expose the same area covered by the LiDAR sensor.

Supplementary, we will record several meteorological parameters. Together with the newly acquired snow depth database these yield important information for different modelling approaches. These are, among others, SNOWPACK, a model of the development of the snowpack during the winter (Lehning et al., 1999), RAMMS::AVALANCHE, a numerical avalanche simulation tool (Christen et al., 2010) and its additional module RAMMS::EXTENDED (Glaus et al., 2023), or approaches for the simulation of wind-drifted snow (Revuelto et al., 2020). Table 2 shows the selected instruments for the different parameters.

Parameter	Instrument
Wind speed and direction	Young Wind Monitor 05103-L
Relative humidity and air temperature	Campbell HygroVUE10
Snow surface temperature	Waljag SnowSurfSDI
Temperature in the snowpack	GeoPrecision M-Log5W-FG2 433MHz

Table 2: List of the selected meteorological instruments

3.3 Autonomous monitoring stations

The LiDAR sensor, the camera and all meteorological sensors (except the temperature sensors for the snowpack), are installed on a crossbar on top of a 3.5 m steel mast (see figure 4). The LiDAR sensor is placed in the middle, close to the vertical pole, to avoid the influence of additional movement of the crossbar. The camera is placed next to the LiDAR sensor, in a fully protective housing. The meteorological sensors are distributed on the outer ends of the crossbar. In the vicinity of station 2 (see figure 1), at the height of the release area we will install an additional station on the ground to measure the temperature within the snowpack at various heights.

Both stations run fully autonomously, controlled by a Raspberry Pi computer module. Remote communication is enabled by a Teltonika Router RUT956 and a Poynting XPOL-2-5G uni-directional LTE antenna. Both stations are equipped with Lead Crystal 12V batteries, which are powered by solar panels. Station 2 is additionally powered by a Stormy Wings 400W wind turbine, because its location is in a north facing slope, which has very limited direct sunlight during the winter months.

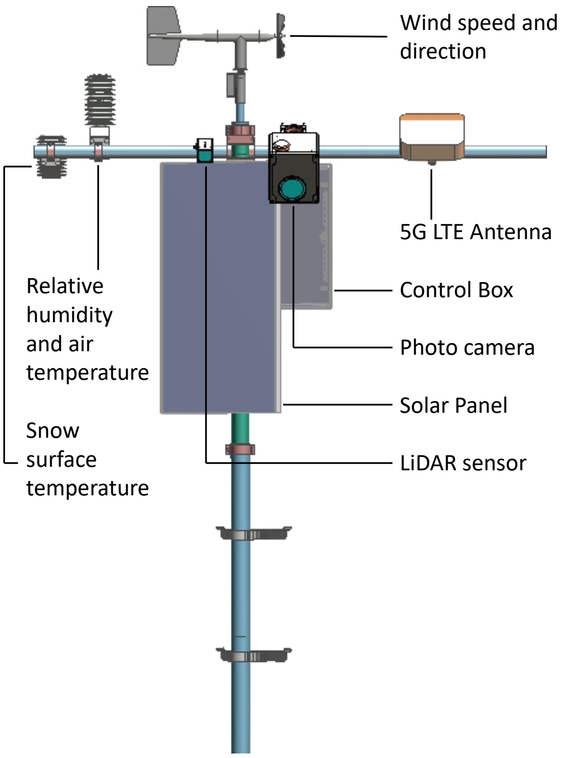

Figure 4: Visualization of the planned station setup.

3.4 Challenges

The setup certainly presents major challenges. The first and biggest one is the setup geometry. The sensors are mounted in the same slope as the avalanche release area, which results in very large angles of incidence (angle between the surface normal and the incident light vector) for the LiDAR sensors. This causes several restrictions: The scattering behaviour is mainly forward, and there is not much back scattering, meaning only little signal is returning to the scanner, which gets even worse with larger distances. The large incidence angle also causes large footprints of the LiDAR scanner signal and large areas per pixel on the photo camera. This causes a smoothing of the resulting surface, since a larger area is averaged at one data point. With the installation being in the same slope as the region of interest, the spatial coverage also gets limited due to the line of sight visibility. The irregularities in the slope cause shadowing and result in areas that can not be acquired from the selected points of view.

Second, the changing weather conditions at the study site bring further constraints. The temporal coverage can be limited during fog, precipitation, or periods with wind-driven snow redistributions. However, the shorter measuring ranges can also be an advantage here compared to e.g. airborne acquisitions, which often have to cover greater distances. The ground-based, autonomous approach is also advantageous here, as short windows of suitable weather can be used with little lead time, which would not be possible for example with a UAV that has to get to the site and return during appropriate weather conditions.

Another challenge is the accessibility in winter, especially at the lower station (see Figure 1). If any (technical) problems occur, it can take days or weeks until the conditions allow a station visit and on site maintenance work.

Despite these challenges we think that the setup will deliver meaningful data. After the first winter we will have the chance to optimize the system based on the experience we gathered.

4. LIDAR SENSOR TESTING

To gain first experience with the Livox sensor we conducted test scans on 7th July 2023 at the end of Dischma valley, at the foot of Piz Grialetsch (due to the snow conditions in July about 10 km away from the main study site). We measured two large snow patches from different viewpoints. Target of the tests was to examine the capabilities of the Livox Avia to measure the snow surface, focusing on the achievable distances and areal coverage with high angles of incidence.

4.1 Experiment setup

We mounted the Livox Avia sensor on a photo tripod, fixed with a clamp and powered by a 12 V 14 Ah battery (see figure 5). As a reference, we acquired a digital surface model using airborne photogrammetry with a Phantom 4 RTK Quadrocopter and a 20 MP DJI camera. Figure 6 shows the acquired orthophotos of the test site. The Livox Avia was controlled using the software Livox Viewer 0.11.0 on a Laptop. For each scan we used an integration time of 20 seconds, recording single returns of the emitted signal.

Figure 5: Setup of the Livox Avia sensor between the snow fields, looking towards snow field 1

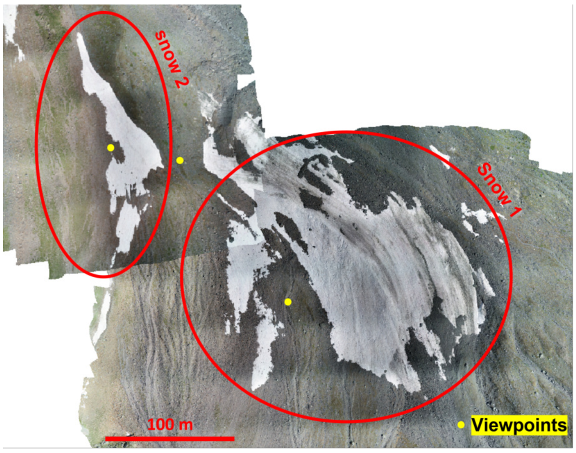

Figure 6: Acquired drone orthophotos of the test site at Grialetsch, giving an overview of the two snow fields and three different viewpoints

4.2 Experiment results and discussion

In figure 7 the resulting point cloud of a 20 second scan is depicted, with the colormap representing the angles of incidence. As expected, the spatial resolution and coverage is high in the vicinity of the viewpoint and decreases with the measured distance. The farthest measured distances are about 186 m, where a small snowfield had an edge facing towards the sensor, resulting in very steep angles of incidence. According to the specification sheet, the Livox Avia sensor has a maximum detection range of 450 m. This range was not achieved in the test scans with the given geometric configuration. This is likely due to the high angles of incidence and to the specific snow conditions.

The setup geometry at the experiment site was similar to the planned main study site at Brämabüel. However, the prevailing snow conditions were unfavourable for the LiDAR measurements. On the one hand the snow was already old, which means that it was already completely metamorphosed and the grains were large. Larger grain sizes lead to less albedo, due to more absorption and forward scattering of the signal (Wiscombe & Warren, 1980). On the other hand the warm temperatures caused the snow to melt and produce a water film on the surface, which also means more forward scattering.

Conditions as described for our first tests above, will most likely only prevail at the end of the winter season. During most of the measurement period we expect the conditions to be more favourable. Fresh snow has smaller grain sizes and significantly better scattering properties. In the final setup, we will also take measurements at night, this also improves the scattering properties as there is little or no ambient light. Nevertheless, the initial tests demonstrated the capabilities of the Livox Avia sensor under difficult conditions, giving an important baseline to build on.

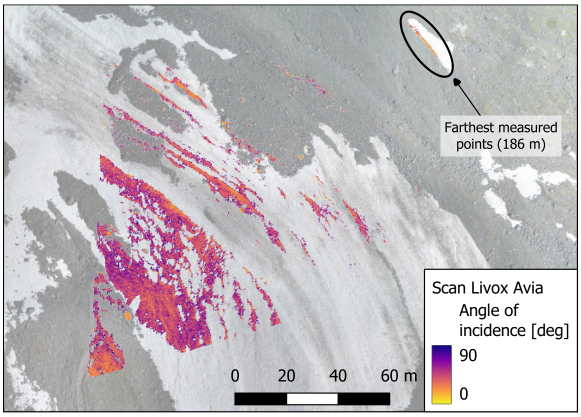

Figure 7: Test scan of the Livox Avia sensor, with the additionally acquired Orthophoto in the background. Encircled in black are the farthest measured points at 186 m from the viewpoint.

5. CONCLUSION AND OUTLOOK

This paper presents the concept of a measurement installation that will acquire snow depth data with high spatial and temporal resolution in an avalanche release area. The main sensor of the setup, a Livox Avia LiDAR sensor was not used in comparable conditions before, therefore we conducted first test scans in the vicinity of the study area. At the time of the experiment the snow conditions were unfavourable for the LiDAR sensor, so that the full potential could not be explored. In the actual measurement period the snow properties will mostly be different, where we expect a better performance. The modular design of the measurement setup also allows stepwise adjustments and improvements with new sensors that come onto the market.

Two stations with the presented design will be installed in autumn 2023 close to the Ski resort Jakobshorn in Davos, Switzerland and are planned to operate for 3 consecutive winter seasons. The main use case is the improvement of a data-driven decision basis for practitioners that are responsible for road safety. The new avalanche release test site fosters the collaboration with other groups and the newly acquired snow depth database will be useful across disciplines. Together with the additionally recorded meteorological parameters it forms the basis for various modelling and simulation approaches that enable further progress in alpine hazard prevention.

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