CABLE CAR-MOUNTED LIDAR SYSTEM FOR CONTINUOUS SNOW DEPTH ASSESSMENT

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ABSTRACT: This paper presents a novel approach for continuous snow depth assessment using lidar system mounted on a cable car. Traditional methods for measuring snowpack characteristics in mountainous regions are often limited by high costs, manual labor, and inadequate spatial coverage. By integrating lidar technology with existing cable car infrastructure, we enhance the spatial and temporal monitoring of snow depth, providing high-resolution data crucial for avalanche risk assessment and climatological studies. Our setup combines moving sensors on cable cars, snowmobiles, piste machines, and static-mounted sensors to cover extensive areas like entire mountain slopes. The system collects data to create both reference and current point clouds, which are then processed using Simultaneous Localization and Mapping (SLAM) algorithms, quality control, and georeferencing. The backend system performs these calculations and stores the data in a PostGIS database with the pgPointcloud extension. A user-facing frontend presents the data as maps and statistics, and triggers alerts and messages as needed. Initial results demonstrate the system's effectiveness in generating high-resolution 3D point clouds with centimeter-level precision, offering a significant advancement in snow monitoring technologies. The integration of real-time data collection and processing enhances early warning systems for avalanches and improves the accuracy of avalanche forecasting models. This study underscores the potential of using lidar technology in enhancing the safety and reliability of snow monitoring in mountainous regions.

Keywords: lidar, gondola, SLAM, cable car, snow-monitoring

1. INTRODUCTION

Understanding snowpack characteristics in mountain regions is vital for evaluating avalanche hazards, among other climatological and ecological impacts (Deems et al., 2013, e.g.). Snowpack dynamics, influenced by factors like snowfall, wind, terrain, and vegetation, pose significant challenges for accurate measurements. Traditional manual assessments of snow depth are costly and disruptive and mostly point-specific observations, which are inadequate in capturing the variability inherent in snow depth across diverse terrains (Bühler et al., 2015).
Lidar technology, capable of high-resolution spatial data acquisition, enhances our ability to monitor snow depth by comparing datasets from snow-covered and snow-free conditions.
To analyze the changes in snow cover over time, it's essential to begin with a snow-free dataset and conduct further surveys during periods of snowfall. Recently, there has been a trend toward using costly terrestrial laser scanners (TLS) (Prokop, 2008, e.g.), which are semi-permanent and can exceed € 150,000 in price due to necessary additional housing and power solutions (Voordendag et al., 2022, 2023). Alternatively, portable, short-range lidars provide more flexibility (Kapper et al., 2023; RSnowAUT-Konsortium, 2023; Ruttner-Jansen et al., 2024), and unmanned aerial systems (UAS) can capture high-resolution data across extensive areas. Nevertheless, the use of UAS is constrained by weather conditions, limited battery life, regulatory restrictions, and the requirement for proficient operators.
In a recently submitted draft to the Journal of Glaciology (Dikic et al., 2024), we focused on accuracy assessment and comparison to conventional laser scanners and Structure from motion (SfM). This showed the general feasibility of the approach and associated challenges. Here, we focus on how cable car mounted lidar, Inertial Measurement Unit (IMU) together with Simultaneous Localization And Mapping (SLAM) in connection with static lidar sensors could be used to cover whole mountain slopes.

2. MAIN SETUP

The primary setup is illustrated in Figure 1. A sensor unit can be installed on various moving parts of a lift, such as gondolas, chairs, or any other suitable components, to consistently and repeatedly measure the three-dimensional position of the snow surface. The sensor unit mainly comprises a Light Detection

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and Ranging (lidar), an IMU, and optionally a Global Navigation Satellite System (GNSS) connected to a data logger and power supply. The GNSS is not always necessary, as satellite coverage can be unreliable in narrow mountain valleys (Kunisada and Premachandra, 2022). Ideally, the SLAM algorithm, along with Ground Control Points (GCPs), should suffice to georeference the point cloud. The lidar can either be a 360° rotating system or have a narrower field of view directed at the snow surface below. Automotive lidars feature frame rates of 10 to 20 Hz, which are essential for avoiding obstacles at speeds of 100 km/h or more. This high frame rate, combined with data from GNSS and IMU, is used to generate a high-resolution cumulative point cloud through a SLAM algorithm.

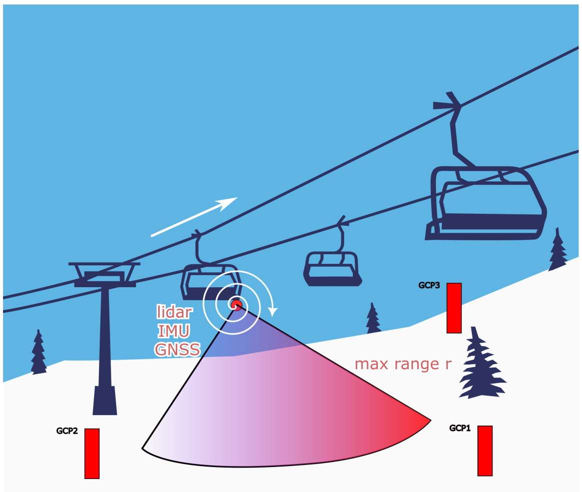

Figure 1: Concept of the setup, where GCPs stands for ground control point (modified from a draft submitted to the Journal of Glaciology Dikic et al. (2024)). A small rotating lidar (10 to 20Hz) is mounted on a gondola or chair. As the lift moves up and/or down, point cloud data is collected and then post-processed with a SLAM algorithm to produce a cumulative point cloud. Subsequently, the snow-free point cloud is subtracted to determine the snow depth.

Figure 2 shows the lidar unit mouted on our test setup on the gondola, up to Mount Sonnblick in Austria.

3. SETUP FOR A MOUNTAIN SLOPE

Depending on the type and manufacturer, a lidar can measure up to 500 meters in width. Therefore, multiple lidars are needed to cover a larger area, such as an entire mountain slope. This can involve a combination of moving sensors on cable cars, snowmobiles, piste machines, and static-mounted ones. To calculate snow deposition or absolute snow height, the following data is needed: a reference point cloud and a current point cloud.

The end user is interested in snow properties, not the raw point clouds. Therefore, an automated

Figure 2: MOLISENS system mounted on tho Sonnblick cable car (Goelles et al., 2022; Dikic et al., 2024)

setup is needed to collect data from multiple sensors, run SLAM, perform quality control, and conduct georeferencing. A backend system is required to perform these calculations and store the data in a database. A user-facing front-end then uses this data to present the results as maps and statistics, and potentially to trigger alerts and messages to other systems or human operators.

Figure 3 shows the basic concept of the architecture, while Figure 4 illustrates the processing pipeline of a single moving sensor. Once the sensor completes a round trip, the processing chain is triggered. After an initial quality check, the SLAM process starts to generate a point cloud along the entire track. SLAM algorithms perform best when the entire loop is closed, which is always the case with a ski lift. For the SLAM to work effectively, it needs features in the landscape that are always snow-free, such as reflectors on rock faces or lift poles. These must have precise geolocations associated with them for accurate georeferencing. After a final quality check, the point cloud with associated metadata is stored in a PostGIS (PostGIS Project Steering Committee and others, 2018) database with the pgPointcloud extension (pgpointcloud, 2024).

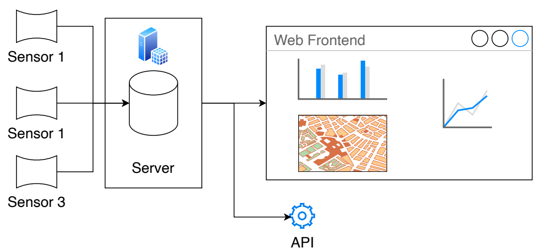

Figure 3: Architecture with mutliple sensors and the user facing frontend and an API for integration with other services.

Table 1: Example of PostGIS Point Cloud Storage with Metadata

ID *integer*	**Point Cloud** *pcpatch*	**Platform** *varchar*	**Timestamp** *timestamp*	**Position** *varchar*	**Sensor ID** *varchar*	**Quality** *int*
1	pointcloud	static	2024-01-17 10:12:55	Pole 2, Lift X	S456	85
2	pointcloud	gondola	2024-01-17 11:15:08	Lift Y, Gondola 34	S457	98
3	pointcloud	snowmobile	2024-01-17 12:57:10	GU3NBR	S458	52

Table 1 provides an example of how resulting point clouds are organized in the database. This structured storage allows for precise calculations of snow height and facilitates the generation of detailed maps and timely alerts.

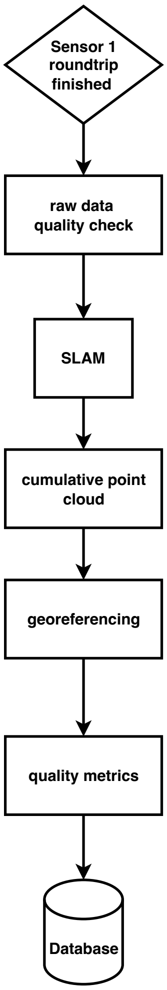

Figure 4: Processing pipeline of a moving lidar sensor.

4. FIRST RESULTS

The results of test case Dikic et al. (2024) demonstrated that our innovative approach of using lidar sensors mounted on cable cars for snow monitoring is highly effective. Our system successfully generated high-resolution 3D point clouds of the study area, providing precision within the centimeter range, with a mean error of -0.0002 meters and a standard deviation of 0.0328 meters. The precision of the measurements was confirmed by comparing multiple runs, which showed consistent repeatability. Accuracy assessments revealed some alignment challenges, particularly in snow-covered areas, where the mean errors ranged from 0.004 meters to -0.23 meters, and the standard deviation ranged from 0.33 meters to 0.57 meters. Despite these issues, the generated snow depth map provided a realistic depiction of snow distribution, with significant accumulations up to five meters in certain regions, especially at the base of the cliffs and inside the couloir. These findings confirm the potential of our method for continuous and accurate snow monitoring, though further refinements in the SLAM algorithm and sensor setup are needed to enhance overall accuracy and reduce noise.

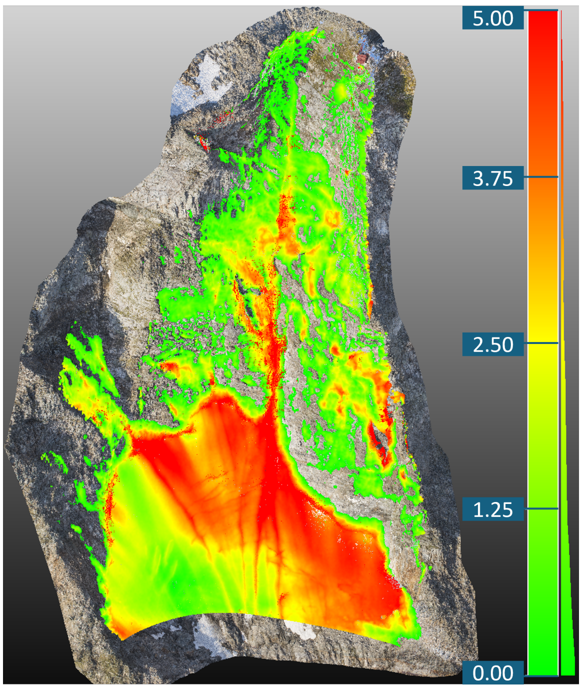

Figure 5: Snow depth in the summit couloir of Hoher Sonnblick in meters calculated by comparison of MOLISENS scan from March 21, 2023 and UAS data from August 23, 2023. The true color 3D point cloud in the background is the reference UAS data and the green to red colored 3D point cloud represents the calculated snow depth. Depths of up to 5 meters can be found at the base of the cliffs and inside the couloir. (from the draft submitted to the Journal of Glaciology Dikic et al. (2024))

5. REAL-TIME MONITORING AND EARLY WARNING SYSTEMS

The potential to continuously monitor snowpack conditions in real-time could greatly enhance the effectiveness of avalanche early warning systems. Data from lidar sensors could be integrated into predictive models that assess avalanche risk based on both current and forecasted snow and weather conditions. This integration could support the development of dynamic risk maps and alerts that might be disseminated to local authorities and the public.

For instance, data from continuous scanning could be employed to create detailed digital surface models Digital Surface Model (DSM) of the snowpack, which might be compared over time to detect areas of significant snow accumulation or erosion. These observed changes could then be correlated with meteorological data, such as wind speed and direction, to predict areas at high risk of avalanche release. As this data is collected in near real time, warnings could be issued with greater certainty and more lead time, potentially saving lives and reducing damage to infrastructure.

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