ENHANCING SLOPE MANAGEMENT THROUGH IoT SNOW MONITORING: A CASE STUDY IN FIEBERBRUNN, TYROL

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ABSTRACT: Climate change poses a significant challenge to ski resorts, requiring advanced slope management systems for optimal use of water and energy resources. Traditional management practices, which mainly focus on snowpack height measurements, fail to provide a comprehensive understanding of slope quality. This research presents a novel Internet of Things (IoT) system that aims to bridge this gap by providing detailed insights into snowpack conditions, thereby facilitating more informed slope maintenance decisions. The proposed system includes a sensor node and a gateway. The sensor node consists of a microcontroller and a set of environmental sensors. The microcontroller is housed in an additively manufactured package. The gateway consists of a single board computer equipped with a communication module and an antenna. This configuration allows for real-time collection and transmission of snowpack data based on a low-power communication protocol. Empirical results from the deployment of this system highlight its ability to continuously monitor the temperature of the snowpack at various depths, with measurements taken every 15 minutes. It was observed that the internal temperature of the snowpack remained stable at 0° Celsius, despite surface temperature fluctuations that closely followed ambient air temperatures. This stability within the snowpack suggests that the snow did not solidify as expected due to the limited duration of temperatures below 0°C and the wet condition of the snow, which indicates a stable internal temperature. The results underscore the importance of additional snowpack parameters (e.g., temperature) for assessing snowpack dynamics, adding an additional source of information to existing slope management systems. The IoT-based sensor system not only provides a novel approach to monitoring snowpack conditions, but also represents a scalable solution that could be expanded with additional sensors to measure other snowpack parameters (e.g., liquid water content). In conclusion, this research highlights the potential of IoT technology to enhance traditional slope management practices at ski resorts, providing a more nuanced understanding of snowpack dynamics that can lead to more effective and sustainable management strategies in the context of climate change.

Keywords: Internet of Things, Slope Management, Snowpack Parameters

1. INTRODUCTION

Artificial slope preparation is crucial for winter tourism, especially in regions with insufficient or unpredictable snowfall. It enhances the attractiveness and accessibility of ski resorts and supports local economies. However, artificial snow production has a significant environmental impact, consuming large amounts of water and energy, and requiring land for water reservoirs as described by Knowles et al. (2024). Climate change, resource scarcity, and energy crises exacerbate these challenges. In particular, climate change causes economic damage, especially for ski resorts at low altitudes as investigated by Scott and Steiger (2024).

Despite economical and climate aspects, the quality of the slope is also important in regard to customer satisfaction. In general, the quantitative determination of the ski slope quality is challenging, as the quality is a subjective impression of the skiing experience. However, general guidelines regarding requirements of a ski slope have been developed and can be addressed for achieving a high quality slope for satisfying user needs as shwon in Wolfsperger et al. (2019).

Current slope maintenance approaches use meteorological data and spatial snow depth measurements to develop a appropriate slope management strategy. Internal snowpack parameters are not fully implemented in public slope management systems yet. However, the benefit of additional snowpack parameters is already established in the preparation of race slopes. Thus, insights into the snowpack might also benefit public slopes.

The gathering of internal snowpack parameters requires sensor devices which are able to assess those. In addition, such a system should also allow scalability to cover wide areas of ski resorts.

Different sensors for snowpack analysis are available and can deliver relevant parameters. These systems can measure snow hardness (e.g. Snow Micro Pen (Schneebeli and Jaggi), Fast Snow Deformer, snow density (e.g. Denothmeter (Universität Innsbruck (07.03.2019))), and snow moisture (e.g. Denothmeter (Universität Innsbruck (07.03.2019)),

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Steinbach Alpin snow measuring device). Another system was developed by Le Breton et al. (2023) which uses RFID signals to measure the snow water equivalent at different heights within the snowpack.
Beside the sensing devices, the transmission of measurement data is also important regarding real-time monitoring of snowpack dynamics. Several wireless sensor networks have been used to study different dynamics of e.g. glaciers. Wireless sensor network approaches enable data transmission over long distances and complement traditional measurement methods. Similar systems have been successfully used in glaciology to provide valuable insights and early warnings for glacier movement and potential disasters. Researchers such as Dong et al. (2023) and Wang et al. (2022) have demonstrated that such technologies can improve the monitoring and understanding of glacier movements by supplementing established observation methods such as satellites with IoT networks.
While significant advancements have been made in snow monitoring technologies, there remains a notable gap in the implementation of wireless sensor networks capable of remotely and autonomously assessing snowpack parameters.
The aim of this study is to develop and evaluate wireless sensor system for real-time assessment of snowpack parameters in a ski resort. Although previous studies have laid the foundation for snow monitoring, this work takes a transformative step by establishing a fully functional wireless sensor network for remote snowpack assessment. The objective of this study is to overcome this limitation by engineering and field-testing an innovative wireless sensor network for remote snowpack analysis.

2. MATERIALS AND METHODS

2.1 System Architecture

The wireless sensor network consists of a sensing unit and a gateway. The communication between sensing unit and gateway is achieved by the long range wide area network (LoRaWAN) communication protocol. The sensing unit was placed at the ski slope whereas the gateway was placed at a lift station.
The sensing unit measured snowpack temperatures at two different positions (surface temperature and internal temperature), ambient temperature, and ambient relative humidity. The snowpack sensors were placed either at the surface of the snowpack (loosely covered by snow to avoid direct exposure to sunlight) and at a depth of at least 30 cm within the snowpack. The sensor for ambient air parameters was mounted on a wooden rod approximately 30 cm above the snowpack surface. The measured data from the sensing unit was transmitted to the gateway and locally stored in a database (InfluxDB).

2.2 Sensing Unit

The sensing unit consists of a microcontroller (HTCC-AB01 v2; HelTec AutoMation) with an integrated LoRa node chip for communication. Energy supply was realized by a 3000 mAh lithium ploymer battery (Makerfocus). For measuring the temperature of the snowpack, two waterproof temperature sensors (DS18B20; Adafruit) with an accuracy of ±0.5 °Celsius were used. The data transmission between snowpack temperature sensor and microcontroller was implemented by the 1-wire protocol. Ambient temperature and relative humidity were measured by a DHT22 (2302B; Ruizhi) sensor. All parameters were measured every 15 min and transmitted to the gateway via LoRaWAN. The module was placed within an additively manufactured housing. The housing material was acrylonitrile styrene acrylate (DuraPro ASA Natur; Extrudr).

2.3 Gateway

The gateway consists of a Raspberry Pi 4 Model B equipped with a LoRa contentrator module (RAK2287; RAKwireless). The power supply to the gateway was achieved by connecting the system to a standard socket outlet. To increase the link budget of the LoRaWAN communication module, an external fiber glass antenna (RAKwireless) was used. The communication software ChirpStack (v3) was used to manage the connected sensing units. In addition, ChirpStack enabled data storage in a local database (InfluxDB). Beside sensor data, parameters of data transmission were stored as well including received signal strength indicator (rssi), signal-to-noise ratio (snr), and transmission frequencies.

2.4 Field Test

The ski resort Fieberbrunn (Tyrol) is located between the Kitzbühler alps and the Loferer and Leoganger Steinberge and was selected as the test area. The altitude within the ski resort ranges between 790 m and 2020 m above sea level. Two distinct positions for the sensing unit were defined: south-facing slope (latitude: 47.4174; longitude: 12.5665; altitude: 1080) and a north-facing slope (latitude: 47.4170; longitude: 12.5795; altitude: 1306).

2.5 Data Analysis

Measurement parameters were stored in a open-source timeseries database (InfluxDB). Data import, cleaning, and analysis were done with Python using the libraries NumPy, Pandas, and Matplotlib. Data cleaning included adjustment of date-time information (time shift due to lack of communication to the internet), removal of outliers (sensor failure for ambient temperature measurement at temperatures lower than 0 °C), and selection of data according to the sensor position. Temperature data were

smoothed by applying a rolling mean with a window size of 10. Subsequently, data from in snow gun integrated weather stations close by to the sensor position was also included into the analysis.

3. SELECTION OF SNOWPACK PARAMETERS

Prior to the implementation of the prototype, it was crucial to select essential parameters. These parameters should be accessible by available sensors and should provide an insight into the dynamic behaviour of the snowpack. At first it is crucial to understand important factors determining skislope behaviour: Ambient air and snow temperature significantly affect internal processes e.g. sintering of the snow. In the case of temperature gradients and their nature (positive or negative), internal processes are triggered and influence the snowpack structure. Humidity influences sublimation and evaporation processes at the snow surface. Dry air enhances sublimation and evaporation, cooling the snow surface, while high humidity can result in frost or dew formation, warming it. Humidity also indirectly affects the snowpack by altering radiation dynamics. Solar Radiation plays a critical role in the thermal balance of the snow surface. Shortwave radiation from the sun can be either reflected or absorbed, depending on the snow's surface properties. Longwave radiation is almost entirely absorbed by the snow, leading to warming. Cloud cover also affects radiation by reflecting longwave radiation back to the snow surface, increasing its temperature. Wind can accelerate thermal exchange between air and snow. Strong winds quickly align snow temperature with air temperature, which can lead to rapid snowmelt under warm conditions. In contrast, weak winds result in slower temperature changes, allowing radiation and precipitation to have a more significant impact on snow conditions. Precipitation directly modifies snow quantity and quality. Snowfall increases the snowpack depth and can enhance snow quality, while rain reduces snowpack depth and softens the snow surface, potentially leading to a slushy consistency. The properties of the snow surface influence the amount of radiation absorbed or reflected. Fresh snow typically reflects more shortwave radiation, whereas older or compacted snow layers absorb more, affecting its temperature and consistency. Snow Density and microstructure are critical to the mechanical properties of snow. High-density snow with a well-bonded microstructure is more resistant to deformation, while low-density snow is more prone to compaction and other changes under stress. Altitude and Geographical Location affect the intensity of UV radiation and overall solar exposure. Higher altitudes and southern latitudes experience greater radiation intensity, significantly impacting snow conditions due to increased energy input. These factors interact dynamically, influencing the thermal and mechanical properties of snow. Understanding these interactions is essential for effective piste preparation and maintenance, ensuring both safety and quality for winter sports enthusiasts Wolfsperger et al. (2019).

To observe these processes, it is necessary to measure relevant parameters. According to Wolfsperger et al. (2019) the most important snow measurements for slope's preparation are temperature, density, wetness (liquid water content), structure, and mechanical properties. Sensors for measuring these parameters are available and are used. On the premise that the sensor should be integrated in a fully autonomous sensor network, the parameters temperature, density, and wetness are well suited. The measurement of the structure requires properly optical sensors and a system to provide snow samples. The effort to implement this process in a IoT-based systems were evaluated as not implementable at the moment. The same applies to the determination of mechanical properties.

Finally, the temperature was selected as parameter to be addressed in the course of the prototypical implementation. Consequently, a temperature gradient ranging from ambient air over the snow surface to the internal snowpack temperature was chosen to be measured by the system. Temperature sensors for assessing snow temperature are available and relatively cheap, thus, this approach is also scalable for larger monitoring areas.

4. RESULTS AND DISCUSSION

4.1 Installation of IoT-system

The installation of the IoT system, consisting of a sensor and a gateway, was achieved without major problems. The sensor was placed on the surface of the snowpack as shwon in figure 1. This was necessary because of the antenna for data transmission. The antenna was placed inside of the sensor housing, thus, a placement of the housing within the snowpack might raised data transmission issues due to the damping effects of snow itself. In addition, the housing had to be fixed to avoid displacement on the slope due to the mild weather resulting in melting of the snowpack. Fixation was done using a wooden pole that was additionally used to mount the ambient air sensor. A placement of a sensor on the slope surface requires additional safety measures to avoid any danger for skiers. To reduce the risk further, the sensor was placed at the slope edge.

The installation of the gateway was done at lift stations which are quite easily reachable and well equipped in terms of power supply. The additional antenna at the gateway enhanced data transmission. Depending on the ski resort, lift stations might also be equipped with internet access, which enables access to the gateway remotely. In addition,



Figure 1: Sensor placed on the test side consisting of sensor housing (microcontroller, battery, and antenna), ambient air sensor (air temperature, relative humidity), and snowpack temperature sensors (not shown)

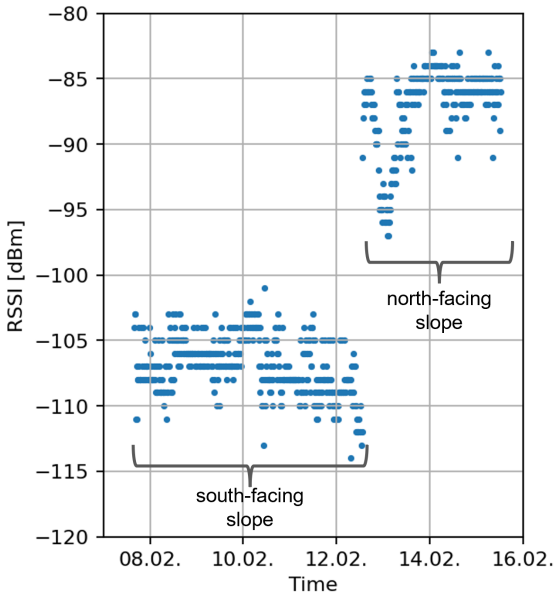

Figure 2: Relative signal strength indicator (rssi) of both setups (south-facing slope, and north-facing slope

an internet connection enables the transmission of data to the cloud.

4.2 Data transmission

Data transmission between sensor and gateway was stable throughout the experiment. The selected protocol exhibited solid coverage in combination with a low energy consumption. However, data transmission requires the sensor to be in line of sight to the gateway. For slopes with changing exposures, a direct link to the gateway might be challenging. However, additional repeaters or placing of the gateway on the opposite slope might solve this issue.

The relative signal strength indicator (rssi) might also be informative to estimate the distance between sensor and gateway. As shown in figure 2, the rssi was different for both positions. In case of the south-facing slope, the distance between sensor and gateway was approximately 125 m, whereas the distance between sensor and gateway for the north-facing slope was approximately 95 m. In general, a lower rssi may be caused also by a greater distance between gateway and sensor and vice versa. However, additional effects e.g. signal damping by obstacles might also influence the rssi.

4.3 Temperature gradient

The sensor measured the ambient temperature and the relative humidity. Two additional temperature sensors measured the snowpack temperature, at the surface and within the snowpack. The three temperature readings together represent a temperature gradient starting from the ambient air, followed by the snowpack surface, and ending inside the snowpack.

As shown in figure 3, the temperature of the ambient air exhibited a time-dependent behaviour. During night time, the temperature decreased, whereas during day time, the air temperature reached a maximum. The temperature of the snowpack surface remained nearly stable. However, an temperature increase was measured during day time. The peak was at the same time as the peak of the air temperature. The internal snowpack temperature remained constant at 0° C throughout the measurement period. The value of the relative humidity was inversely proportional to the air temperature.

The constant internal snowpack temperature might indicate wet snow conditions. As known from the literature, wet snow exhibits a constant temperature of 0° C. Thus the positive temperature gradient between snowpack and ambient air causes melting of the snowpack which was also confirmed by snowpack height measurements (data not shown).

The data for the north-facing slope is shown in figure 4. The sensor for the ambient air temperature failed to measure negative temperature. However as confirmed by measurement from a weather station nearby, the temperature dropped below 0° Celsius which is visible as a gap in figure 4. It can also be seen, that the surface temperature decreased below 0° C. However, the internal snowpack temperature remained constant at 0° C. Although the temperature gradient became negative, the dura-

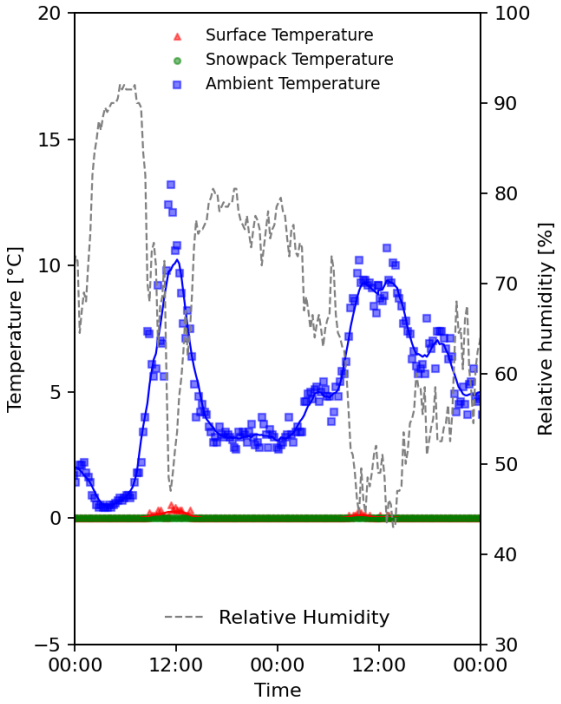

Figure 3: Temperature and relative humidity of ambient air measured at the south-facing slope

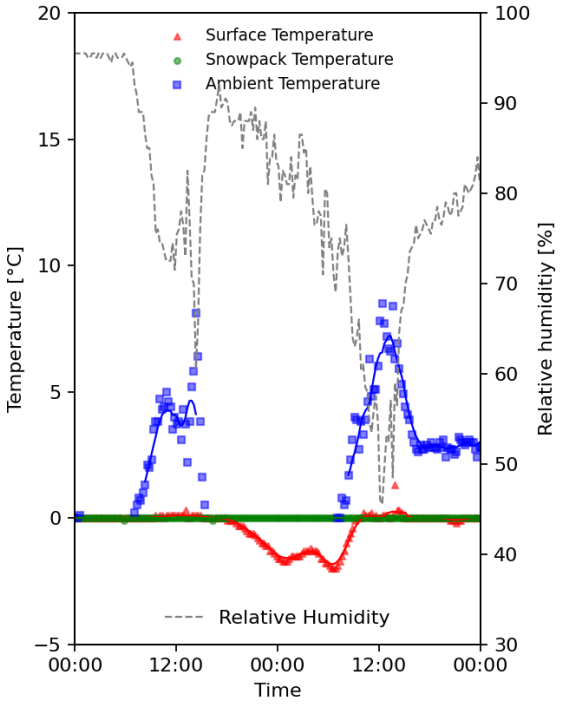

Figure 4: Temperature and relative humidity of ambient air measured at the north-facing slope

tion was not sufficient to foster freezing withing the snowpack. It might be, that the snowpack remained wet. Thus, sintering has not occurred.

5. CONCLUSION

The study implemented an IoT system for accessing snowpack parameters with focus on temperature gradient measurement. Two distinct positions on two different slopes (north-facing and south-facing) were selected as test areas. The system was able to measure continuously snowpack parameters throughout the test period. Temperature gradient assessment enabled a basic insight into the behaviour of the snowpack. Although temperature is quite well accessible by established sensors, it might be not sufficient to fully characterise the snowpack. As an example, the liquid water content is an additional and quite important parameter. It is also important to collect, link and evaluate other key values such as light irradiation and UV intensity in a centralised manner, taking into account their context. In conclusion, the assessment of snowpack parameters can be integrated into a digital twin of the ski slope, which would include simulation models and additional data sources, such as weather forecasts. The digital twin may facilitate more accurate forecasting of snowpack behaviour. Based on the aforementioned information, it may be feasible to optimise the preparation of the skislope even further. The study demonstrated that an IoT system can be established and is capable of providing valuable data about the snowpack. Furthermore, the type of sensor connected to the microcontroller can be adapted, allowing the integration of available sensors for snowpack characterisation into the IoT system. In conclusion, the implementation of an IoT system for characterising ski slopes is a viable approach that could enhance and expand existing skislope management systems.

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