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AvaRange – Using Sensor Network Ranging Techniques to Explore the Dynamics of Avalanches

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Abstract—**Snow avalanches are an ever-present reality in alpine regions – They can cause heavy damage to settlements and infrastructure. Thus, understanding the behavior and the dynamics of avalanches is an important challenge. Current modeling and simulation techniques of avalanche dynamics do not yet consider a precise description of the inner dynamics. In this paper, we present AvaRange, a measurement based approach towards a better understanding of these dynamics. AvaRange adapts ranging techniques that we successfully applied to sensor networks to track particles that move with the avalanche. In particular, we place sensor nodes in rugged spheres and deploy them in an avalanche slope. The idea is that after triggering the avalanche, the sensor nodes collect ranging data to determine their relative position. We present first results of ranging techniques in snow fields from a series of experiments that confirm the feasibility of our approach.**

I. INTRODUCTION

To protect alpine regions and their infrastructure, surveyors and scientists have to rely on snow avalanche models to predict and simulate the avalanche flow. One method to test and optimize these models are post-event calculations of known events. Here, basic *a posteriori* measurable avalanche properties are reproduced, such as run out lengths or deposition volume. With a better knowledge of the inner dynamics of snow avalanches, existing models could be improved significantly both in accuracy and reliability. Due to technical constraints, measurements of pressures, velocities, depths, or other flow details throughout the avalanche descent are rarely performed.

Two general techniques can be distinguished: Invasive techniques, where measurement devices are placed at fixed positions in the avalanche path and provide valuable data when the avalanche interacts with the measurement device; and non-invasive technologies, where the devices are placed outside the avalanche path and measure with a signal reflected by the avalanche (e.g., using radar or video analysis). However, the availability of measurement data from the interior of an avalanche body throughout the avalanche descent is limited.

Our idea is to introduce artificial particles of similar size and density to lumps of snow into an avalanche and reconstruct the trajectory of those particles assuming they follow the normal movements that occur in an avalanche. First field experiments with spheres containing gyroscopes, magnetometers, and accelerometers led to promising results [1]. The evaluation of the data and reconstruction of trajectories proved to be difficult due to the high forces that work in an avalanche. Thus, the need arose for different methods to reproduce the inner dynamics of avalanches and help to validate and correct the data gathered from inertial sensors.

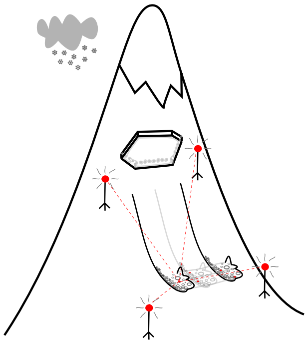

Figure 1. Sketch of the application scenario

A conceptually similar approach has been described by Vilajosana et al. [2]. They use a TelosB sensor node equipped with a 2D accelerometer in combination with video recording and tested the system in a small scale artificial snow chute. The conclusion was that the electronics and sensors are basically suited for small scale measurements.

We aim going one step further. Our idea is to use wireless sensor nodes and place them into custom-made 3D-printed spheres that move with an artificially triggered avalanche. This scenario is sketched in Figure 1. The moving nodes communicate with fixed sensor nodes (so-called anchors) outside the avalanche, allowing to estimate the distance between the moving node and the anchors using radio based ranging techniques. Using a large enough set of ranging data, a 3D trajectory of the moving node can be reconstructed – which is then further fed into the mathematical modeling process of avalanche dynamics. Our prototype is shown in Figure 2.[1]

In this paper, we focus on establishing ranging techniques to be used in snow. In a set of experiments, we experimented with Received Signal Strength (RSS)-based and Time of Arrival (ToA)-based solutions. As can be seen from the presented

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[1] Please also check our concept video at https://youtu.be/XXcZI-OkbpE

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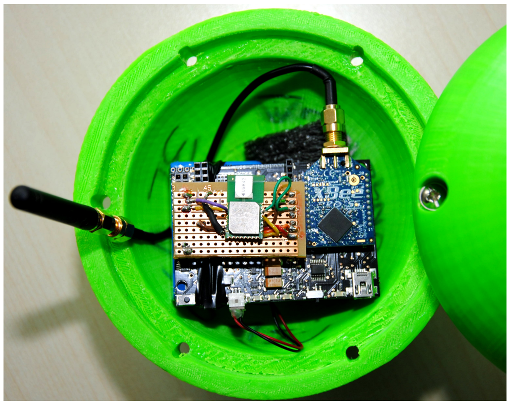

Figure 2. Sample of our 3D-printed spheres with the Waspmote sensor node, ranging module, and radio attached

results, the combination of the different techniques can help to reduce noise and measurement errors.

II. General Concept and Technical Approach

There are several methods to estimate the distance between two objects. For outdoor locations usually (assisted) GPS is used, but it does not work under snow. So we have to adapt techniques that are usually used indoors or in rather static scenarios [3]–[6].

Considering RF-based methods, the following techniques could be used: RSS-based measurements exploit the fact that an emitted radio signal fades over distance and, thus, is weaker the longer it travels. ToA-based systems measure the time it takes for a radio signal to travel to the receiver (and possibly back). If a highly accurate time base can be maintained, phase based ranging could be considered. These techniques can further be combined with statistical models for handling uncertainties and measurement errors.

The application scenario poses a number of technological challenges that need to be taken care of:

- The time of deployment plus the intervals between deployment and triggering of the avalanche plus the time to recover the devices demand low energy consumption.
- The devices must be able to withstand the forces that arise during a descent of an avalanche without affecting the measurement.
- The measurement technique must function in an element as diverse (in terms of density, reflection properties, etc.) as snow.
- To allow to reproduce the trajectory as precise as possible, the measurement frequency (at least 10 Hz) and accuracy must be quite high (sub-meter).
- Because the used spheres must correspond to the density and possible sizes of snow particles, the internal space to carry electronic devices is restricted.

Wireless sensor network based solutions using RSS or ToA measurements are appropriate candidates for ranging and calculating 3D trajectories. Before evaluating the two methods, we conducted a general study to evaluate signal propagation in snow. Until now, most publications, e.g., [7], [8], only cared about radio frequencies for the assessment of glacier quality and, thus, are of little use for our purposes.

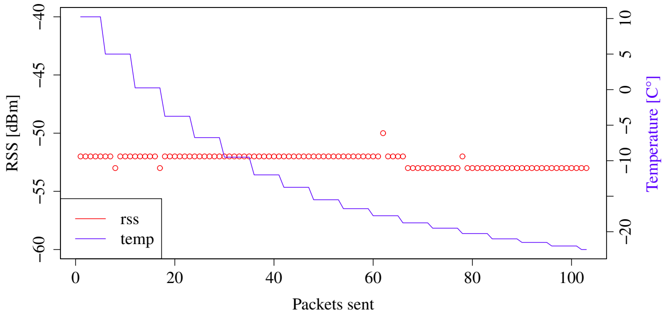

Figure 3. RSS at sub-zero temperatures

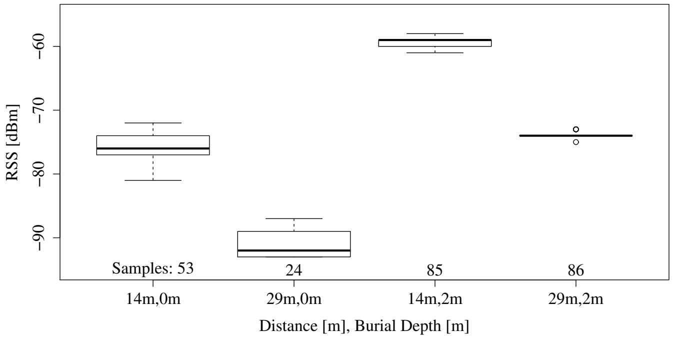

Figure 4. Measurement results in the 2.4 GHz band

In a first experiment, we exposed the sender to very cold temperatures and measured the emitted signal strength at the receiver to evaluate the influence of cold environments. As Figure 3 shows, even at −25 °C there was no significant impact on the RSS or the performance of the devices. It was not the scope of this test to measure the influence on battery life.

In the next experiments, we measured the RSS at 2.4 GHz and 868 MHz. The hardware used for all experiments was the Waspmote sensor node platform[2] and corresponding XBee Pro[3] radio modules. The experiment location was a snow field at an altitude of about 3000 m. We repeated the experiment at different depths in the snow.

The results show that with a sending power of 15 mW at (2.4 GHz) and 1 mW (868 MHz) communication was possible over a distance of 29 m even when sender and receiver where covered with 2 m of snow. Only when the radios where on top of the snow cover at a distance of 29 m we had notable packet loss. Surprisingly, this was not the case when both radios were covered by 2 m of snow. The RSS was even higher below the snow cover (see the boxplots[4] in Figure 4). A look at the snow profile showed that there was a very hard layer of snow at a depth of 1 m. Very likely the higher signal strength resulted from a *channel effect* caused by the radio waves reflecting

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[2] http://www.libelium.com/products/waspmote/

[3] http://www.digi.com/lp/xbee/

[4] A boxplot shows the statistical evaluation of the results. The box contains 50% of the measurement data, the bar denotes the median, the whiskers show extreme values and extend to a maximum of 1.5 times the box length, outliers shown as dots.

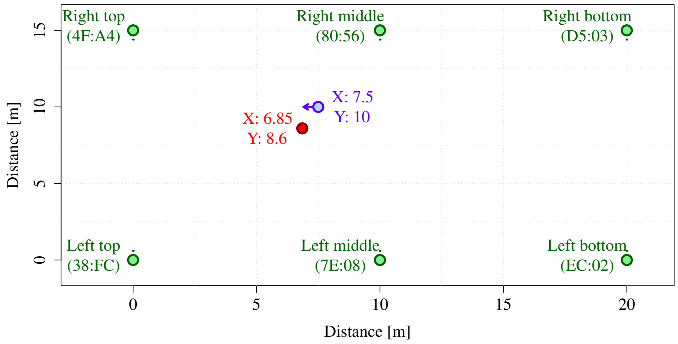

Figure 5. Scenario (transposed) of the RSS-based experiments: The two dots in the middle denote the real position and the estimated position of a sensor node.

between the ground at 2 m and the hard snow layer at 1 m of depth. This means that the radio wave propagation in avalanches is harder to predict than in a homogeneous snow cover because of the complete lack of continuous layers and the irregular density in avalanches.

III. RSS-BASED RANGING EXPERIMENTS

To evaluate which of the above described two ranging techniques is suited better for our application, we conducted several experiments with the above mentioned hardware again on and in snow. In these tests, we placed six anchor sensor nodes at predefined positions at the border of a field (on top of the snow cover and buried) of 15 m per 20 m (see Figure 5).

We placed three spheres containing sensor nodes (each having a different antenna orientation) at different positions inside the field and measured the ground truth using a meter. The anchors were configured to continuously send messages containing the sender ID and the used transmit power. As anchors we used TelosB[5] sensor nodes. The receiving sensor node (here, we used Waspmotes), saved these messages plus the RSS. Knowing the position of each anchor and the RSS as well as the transmit power a calculation of the exact location of the sensor node should be possible.

The RSS is well known not to provide accurate measurements [5], [6]. A baseline was to use just the transmit power as an indicator. We continuously increased the transmit power in the hope that packets with a low TX power would be received only in the immediate vicinity of the sender while packets with a higher TX power would be received by nodes with a higher distance. But as Figure 6 shows, with the lowest TX power (1) only one packet over the whole experiment was received, while packets with more TX power (3-10) where received over the whole test field. The next approach was to use the RSS of packets with the same TX power to estimate the distance. Again, Figure 6 shows this is not feasible. For instance, at 15 m the avg. RSS is always lower than at 21.5 m. This resembles the Two-Ray Interference effect [9].

The above results show that one factor (RSS, number of messages received from different anchors, transmit power) alone is not enough to give a satisfactory result. Thus, we continued by combining these factors. To calculate the influence of the single factors, we adapted the *Weighted Centroid Localization* algorithm [10]. Here, the position is estimated according to the weights of the single factors and position of the anchor the packet comes from. The results were considerably better and often in the range of 1 m to 3 m (see Figure 7). However, in the worst case we observed localization errors as high as 9 m. As the packet rate of all devices was quite high, these outliers are very likely the result of positive interference of signals. It might be possible to work on interference mitigation techniques, yet, in the final experiments the dynamics of the avalanche need to be reported as fine grained as possible and lower sampling rates are not possible. These results urge for a solution with higher accuracy.

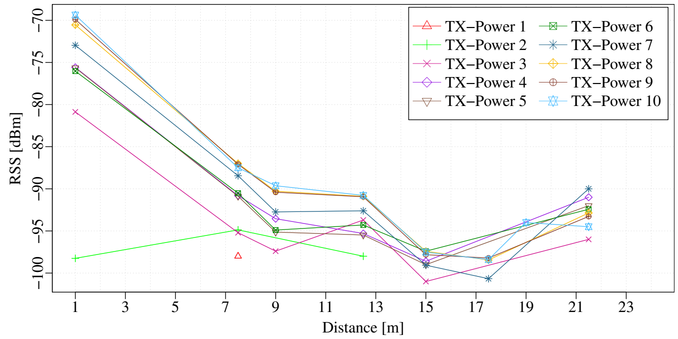

Figure 6. The mean RSS over distance for different TX powers

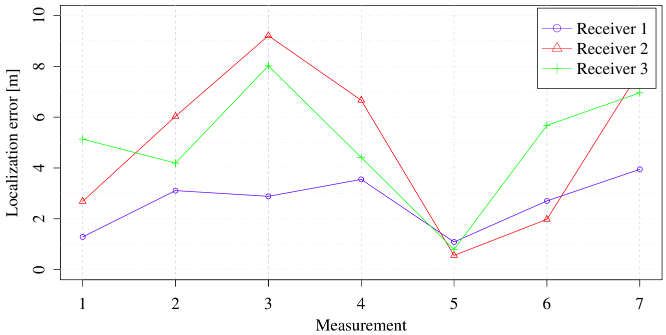

Figure 7. Localization error of RSS based experiments. The difference between receivers is caused by different receiving antenna orientations.

IV. TOA-BASED RANGING EXPERIMENTS

To assess the suitability of ToA-based methods, we had to switch the radio component of our appliances as it is not possible to accurately measure the time of arrival of network frames without dedicated hardware. Furthermore, we wanted to mitigate multipath effects [11] and benefit from direct Line of Sight (LOS) paths when doing ranging measurements. Thus, the decision was made to use the IEEE 802.15.4a standard [12] that defines a physical layer for Impulse Radio Ultra Wideband (UWB), which is compelling for ranging experiments. There are only very few manufacturers that implement this standard in dedicated radio chips. Because of the small dimensions, the existing library, and the costs, our choice was a Decawave

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[5] http://www.memsic.com/wireless-sensor-networks/TPR2420

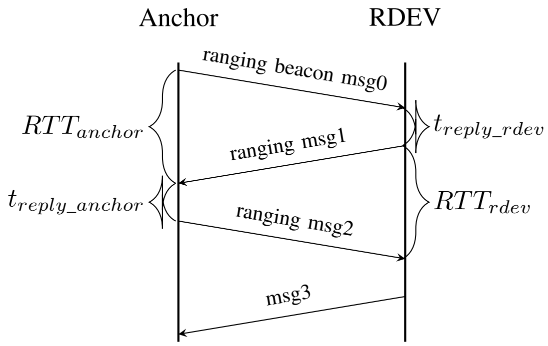

Figure 8. Message exchange in the SDS-TWR algorithm

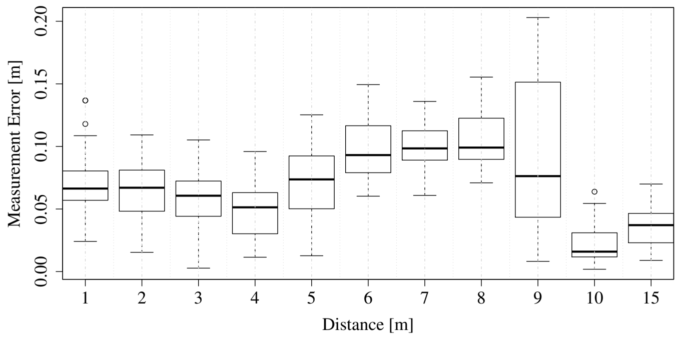

Figure 9. ToF results plotting the variance of the measurement error

DWM-1000[6] chip. According to the specs, this system should be able to provide a ranging precision of 5 cm even for moving objects. We had to adapt the available libraries for usage with the Waspmote platform.

The IEEE 802.15.4a standard only mandates the generation of time stamp reports. The ranging algorithms have to be implemented at the application layer. As time synchronization is not an option in our scenario, we selected a Symmetric Double Sided Two Way Ranging (SDS-TWR) algorithm to cope with possible clock drift of the used oscillators. Additionally, we used a bias correction algorithm to cope with the bias which varies with the RSS. Both algorithms are described in detail in a Decawave application note.[7]

The SDS-TWR algorithm uses four messages as shown in Figure 8: `msg0` is a ranging beacon from the anchor. If a Ranging Device (RDEV) receives this message, it responds with a second message that contains t_{reply_rdev} (the time between reception of the message and sending of the response). After receiving the reply in `msg1`, the anchor could already compute the distance by calculating $((RTT_{anchor} - t_{reply\_rdev})/2) \times c$. To avoid errors introduced by clock drifts between the two devices, the calculation is postponed to the end of the message exchange, taking into account also RTT_{rdev}. The anchor now answers with a similar message `msg2` containing t_{reply_anchor}. Finally, `msg3` from the RDEV to the anchor contains RTT_{rdev} (the Round Trip Time (RTT) between `msg1` and `msg2`). This way, the anchor has the RTT from both sides and can now calculate the Time of Flight (ToF) and thus the distance.

Figure 9 shows the error of first ToA-based experiments (measured outdoors during the summer, not yet in a snow field). Two nodes were mounted on a 125 cm high pole. The distance was increased from 1 m to 10 m in steps of 1 m with an additional measurement at 15 m. At least 24 ranging measurements have been done for every distance point, 391 in total. As can be seen, the maximum error over all measurements was about 20 cm, the mean error over all measurements was 6.9 cm. These are already very promising results and can hopefully be validated in the snow field.

V. CONCLUSION

We presented the concept of a measurement based approach for investigating avalanche dynamics in the field. Current mathematical models only consider initial snow conditions and radar or video based observations. However, the inner dynamics are still unknown and need further validation of the underlying models. Our AvaRange system will be able to close this gap. Our preliminary results already outline the challenges when it comes to ranging experiments in snow. First field tests using RSS-based techniques have been done in the field and new experiments are planned using ToF measurements (which already show excellent performance in a lab environment). We plan to continue our efforts with comprehensive field experiments in the coming winter season.

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[6] http://www.decawave.com/products/dwm1000-module/

[7] Application Note: APS011 – Sources of Error in DW1000 based Two-Way Ranging (TWR) Schemes, http://www.decawave.com/support