New Insights on a Sensor Network based Measurement Platform for Avalanche Dynamics

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ABSTRACT: We present the core concepts of our AvaRange system, a measurement based experimentation framework for studying the internal dynamics of avalanches. Snow avalanches are an ever-present reality in alpine regions, which may cause substantial damage to settlements and infrastructure elements. Even though avalanches have been studied for a long time, current modeling techniques of avalanche dynamics lack a precise description of their internal dynamics. This also holds for recent simulation models and techniques. The core problem is that the mechanics of important physical effects, such as particle-size segregation and phase separation inside the flowing avalanche, are currently invisible to us. In this work, we present selected new results of our AvaRange system. AvaRange is based on radio ranging techniques, which we previously successfully applied to a variety of sensor network applications, to track particles that move with the avalanche. The idea is to place sensor nodes in rugged spheres of varying shape, size, and density; and to deploy them in an avalanche release area. After (artificially) triggering the avalanche, the sensor nodes move with the avalanche and continuously obtain ranging data to determine their relative position. The obtained data allows to gain insights into particle trajectories and local properties. In this paper, we evaluate the most promising radio based ranging techniques, namely Received Signal Strength (RSS) and Time of Flight (ToF).

Keywords: Avalanche trajectories, avalanche dynamics, radio-based ranging, sensor networks, received signal strength, time of flight

1. Introduction

In order to protect alpine regions and infrastructure, surveyors and scientists have to rely on snow avalanche models to predict and simulate the avalanche flow. This is typically done by comparing the models to real events and continuously improving the calculations. Frequently used metrics are run-out length and deposition volume. These properties can be relatively easy measured after an avalanche event. Due to technical constraints, measurements of pressures, velocities, depths, or other flow details throughout the avalanche descent are rarely performed. The problem is that all of the above data only allow rough estimates about the inner dynamics of avalanches. Our idea is now to introduce artificial particles into an avalanche and reconstruct the trajectory of those particles assuming they follow the normal movements that occur in an avalanche. A particle is here defined as sensor node in a robust housing of a similar size and density compared to lumps of snow.

This approach requires to estimate the position of the artificial particles over time. Usually, Global Navigation Satellite Systems (GNSS) are used for positioning in this application domain. However, the satellite signal has a very low signal strength, which is further weakened by snow and ice. Schleppe and Lachapelle (2006) conducted experiments with Global Positioning System (GPS) receivers buried in snow. If a position could be estimated at all, it had errors of up to 50 m. Averaging the position estimates over a time interval of 10 min improved the accuracy significantly. This, however, is not feasible for highly mobile receivers.

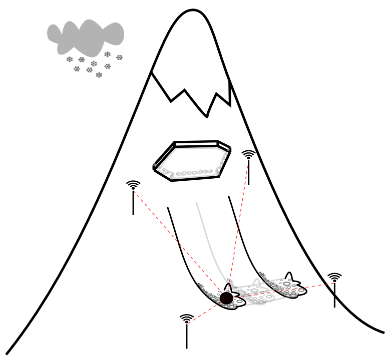

Figure 1: The AvaRange approach: Sensor nodes in robust housings matching the size and density of snow lumps are distributed in the avalanche area and travel together with the avalanche to the run-out.

Higher accuracy can be expected from radio-based ranging methods. Usually, such techniques are used indoors and in rather static environments

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(Nowak et al., 2015; Wang et al., 2017). Based on our previous experiences with radio ranging (Eckert et al., 2011; Nowak et al., 2015), we chose the following two radio-based methods and evaluated them for the AvaRange scenario (cf. Figure 1):

- RSS-based measurements exploit the fact that an emitted radio signal fades over distance and, thus, is weaker the longer it travels. Using a model for signal attenuation over space that needs to exactly match the environmental conditions, the RSS can be mapped to a distance (Wang et al., 2015).

- ToF-based systems measure the time it takes for a radio signal to travel to the receiver (and possibly back to the original sender). By exploiting the fact that radio signals propagate at a certain speed, the distance between two nodes can be calculated (Sahinoglu and Gezici, 2006).

In this paper, we present the results of experiments to assess the feasibility of the above radio ranging methods for the AvaRange approach.

2. Ranging and localization in gravitational mass flows

Radio ranging techniques have been applied to various kinds of mass flows. Allan et al. (2006) investigated RSS based methods with Radio Frequency Identification (RFID) tags in cobble stones to track their movement on sand and gravel beaches. Considering the very limited range of RFID transmitters this is not an option for our scenario.

Vilajosana et al. (2011) describe a conceptually similar approach to AvaRange. They use sensor nodes with 2D accelerometers in combination with video recording and evaluate the system in a small scale artificial snow chute. The conclusion was that the electronics and sensors are basically suited for small scale measurements.

Volkwein and Klette (2014) apply a related approach to determine rockfall trajectories. They equip a block of rock with a microcomputer, sensors for translational and rotational movement, and an off-the-shelve 2D radio ranging appliance. They evaluated the system on a plain field. The 2D ranging system showed accuracy errors of up to 5 m. Especially sharp turns proved to result in high errors. They did not use the inertial data for trajectory reconstruction.

Caviezel et al. (2018) developed the StoneNode, a low power sensor node which is used to conduct experiments to assess the forces that occur during rock fall. The used sensors have high temporal resolution and dynamic ranges and the comprehensive evaluation showed that the system is robust enough

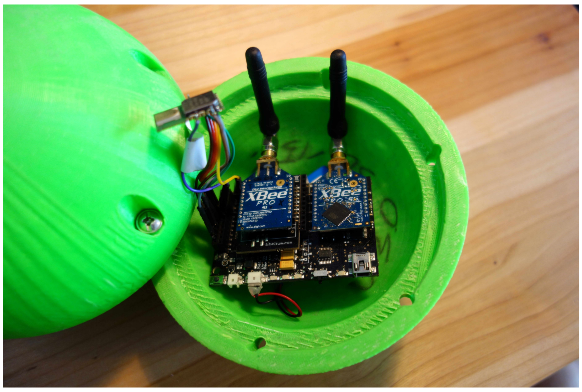

Figure 2: Prototype sample of our 3D printed spheres with the Waspmote sensor node that has a Decawave ToF ranging module and two radios attached

to withstand the forces occuring in rockfalls and provide the desired data. Again, they did not use the inertial data for trajectory reconstruction.

3. Experiments and sensor design

We conducted first field experiments for the AvaRange approach using spheres containing a micro-computer node equipped with inertial sensors (gyroscope, magnetometer, and accelerometer) (Fischer and Rammer, 2010). The results were promising, although the evaluation of the data and the reconstruction of the trajectories proved difficult due to the highly turbulent motion, including impacts and large rotational rates that occur in an avalanche (Winkler et al., 2018).

We further designed a new prototype to evaluate the use of radio-based ranging techniques in snow (Erlacher et al., 2016).[1] The basic idea is that the moving nodes communicate with fixed-position nodes (so called anchors) outside the avalanche, allowing to estimate the distance between the moving node and the anchors using radio-based ranging techniques (cf. Figure 1). Combining a large enough set of distance estimates, a 3D trajectory of the moving node can be reconstructed. These 3D trajectories can then be fed into the mathematical modeling process of avalanche dynamics.

To be able to adapt the shape and density to the exact experimental requirements without sacrificing stability, we used custom made 3D printed spheres. Inside the sphere is a micro computer which is equipped with different sensors and multiple interfaces to attach additional hardware (cf. Figure 2). For the experiments presented here, we used the Waspmote platform[2] that is based on an Atmel ATmega 1281 Microcontroller Unit (MCU),

[1] A complete video documentation of the field trial is available at `https://youtu.be/XXcZI-0kbpE`

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

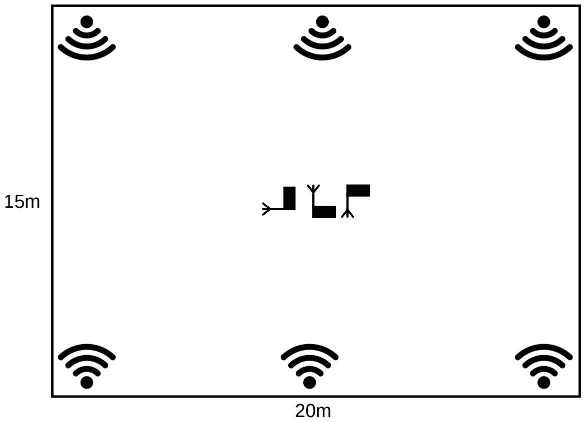

Figure 3: Sketch of the snow test field for the RSS tests: the senders were buried along the outside of the snow field and the receivers were placed in the middle of the area

and attached XBee radios[3] as well as a Decawave ToF radio ranging module.[4] The interfaces also allows attaching other types of sensors (e.g., high-accuracy inertial sensors).

4. RSS measurements

The main goal was to test the feasibility of the aforementioned radio ranging methods in snow. Figure 3 depicts our experiment setup for the evaluation of RSS based methods: As a sender, we used TelosB sensor nodes[5] using an TI MSP430 MCU and as a receiver, we used the aforementioned Waspmotes with the XBee radios. As already discussed in (Erlacher et al., 2016), we experimented in a fresh snow field at our test site on the Stubai Glacier (Tyrol, Austria). We buried six senders along the outside of our 15 m × 20 m snow field (cf. Figure 3). Furthermore, we positioned three receivers with different antenna orientations on top of the snow cover in the middle of the test field.

All the sensor nodes were communicating using the IEEE 802.15.4 protocol at 2.4 GHz. The results showed that even with transmit powers of less than 1 mW, the radio packets could be received all over the test site. The localization accuracy was less satisfying with a positioning error of 0.2–9 m.

5. ToF measurements

To evaluate ToF based ranging, we used only Waspmote sensor nodes. We attached the Decawace DWM-1000 ranging module, which provides a highly accurate timestamp – it is infeasible to accurately measure the time of arrival of network frames without dedicated hardware. This module implements the IEEE 802.15.4a standard, which defines a physical layer for impulse radio Ultra Wideband (UWB). The rest of the ToF ranging algorithm has to be implemented in software. This gives high flexibility to adapt the algorithm to the application scenario.

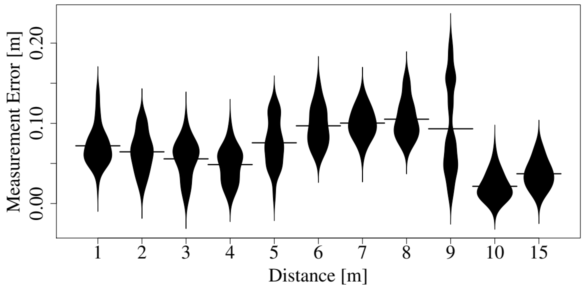

Figure 4: ToF measurement results in line of sight conditions; the horizontal lines show the mean value (Erlacher et al., 2016)

Our first ToF experiment was conducted with sender and receiver mounted on a 125 cm high pole in Line Of Sight (LOS). The distance was continuously increased from 1–10 m with an additional measurement point at 15 m. At least 24 distance estimations have been done per measurement point. The results are shown in Figure 4 and show very good accuracy. The maximum error over all measurements was 20 cm and the mean error was 6.9 cm.

With these results in mind, we conducted a new set of ToF experiments, this time assessing its suitability in snow. We buried the sender and the receiver in snow holes, each 50 cm deep, and started the distance measurements. We performed four experiments, always increasing the distance between sender and receiver. Figure 5 shows the results of the first three experiments. In the fourth experiment over a distance of 12 m, the RSS was too weak to allow for any distance estimation. The error increased continuously over distance with a maximum error of 2.8 m. These measurement errors are far away from the excellent results we achieved in line of sight conditions. This means that the ToF method has to be further adapted to snow conditions. Especially the transmit power has to be increased, to make this method applicable in larger avalanche scenarios.

6. Conclusion

In conclusion, the RSS based approaches prove to be simpler to apply but less accurate than ToF based approaches. With ToF based approaches, we finally achieved accuracies of less than a meter. The findings suggest that the accuracy could be improved by: First, further adaption of algorithms to the special requirements of the application scenario in moving avalanches and, second, customization of

[3] http://www.digi.com/lp/xbee/
[4] http://www.decawave.com/products/dwm1000-module/
[5] http://www.memsic.com/userfiles/files/Datasheets/WSN/telosb_datasheet.pdf

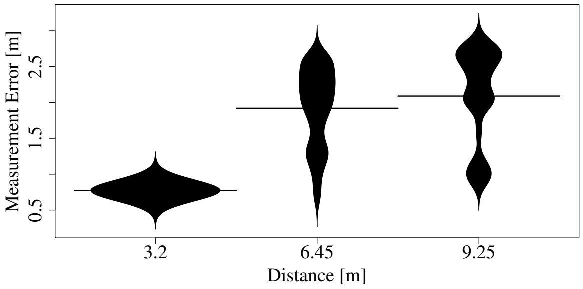

Figure 5: ToF measurement results with sender and receiver buried in snow; the horizontal lines show the mean value

the radio hardware for a bigger transmission range in snow.

However, our experiments focused mainly on static signal transmission and localization accuracy in snow. In future work, we plan to combine trajectory calculation of the radio based measurements with inertial measurement trajectory calculation. Radio ranging methods have a relatively high measurement error due to the imponderabilities of the environment but the precision of the position data is constant over time. Trajectories calculated with inertial measurements, on the other hand, are very precise, but the error propagation over time is disastrous. Thus, a combination of both methods promises to deliver more accurate position estimates over a longer time frame.

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