OPERATIONAL INTEGRATION OF UNCREWED AERIAL VEHICLES INTO ROADWAY AGENCIES' SNOW AVALANCHE RISK ASSESSMENT PROCESS

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ABSTRACT: In Norway, as in other mountainous countries, snow avalanches pose a serious threat both to the users of their transport network and that system's infrastructure. Road closures caused by avalanche danger or occurrence result in high economic costs and impact the reliability of Norway's critical transport network. The Norwegian Public Roads Administration (NPRA) is responsible for maintaining important routes that are threatened by snow avalanches. Keeping these roads open requires expensive operations to assess and mitigate avalanche risk. The GEOSFAIR (Geohazard Survey from Air) project has explored the use of Uncrewed Aerial Vehicles (UAVs) for snow avalanche assessment to support the NPRA's programs to keep critical mountain roadways open and safe. A three-year effort, GEOSFAIR was led by the NPRA in collaboration with the Norwegian Geotechnical Institute (NGI) and SINTEF research institutes. This effort focused on developing effective methodologies for integrating UAV technology and UAV-collected data into the present NPRA decision support system for avalanche risk assessment. The project has provided new and valuable information for decision-making and has developed guidance for roadway agency staff to assess avalanche risk using UAV data, including determining the effective use of UAV-carried sensors and cameras. A on-line table was created to relate snow, avalanche and terrain properties, important to the NPRA's avalanche forecasting staff, to the capabilities and feasibility of UAV data collection. A detailed workflow for UAV operations by NPRA staff was developed by the project team. The team also demonstrated that effective avalanche data collection required operation in difficult weather and complex terrain, such that an occasional loss of aircraft and equipment damage will occur and should be accepted by roadway agencies operating avalanche programs.

KEYWORDS: avalanche, unmanned aircraft, roadway agency operations, sensors

1. INTRODUCTION

The Norwegian public-sector innovation project GEOSFAIR (Geohazard Survey from Air) project has explored the use of Uncrewed Aerial Vehicles (UAVs, i.e., drones) for snow avalanche assessment to support keeping critical mountain roadways open and safe. This three-year effort was led by the Norwegian Public Roads Administration (NPRA) in collaboration with the Norwegian Geotechnical Institute (NGI) and SINTEF research institutes.

The GEOSFAIR effort has focused on developing effective methodologies for integrating UAVs and UAV-collected data into the present NPRA decision support system for avalanche risk assessment. This project has involved the systematic evaluation of UAV aircraft, mission planning and flight software, cameras, airborne sensors, and data processing tools to determine recommended specifications for the NPRA, while also exploring the effective use of UAV technology operating in realistic field conditions.

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The project has provided new and highly usable information that supports the integration and implementation of UAV data into the NPRA's decision-making process. This paper discusses the project's findings towards making UAVs routinely and operationally useful to the NPRA (and, by extension, other roadway owning and operating agencies). A detailed state of the art review has indicated a handful of research organizations have used UAVs in snow avalanche assessment applications, typically operating in ideal conditions over known terrain, but no roadway agencies were found to have used UAVs to operationally and routinely explore snow avalanche conditions and risk (McCormack et al., 2024).

2. OPERATIONAL NEEDS OF THE NPRA

Every year in Norway, as in other countries with mountainous terrain, snow avalanches pose a serious threat to both the users of their transport network and the roadway infrastructure (Schutz 2007, Brundt et al. 2021). Road closures caused by snow avalanches danger or occurrence incur high economic costs and impact the reliability of Norway's critical transport network (Eversen 2013, Frauenfelder et al.

2013). The NPRA is responsible for maintaining important routes threatened by snow avalanches, and keeping these roads open requires costly operations by the NPRA to assess and mitigate snow avalanche risk. The widespread coverage of the transport network, growing volumes of travelers, as well as climate change (Eckert et al. 2024), have resulted in more severe, more frequent, and less predictable natural hazards, and have increased the NPRA's costs. In addition, closing transport infrastructure for extensive periods has severe societal and financial consequences because in many areas in Norway there is little or no road redundancy. Mitigation measures tend to be reactive, based on immediate risk or after an avalanche event rather than on proactive monitoring.

The present cost situation, in combination with the current and future risk picture, forms the backdrop for the GEOSFAIR project. A series of sensor tests and data collection campaigns in avalanche areas by the GEOSFAIR team have shown that UAVs can provide valuable information on avalanche risk and can support the decision-making process to open or close roads. While completing GEOSFAIR, the project team learned how to make the NPRA's use of UAVs more efficient and effective on an operational level.

Initially, a questionnaire was prepared by the GEOSFAIR team and distributed to personnel from the NPRA and several county road administrations. The aim of the survey was to evaluate the current and potential use of UAVs and UAV-derived data for assessing roads exposed to avalanche hazards, and to identify potential barriers to the uptake of UAVs, while also guiding the GEOSFAIR research program (Reutz et al. 2022). This effort indicated roadway agency staff had limited knowledge about the use of UAVs and a pervasive challenge was having access to staff who could operate the equipment. Overall, the survey suggested that the roadway agencies needed more trained UAV operators, more expertise in processing the data, and more available UAV equipment. In addition, the survey findings supported the concept that fully automated systems with remote deployment and near-real time automated data processing could address current roadway agency limitations and needs.

3. UAV DATA COLLECTION GUIDANCE

As part of the GEOSFAIR effort, one crucial step was a systematic effort to relate snow, avalanche problems and terrain properties, important to the NPRA's avalanche forecasting staff, to information that could be collected by cameras and sensors on UAVs.

This process resulted in a detailed information collection table that lists twenty-one snow avalanche problems and terrain features critical to avalanche risk assessment (location, terrain, grain, water content, subsurface snow, etc.). An excerpt of the table is presented in Figure 1. With each one of the listed properties, there are key applications (for snow surface, for example, one application is to "measure snow height/volumes estimate potential avalanche size").

Category	Target element	Target property	Target description	Key applications	Storm slab, dry loose avalanche	Wind slab	Persistent/ deep persistent sl	Wet slab, wet loose avalanches	Glide slab
Avalanches	Snow surface	Location	3D surface mapping	Analyse lengths, heights and volumes of avalanches Document natural avalanches Document effect of active avalanche control (before/after)	D, A	D, A	D, A	D, A	D, A
Avalanches	Snow surface	Structure	2D/3D surface mapping Recognition of surface features in avalanche starting	Map recent avalanche activity and avalanche cycles Classify avalanches (types, phases)	D, A	D, A	D, A	D, A	D, A
Avalanches	Snow surface	Thermal radiation	Measure differences in thermal radiation between avalanche path/debris and unaffected snow	Map recent avalanche activity in poor weather/light conditions	D	D	D	D	D

B - **Before** avalanche/avalanche hazard situation
D - **During** avalanche/avalanche hazard situation
A - **After** avalanche/avalanche hazard situation

Figure 1. Excerpt of the dynamic information collection table for the category "Avalanches" and target element "Snow surface". Other categories considered are "Snowpack" (snow surface, sub-surface snow, ground), "Weather", and "Terrain".

These applications are linked to the type of avalanche problem (wet slab, glide slab, etc.) and a judgment of the value of that information (low, moderate, high) plus how that information is currently collected (snow pits, manual observation, etc.), and how the information potentially could be collected and related challenges, if any, to collecting this data. The table is dynamic and can be updated when new sensor applications are developed in GEOSFAIR or when relevant information is found from outside sources.

This dynamic information collection is a resource for NPRA staff who are planning to utilize UAVs and can be used to support operations by staff with various levels of UAV expertise. The table can help determine what avalanche information collection can be supported by UAV flights and what information needs to be collected by other non-UAV methods, such as snow pits. This information can also be directly integrated into the NPRA's avalanche forecasting workflow to assess the viability of collecting data using UAVs. The table resides on an NPRA website (vegvesen.no/geosfair) and will ultimately be available to other roadway agencies interested in UAV operations.

4. UAV SENSORS/CAMERAS

During the GEOSFAIR project's duration, several vendor demonstrations of UAVs and sensor and camera technology oriented towards avalanche data collection were held. In addition, laboratory, roadside, and field station tests were conducted to evaluate which technologies provided usable information for avalanche assessment and mitigation operations. (Dupuy et al. 2024a) These efforts clearly demonstrated that UAVs can be used by roadway agencies to collect critical information. This process also provides guidance on the required investment in aircraft, sensors/cameras, software, and the level of training needed by staff to process the collected data and extract meaningful information.

The most promising technologies identified are:

Optical images from cameras (Figure 2) provide a general useful overview of conditions and terrain. This information is easy to collect since most UAVs have cameras but are limited to conditions with reasonable visibility. Multispectral and thermal infrared cameras may provide information in conditions of low visibility where conventional cameras do not work as well.

Optical images also support photogrammetry (typically Structure-from-Motion Multi-View-Stereo, or SfM-MVS), which is used to map terrain and provides accurate information about snow heights and surfaces, but high-quality results require using flight paths with suitable image overlap and altitude (Dupuy 2024). While SfM-MVS mapping methods can provide good qualitative interpretation, lighting conditions (low contrast), or poorly textured surfaces such as fresh snow limit the usefulness of SfM-MVS for operational purposes by a roadway organization.

Figure 2. Upper panel: DJI Mavic 3E RTK drone with integrated optical camera. Lower panel: Typical optical imagery gained by consumer-grade UAVs.

LiDAR measurements can map snow-covered terrain and provide information about snow surfaces (Figure 3). These sensors produce relevant information such as shaded relief maps, snow height, change detection maps, and snow surface inclination maps. The elevation maps generated from LiDAR data are accurate and usable for a roadway organization (Salazar et al., 2023, Dupuy 2024). UAV LiDAR can be used to collect data in low-light conditions and in winter weather. Multiple-return laser pulses enable mapping, even in active precipitation during snowfall and rain, using post-process filtering (surface classification).

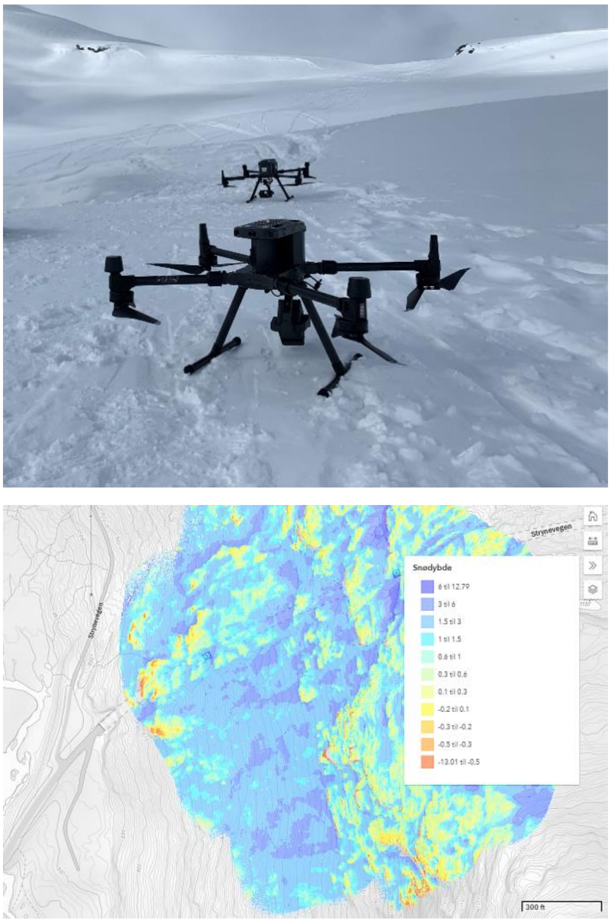

Figure 3. Upper panel: DJI Matrice 300 RTK drone with a Zenmuse L1 LiDAR sensor. Lower panel: Snow height map derived from LiDAR data captured on two consecutive dates.

Ground Penetrating Radar (GPR) provides inferred measurements of snow height, snow properties and layering (Figure 4) and this information can be correlated with data from other sources (surface mapping, snowpits). Different flight height and speeds are required to optimize the survey and data quality. The research team found that the GPR sensor needs to be flown close to the snow surface which can complicate flight operations. Successful BVLOS (Beyond Visual Line Of Sight) have however been carried out along steep mountain slopes. While data processing can be automated and provides results in less than an hour, direct interpretation of the processed data usually requires expert assessment but could be aided by Artificial Intelligence (AI). Identification of snow surface and snow-ground interfaces is straightforward, and centimeter thick internal layers can also be mapped if they have sufficient density contrast with over and underlying layers, i.e., melt-freeze crusts (Dupuy et al. 2024b). On-going machine learning tests are also promising to derive snow density profiles directly from the GPR data.

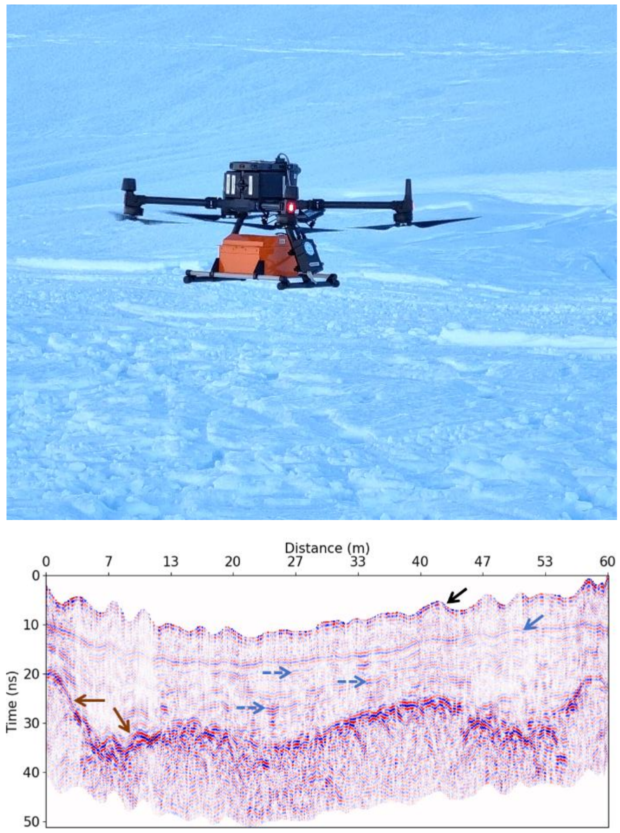

Figure 4. Upper panel: DJI Matrice 300 RTK drone carrying a Radsys Zond Aero GPR with a 1 GHz shielded antenna. Lower panel: Typical GPR profile of a snowpack where the black, blue continuous, blue dashed and brown arrows identify UAV location, snow surface, internal layers and snow-ground interface, respectively.

5. MOUNTAIN OPERATIONS

Given that the NPRA needs to make rapid decisions to open or close roads, particularly during and after storms, the need to fly a UAV in demanding situations is common and should be part of a real-world integration assessment. Multiple tests at NGI's avalanche research field station 'Fonnbu' and at roadside sites have provided guidance on UAV operations in steep terrain and in the poor flying weather that typically accompanies avalanche risk assessment operations.

5.1 Operations and Aircraft Loss

Initial operation of UAVs for avalanche related data collection showed a steep learning curve with considerable setup times and equipment failures. As the team's expertise grew, later tests resulted in more efficient operations but also resulted in aircraft crashes as the operators pushed the UAVs into the steep and complex terrain that accurately reflected where roadside avalanche hazards originate. Crashes were related to defective equipment, mission planning mistakes, and flying too close to the terrain.

Effective assessment of avalanche risk by the NPRA will require the acceptance of the occasional loss of an aircraft. An analogy is that most roadway owning agencies operate a range of roadway vehicles, and an occasional loss of these vehicles occurs.

As the cost of UAVs drops, and as the data collected by this technology becomes more used, institutional acceptance of aircraft loss will increase. Given that avalanches can pose a human safety concern, risk to UAV equipment may be acceptable. If risk of losing equipment is assessed to be high, less expensive sensors and UAV platforms can be used even though data quality maybe lower.

Efforts to increase the efficiency of operations and reduce problems with equipment or aircraft losses include effective training of pilots, up to date and well-maintained equipment, supported by increasing flight experience by the pilots. Concurrently, UAV technology and mission planning software are improving rapidly which will contribute to few equipment failures and crashes.

5.2 Aircraft Recovery

The aircraft crash that occurred during the GEOSFAIR data collection campaigns highlighted the importance of a recovery plan that reduces risk to the equipment retrieval team. In some cases, the recovery was aided by a second UAV exploring the nature of the terrain around the disabled aircraft.

For the NPRA and NGI staff, the recovery process was treated like any trip that required staff to travel in potential avalanche terrain. This included a safety meeting where different recovery options were discussed, maps of the area were reviewed and a final recovery plan was made (including deciding on a retreat plan in case the recovery mission needed to be abandoned). In addition, a method to safely carry the recovered equipment must be considered, especially if the recovery team needs to ski or travel on steep slopes or if the aircraft is large. Recovery of the UAV equipment is desirable, both in terms of the salvage of valuable sensors and parts, but also due to potential for environmental harm if the UAVs are left in place (particularly if the aircraft has lithium batteries). It is also possible that some aircraft will not be able to be recovered until after the snow has melted, or perhaps not at all.

6. WORKFLOW FOR UAV OPERATIONS

The GEOSFAIR team developed a simplified workflow which will guide the use of UAV operations by NPRA staff. The workflow covers necessary steps of using UAVs from initial planning of a flight to the final decision-making to open or close a road (Figure 5).

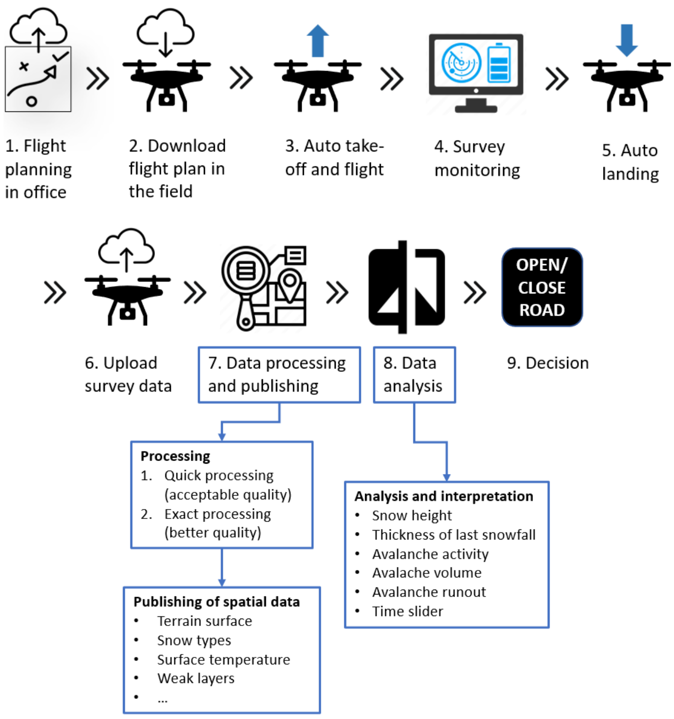

Figure 5. Simplified workflow for UAV operations in avalanche terrain.

6.1 Workflow

The workflow steps in Figure 5 are as follows:

1. Flight planning in the office: This step can be completed by NPRA staff in advance, but this planning can also occur on short notice if required by a new situation, such as unusual weather or a transport network-related need.

2. Download the flight plan in the field: This typically occurs using a cellular connection.

3. Auto take-off and flight: This step requires a pre-flight checklist based on the UAV manufacturer's requirements, as well as additional steps developed by the NPRA for their flight operations.

4. Survey monitoring: This step involves monitoring the operational volume, the flight characteristics (altitude, flight path, signal strength, battery life, etc.) of the aircraft, as well as the quality of the sensor data.

5. Auto landing: Many UAVs are capable of autonomous landing.

6. Upload survey data: The sensor and/or camera data is uploaded to a local computer or via cellular connection to a remote computer.

7. Data processing and publishing: This step involves publishing the resulting spatial data, such as the terrain and snow surface and potentially snow types, surface temperature, and weak layers (this information is correlated with the snow property table presented in Figure 1). The data can be rapidly pro-

cessed for immediate results in the field, but this often comes at the cost of quality. More detailed processing, which can take more time, will however result in more detailed, and usually more accurate, data.

8. Data analysis: This step requires the avalanche staff to use their experience to evaluate and interpret the resulting processed data.

9. Decision: The goal of the workflow is to provide information to support NPRA staff when managing decisions to re-open or close a road under increased avalanche risk. This step's development was guided by Haddad (2023) who developed a methodology to quantify the impact of complex data streams on the uncertainty of avalanche forecasting.

6.2 *Concepts for conducting UAV operations*

The operational needs and requirements for both current and future UAV operations have been divided into three categories which reflect how they might practically be carried out. These categories will inform operation manuals and other educational material and will result in more detailed workflow guidance.

Local operations: This type of operation is conducted by staff on site. This currently is the most common way to operate a UAV where people with the necessary pilot and specialist skills are present.

Assisted local operations: The operation is carried out by the pilot on site, with the support of another pilot or avalanche specialist who is not present. Such support can ensure that collected data meets professional needs and can include everything from verbal instructions along the way to planning and mapping missions or remote control of sensors and remote assistance with data processing and analysis.

Remotely controlled operations: Flying is completed by a pilot who is not present or is automatically following pre-programmed missions. The UAV and sensors can be prepared manually by local maintenance staff or deployed from a remote location. There is no need to have either pilot or specialist skills on site. This approach is under planning by the NPRA and may use an on-site “drone garage”. Data will also be downloaded and analyzed to the level of an operational product rather than just as raw data.

7. CONCLUSIONS

The findings from the three-year GEOSFAIR project will support and guide use of UAVs by roadway agencies for snow avalanche assessment.

An initial questionnaire evaluated roadway agencies' uses and needs for avalanche data collection by UAVs. The survey results suggested that roadway agencies need more trained UAV operators, more expertise in processing the data, and more available UAV equipment. Training must also include knowledge of relevant laws and regulations.

GEOSFAIR has developed guidance and information for roadway agency staff including:

- An evaluation of the effective use of sensors and cameras carried on UAVs.
- Guidance to relate snow, avalanche and terrain properties, important to the NPRA's avalanche forecasting staff, to UAV data collection.
- A workflow for UAV operations by roadway agencies.

The team has demonstrated that an occasional loss of aircraft and equipment damage will occur and should be accepted if usable avalanche data is to be collected.

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