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Avalanche Hazard Assessment Supported by UAS

State of the Art Review

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Sammendrag

Rapporten sammenstiller kunnskapsstatus ('state of the art') som er relevant for Statens vegvesen sin bruk av ubemannede luftsystemer (droner, UAS) for overvåking og vurdering av snøskredfare og andre naturfarer. Den presenterer erfaringer og ideer og er spesielt rettet mot bruk i vegsektoren.

Rapporten gjør rede for pågående teknologiutvikling og beskriver bl.a. operasjoner utført i krevende omgivelser og bratt terreng over veg.

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NPRA reports

Norwegian Public Roads Administration

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Summary

This state of the art review presents ideas relevant to the Norwegian Public Road Administration's (NPRA) use of uncrewed aerial systems (UAS) for roadside snow avalanche monitoring and assessment and, by extension, other natural hazards.

This review covers UAS technology advances and operations in harsh environments and steep terrain by transportation agencies.

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Avalanche Hazard Assessment Supported by UAS

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EXECUTIVE SUMMARY

This state-of-the-art review presents ideas relevant to the Norwegian Public Road Administration's (NPRA) use of uncrewed aerial systems (UAS) for roadside snow avalanche monitoring and assessment and, by extension, other natural hazards. This review covers UAS technology advances and operations in harsh environments and steep terrain by transportation agencies. The review also explores technology that is usable on UAS for assessment of snow avalanche risk and other natural hazards.

Specific recommendations based on this review are:

- **Photogrammetry (Structure-from-Motion or SfM)** has been shown by both the NPRA and others to offer usable data on snowpack depth and snow surface conditions. Because of the low-cost nature of collecting SfM data using digital cameras, the NPRA should continue to consider this technology. Given the limitations of SfM in low light conditions, it may be useful to explore the use of infrared or multispectral images with SfM processing.
- **Lidar** has been shown by the NPRA and others to provide highly useful snowpack information including in darkness and light precipitation. Lidar may ultimately be the main source of UAS information for avalanche assessment since the cost of lidar sensors is rapidly decreasing and is becoming more widely available for various aircraft platforms. The NPRA may want to consider developing operational protocols and supporting software for widespread and routine collection and processing of lidar data.
- **Ground penetrating radar (GPR)** has promise because it can cover wide areas and can provide snowpack layering (stratigraphy) information which is important for avalanche forecasting. However, challenges related to data collection and data processing need to be addressed before GPR can provide usable data on a routine, operational basis. The NPRA should continue to monitor advances with radar technology and to conduct field tests.
- **Cold weather:** Studies cited in this report have addressed flying in difficult conditions and dealing with challenges such as aircraft icing and reduced battery duration due to cold temperatures.
- **Formalized procedures:** A few transportation agencies have formalized the procedures for operating UAS by their staff. These reports may offer ideas for the NPRA as they build procedures to use UAS on a routine operational basis to assess natural hazards.
- **Advancing technology:** The studies reviewed clearly indicated that the technology behind UAS is rapidly advancing. The NPRA will want to follow this area and consider how artificial intelligence (AI) and anti-icing technologies can make a UAS more useful in a wider range of conditions.
- **Artificial Intelligence (AI):** Several studies have looked at using Artificial Intelligence (AI) and other tools to process data captured with UAS. This should be of interest to the NPRA as they develop tools that help make rapid decisions to open or close roads under threat of avalanches. AI may be increasingly successful at modeling avalanche activity using data from UAS which could impact the NPRA's operations.
- **Autonomy:** One promising area is the ability of UAS to fly autonomously. This creates opportunities to collect data on avalanche release areas remotely, perhaps using UAS garages for remote operations. This will support timely collection of snowpack data.
- **Beyond line of sight (BLOS):** The ability to fly beyond line of sight (BLOS) could notably enhance the collection of snow data. New technology such as see and avoid sensors should make BLOS more feasible for regulators and the NPRA should monitor developments in this area.

- **Sensor drops and pick-ups:** A UAS capability to drop and pick up snow sensors or use probes can provide autonomous snowpack information, particularly in areas dangerous for humans, and should be explored by the NPRA.
- **Other geohazards:** The same UAS aircraft, cameras and sensors used by the NPRA to evaluate avalanche risk can be deployed for infrastructure inspection and mapping and to study other natural hazards. The experiences gained by the NPRA staff in operating UAS for monitoring avalanches will likely lead to more effective use of UAS for other natural hazards applications.
- **Railroads:** This review found that railroad owners are active users of UAS to assess infrastructure risks, and this suggests the NPRA may want to track developments in railroad-based applications of UAS.

PURPOSE

This is a state-of-the-art review of uncrewed aerial system (UAS) technology (i.e. drones) that can be used by the Norwegian Public Roads Administration (abbreviated NPRA, or officially 'Statens vegvesen' in Norwegian) and other roadway operating agencies to support natural hazard assessments, monitoring, and event detection, with the ultimate goal of increasing safety and limiting the extent of damages. This review has an emphasis on technology used for snow avalanche risk assessment since monitoring this type of hazard can require frequent UAS operations over an entire winter to keep roadways safe and open for travel. Avalanche assessment is notably challenging as this typically requires flying UAS in severe weather, in rugged terrain and often in darkness. A transportation agency with the skills and equipment needed to inform snow avalanche risks with the assistance of UAS likely can use the same UAS to evaluate other natural hazards that threaten roadways. This review summarizes knowledge about various sensors and drone-related technologies that work well on UAS for snow avalanche monitoring purposes, but also notes whether these tools can be used to assess other natural hazards such as wildfires, landslides and rockfalls, and floods.

BACKGROUND AND MOTIVATION

Over the last decade, small, unmanned (hereafter termed uncrewed) aircraft have become increasingly capable, affordable, and commercially available. There has been a wide range of transportation-related applications of this technology including natural hazards monitoring, infrastructure inspection, surveying, and mapping (see for example, Ni et al. 2017; Fischer et al. 2020; Gupta et al. 2021; Trubia et al. 2021; Hubbard and Hubbard 2023). The NPRA was involved in a state-of-the-art review exploring the use of UAS for natural hazard assessment in 2014 (Grøtli et al., 2014). This report suggests that NPRA (and others) should motivate UAS providers to become more engaged in evaluating natural hazards. This includes starting test projects using LiDAR and radar on UAS and developing operational workflows where data from UAS could be collected, interpreted and presented in a more user-friendly way and on a routine basis.

The NPRA is responsible for maintaining roads that are in a cold, often dark, northern climate with severe winter weather. Part of the NPRA's mission is to monitor, give warnings, and react to snow avalanche hazards in steep areas above their roads. A common situation is where a road is closed due to a snow avalanche and the NPRA's geological staff are required to determine, as quickly as possible, if it is safe to reopen the road or if it is necessary to do roadway clearance work (Figure 1). If clearance is required, NPRA staff evaluate if it is safe for the maintenance workers removing snow debris. This can be a challenging evaluation since the

Figure 1. NPRA Avalanche staff working with Roadway Clearance Contractors (photo: Tore Humstad).

clearance activity can take time thus increasing the workers exposure to avalanche risk. In addition, the NPRA is also concerned with other hazards that threaten roadways including rockfall, landslides, and floods.

For snow avalanche monitoring, NPRA staff uses various means to view and evaluate the slide area including roadside observations with binoculars and travel by foot, ski, snowmobiles, and manned helicopters. If the avalanche forecasting staff can adequately view the release area and the avalanche path, obtain snowpack information, and in some cases dig snow pits, they typically can make a well-founded, but time-consuming, assessment whether to keep the road open or to implement closure.

Given the growth of commercially available UAS and of less costly and lighter weight cameras and sensors able to be flown on these aircraft, the NPRA has supported a series of tests and demonstrations to explore if these technologies could replace or enhance their current methods of monitoring avalanches. One notable motivation was the possibility that UAS could make avalanche monitoring safer by permitting staff to view avalanches without traveling close to avalanche release areas or without having to fly expensive manned helicopters in the mountains. The use of UAS potentially could support more effective monitoring, perhaps with a quicker response time, resulting in a safer and more reliable roadway network. As a result, the NPRA has an active research program to explore the use of UAS for roadside avalanche monitoring with an overview of this activity found in Appendix 1.

This report, completed as part of the NPRA's avalanche program and supported by the Borealis[7] and the GEOSFAIR[8] projects, is a state-of-the-art review of UAS with a focus on:

- relevant technology advances,
- operations in harsh environments and steep terrain,
- operation by transportation agencies, and
- cameras and sensors usable for assessment of avalanches and other natural hazards.

This document is the product of a review of interviews, websites, blogs, project reports, and journal articles that are relevant to the use of UAS for assessment and monitoring of snow avalanches and other natural hazards. This review does not cover regulatory issues related to flight rules as required by the Norwegian Aviation Authority (Luftfartstilsynet) or any legal /privacy issues that might impact UAS operations. In addition, while the processing time of the camera or sensor output is relevant for operational use of the data by a roadway agency, this quickly changing area is not covered in detail in this review.

LITERATURE REVIEW

UAS Technology Advances

Advances in technology suggest potential improvements in UAS that will make this technology more capable for use by the NPRA for avalanche and other natural hazards assessment. These improvements include better airframes, motors, and longer battery life which will increase the durability and performance of the aircraft. Given that limited flight duration is a common issue for many UAS

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[7] Borealis project: vegvesen.no/vegprosjekter/europaveg/e8borealis/

[8] GEOSFAIR project: vegvesen.no/geosfair

operators, articles mention alternative improved power sources such as hydrogen or methanol fuel cells which point towards better, but unspecified, flight duration (Ahmed et al. 2022; Mohsan et al. 2023).

Kraev (2023) recommends the:

> “use of drones with electrical propulsion based on methanol fuel cells for Arctic use. Such fuel cells have numerous properties that are valuable for aviation fuels. In particular, their high density decreases the size of the fuel tanks and improves the aerodynamic characteristics of the drone”.

Other technology advances noted as ‘under development’ or ‘feasible’ (Ahmed et al. 2022; Mohsan et al. 2023) include:

- better communications between the aircraft and the pilot or ground station,
- fully autonomous flight (including collision avoidance)
- solar powered or laser beam battery charging, and
- new types of aircraft such as with flapping wings and blimps (lighter than air) UAS.

In aggregate, these advances will lead to greater payloads, more stable flights, and a longer flight range and the possibility of more ambitious missions and the ability to collect data over larger areas. This will support the NPRA by resulting in more complete and more effective avalanche and natural hazard data collection.

Flying an aircraft out of view of a UAS pilot, known as beyond line of sight (BLOS), is useful for the NPRA’s operations. The main limitation to BLOS operations is regulatory. This is related to concerns about colliding with obstacles including manned aircraft (Matalonga et al. 2022). Many technical articles (for example, Rashid et al. 2002; Ploti et al. 2022) suggest improved detect-and-avoid (DAA) or sense-and-avoid (SAA) technology. These approaches will allow UAS to detect obstacles and make rapid flight changes to avoid these obstacles. This BLOS technology may include visual cameras, lidar or acoustic sensors, transponders, or radar (Spartan 2021). Another approach is to use a secondary UAS as a relay to provide a connection between a ground station and a UAS operating out of sight of a pilot (Autonomous Flight Systems Lab 2023). These technologies should support the acceptance of BLOS flights by regulatory agencies.

Under new Europe Union regulations known as Remote ID[9], UAS weighing more than 249 grams must be equipped with a Direct / Broadcast Remote ID system by mid- 2024 (DroneTag 2024). New UAS will have the equipment built in whereas as older UASs will need to add the Remote ID transmitter. The regulation is designed to increase UAS safety, visibility, and accountability. The use of Remote ID may support flights previously limited by safety concerns. However, the range of the Remote ID technology is uncertain and may vary considerably based on the equipment used and the operating environment.

Docking stations for UAS (also called ports or garages) support remote or autonomous flight and allow automatic recharging of batteries (Grlj et al. 2022; Howe 2022,). These systems can include a power supply, a landing platform, battery recharging setup, and an aircraft storage system and could even be mounted on a vehicle (Mohsan et al. 2023). A handful of commercial UAS multirotor vendors already

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[9] Remote ID: https://drone-remote-id.com/

offer docking stations that allow an aircraft to land and recharge or swap batteries without direct human intervention. Figure 2 shows two commercially available stations.

Power to a remote docking station in an avalanche area could be a challenge. Several reviews of UAS have suggested that solar charging in a docking station is feasible (for example, Zang et al. 2020; Grlj et al. 2022) with at least one commercial vendor offering this option (Langshaw 2016). However, solar charging in Norway in the winter may not be possible due to the lighting conditions, and the need for heating of the system.

Figure 2. Examples of Commercially Available Docking stations (Left: IDIPLOYER Nexus Dock, Right: DJI M30cDock) (Ghosh 2022).

The use of a station is feasible because precise positioning systems allow accurate landing by the aircraft on a docking station. Docking stations could be relevant for the needs of avalanche assessment because snowpack assessment flights may be required on short notice after, for example, recent snow accumulation. This approach is applied in Alaska using a UAS stored in a garage to autonomously map and model the snowpack in an avalanche prone area above neighborhoods and roadways in the city of Juneau (Canny 2023) and other remote areas in Alaska (Dryer et al. 2023). These efforts are currently exploring the aircraft's battery life, data storage, and resilience to weather. The anticipated benefits are the ability to reduce flight specific training and allowing avalanche staff to focus on data analysis in areas where resources are limited. Their goal to determine if:

> "UAS docks allows for the scheduling of flights, enabling repeatable mission planning and providing situational awareness for pre- and post-storm events as well as documentation following avalanche mitigation efforts. (Dryer et al. 2023)"

The literature on the use of docking stations suggests a few challenges (beyond regulatory limitations on unsupervised flight without human pilots) and questions that might need to be addressed before the NPRA could routinely use docking stations. These questions include:

- how to ensure that the station is operational in winter conditions (including snow accumulation, drifting, and ice formation)
- Battery management for electric UAVs? Swap batteries or recharge them inductively?
- How to transfer data from the camera and sensors to NPRA staff/systems after a flight? Cellular or Fiber?
- Safe storage of the aircraft in the docking station to avoid theft and weather damage and well as temperature control within the station?
- Locating, maintenance, and security of an unattended docking station?

- How to provide power to a station? If there is not electrical infrastructure, will solar work?
- Suitability for a flight. In other words, does the local weather (mainly wind) allow for a flight? Some commercial stations incorporate wind gauges. This might also be addressed if a remote roadside weather station was near a docking station.
- Autonomous UAS operations collect large amounts of data which is time consuming to study manually. Can, for example, artificial intelligence help study the collected data at right time and area?

UAS Operations

This section reviews literature concerning operational approaches that could improve the NPRA's ability to operate UAS in support of natural hazard assessment. UAS operations are more challenging in cold weather and reduced visibility and in steep terrain common to locations where avalanches and other natural hazards occur. NPRA staff is aware of this and sponsored a test in the winter of 2016 to explore the concerns about flying in these situations (McCormack, Vaa, and Håland 2016). The findings suggested that UAVs had the capability, with limitations, to provide useful information in a variety of weather conditions and terrain. UAS technology such as battery life, aircraft design, and UAS mission planning/operating software has improved since these tests, as well as the level of experience of the NPRA pilots, suggesting that operating capabilities are even greater than found in these tests.

In Harsh Environments

Beyond the NPRA's tests, numerous drone websites and blogs offer advice for flying in bad conditions (for example see, DJ Support 2017; Wawrzyn 2021; Jackson 2021; Drone XL 2023). Given that many UAS aircraft use electric motors, perhaps the biggest limitation noted in these sources is reduced battery life due to cold temperatures. These sources offer common sense advice for flying in bad conditions with most of the information likely apparent to experienced UAV pilots. However, these sources could be useful for newer pilots. Typical advice includes:

- Monitoring of battery life since cold degrades their performance and accounts for reduced flight duration.
- Store batteries in a warm location and consider a battery heater.
- Push the control sticks gently to prevent any battery voltage drops.
- Fly perpendicular to the wind.
- Note that condensation and icing can reduce flight ability and damage aircraft.
- To keep a pilot warm, fly the UAS from inside a vehicle (only applicable for BLOS operations).

Many of these sources suggest avoiding flying in rain and snow which could be problematic for flying in conditions required for avalanche assessment. One Norwegian University of Science and Technology (NTNU) study noted that in-flight icing poses a "severe threat to the UAS industry" (Hann and Johansen 2020; Hann 2021). The documentation in these articles about the hazards of icing and recommendations for increased awareness about UAS icing is relevant to NRPA winter operations. Their suggestion for additional research studies to explore the icing conditions that are typically encountered by UAS and their effect on different UAS types is an area of research that the NPRA may wish to follow simply because it can improve their ability to operate UAS in a great range of conditions.

A review of the technical literature seeking information on operating a UAS while collecting data for snow avalanche assessments found minimal information specific to this task. There are several studies exploring the use of UAS with sensors to locate victims of snow avalanches, but this type of activity is likely beyond the typical mission of a roadway operating agency.

A 2021 study categorically explored “UAS under adverse weather conditions including temperature, humidity, fog, precipitation, sturdy winds” but not extreme cold (Rajawat and Gautam; 2021). This article listed the weather types, hazards, and severity such as *hail* can result in *severe damage or aircraft loss*. An image from this study is shown in Figure 3.

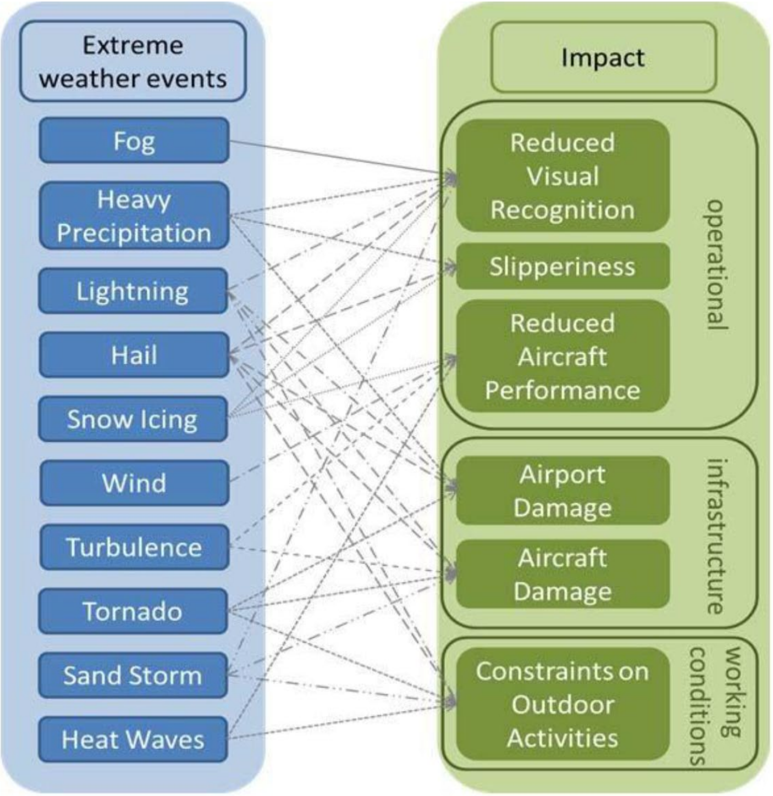

Figure 3. (Rajawat and Gautam 2021).

Related to this approach this was another study that methodically looked at operating lightweight UAS in challenging environments and focused on lesser noted pitfalls of UAV deployment (Duffy et al. 2018). This study, completed by researchers who completed numerous flights in range of environments including polar, noted a “dearth of information describing the operational complexity of drone deployment about the practices of flying in the field.” The challenges were grouped into logical categories such as pre-flight planning, operation, and data quality.

Such a systematic approach addressing flight limitation as covered by the two previous studies could be useful if the NPRA was to develop systems or rules for flying in different weather conditions, perhaps in support of or for training newer pilots.

Another research study looking at UAS operations in “harsh arctic environments” (Hasan et al. 2022) noted operational limitations due to winds and cold leading to flight performance degradation, as well as battery life and icing concerns. This article suggested that Artificial Intelligence (AI) could be applied to detect and respond to flight challenges caused by these limitations and to address human physiological factors such pilot endurance due to cold. The article also noted that a solution to battery life limitations may be new technologies such as Hybrid Electric Propulsion Systems (HEPS). A variety of solutions for flying during active snowfall and for the icing of the aircraft were proposed including automatically detecting the effects of these factors by using software to monitor the flight performance of the aircraft as well as electro-thermal deicing and anti-icing (such as developed at NTNU) that could be effective on small UAS.

A Norwegian effort, with a partial military focus, to provide information for the safe operation of UAS in arctic conditions (Håheim-Saers 2022) initially defined the operating environment and then developed a knowledge base for the design and use of UAS in these conditions. The arctic environment, as defined in this study, had obvious overlaps with the mountain operations of UAS by the NPRA. The report listed a wide range of technical (cold, wind, fog, icing, etc.) and operational (regulations, supply shortages, etc.) challenges to arctic UAS usage. This report could be a useful resource for NPRA operators. A detailed study that explored Nordic operations of UAS (Kramar et al. 2022) completed a systematic review of Arctic/Nordic related UAS operational risks such as cold pilots, electronic failure, icing, and limited communications. Solutions suggested to address these challenges include assistive technology and mission-specific sensors which can detect and address flight risks and operation challenges. Such approaches to improve operation could use technology such as multiple cameras, integration with Internet of Things (IOT) services, data fusion, and UAS swarms.

Other areas in the Kramar et al. (2022) article cover progress related to UAS flight operations included improved battery technology, better aircraft material technology, smart control interfaces such as 3D interfaces or first-person view (FPV), and advanced control or aerodynamic software for responding to gusty winds. This report also suggests AI data post-processing could help deal with large volume of UAS derived data particularly when there is need to make rapid decisions based on the data. Many of the challenges and mitigation suggested by Kramer could be a useful resource to support tools refining the NPRA's UAS operating procedures as well a guidance for future research proposals.

Two studies looked at Antarctic UAS field operations may offer insight for Norwegian UAS operation. One article was a review of scientific publications that mentioned UAS use in Antarctica (Pina and Vieira 2022). Of the 190 articles reviewed, the most common sensor used in the polar environment was a camera. Twenty four percent of the studies dealt with the collection of ice and snow data including looking at crevasses and snow depths, but none assessed snow avalanches. Lidar use was uncommon, and the report noted this was "probably due to its excessive cost in relation to that of the platform itself". In the aggregate this article highlights the ability to collect a wide range of different types of data in a harsh environment similar to areas where the NPRA needs to collect avalanche and other natural hazards data.

The second Antarctic-based article looked at the environmental impacts of UAS and developed UAS operational guidelines to mitigate those impacts (Harris et al. 2019). These guidelines are in a framework which may be useful for reducing any impacts of NPRA UAS operations in protected areas, parks, and mountainous terrain. The framework includes detailed guidelines for pre-flight preparations, on-site and in-flight protocols, and for post-flight actions.

In Steep Terrain

Numerous studies, including recent work by Peitzsch et al. (2018), Redpath et al. (2018), and Miller et al. (2022) have used UAS for assessing snow conditions in avalanche paths in North America, with steep terrain over 30° slope angle, and an elevation range exceeding 300m. These studies demonstrated the ability to conduct repeat observations (using SfM) in steep alpine, avalanche terrain.

Bühler et al (2018) successfully collected structure-from-motion photogrammetry of snow using UAS over a 0.12 km2 area with some steep slopes. The researchers concluded that in well illuminated conditions they could generate accurate and precise digital surface models (DSMs) and snow depth maps.

Maier et al (2022) mounted a multispectral camera on a UAS and used SfM software to successfully create three-dimensional (3D) snow surface in "challenging alpine terrain" in Sweden. The two test sites were 50,000 m2 with a mean slope of 6.3◦ and 7.6◦ but were not as steep as many NPRA operational areas. The study was of interest because their survey did not require ground control points since they used Real-Time Kinematic (RTK) positioning which enabled direct georeferencing of the images used in the SfM software Operation by Transportation Agencies

UAS Operation by Transportation Agencies

This section sought information on UAS use specifically by roadway owning and operating agencies. There are many documents discussing the use of UAS for monitoring and performing inspections of critical infrastructure such as bridges and highways, support for mapping, storytelling for public relations, and data collection (see for example, World Road Association 2023, American Planning Association, 2020; Mallela et al.; 2020; Reed, 2022).

A study completed for the transportation agencies in the northeastern United States developed a series of detailed implementation plans for integrating UAS operation (Mallela et al. 2021). While these plans address American laws and regulations, the safety plans, emergency procedures, training recommendations and data management in this document may be relevant for any transportation agency.

Another American study developed a UAS use framework for transportation agencies prioritized by: (1) benefits, (2) ease of adoption, (3) stakeholder acceptance, and (4) technical feasibility (Hubbard and Hubbard 2020). Their approach emphasized addressing technology and determining the benefit and feasibly of innovative technology when using UAS as tools. Given the NPRA's ongoing interest in UAS technology, this approach is relevant to guiding decisions dealing with agency level UAS usage.

The British Columbia Ministry of Transportation (BCMoT) in Canada commissioned one of the few studies found to specifically explore the use of UAS to support roadside avalanche data collection by a roadway owning organization (BCMoT 2020). The work was conducted over two winters in 2018-2020. The project tested different UAS and explored the use of different photogrammetry processes to understand snow-covered surfaces and estimate snow depth. They concluded:

> "The increased performance of RPAS (*i.e. UAS*) in terms of flight time, weather resistance and flight planning combined with the incorporation of high precision geolocation techniques open a multitude of applications for environmental monitoring of complex terrain."

And that;

> “The methodology can be applied to other field situations for detailed insight of the terrain.”

Of potential interest to the NPRA was that the researchers in this study developed an online portal to enable rapid data sharing and visualization. This is similar to one of the goals of the NPRA’s GEOSFAIR effort (project link here). This study also noted that UAS technology is valuable for emergency natural hazard assessment because of the ability of the UAS to fly long distances and create Digital Elevation Model (DEM) and Digital Surface Model (DSM) maps to assess damage and risk levels which support a rapid and focused response.

The research institute SLF in Switzerland’s “Avalanche Safety for Roads” project which started in 2022 is developing decision support tool to support road safety (WSL Institute for Snow and Avalanche Research undated). This effort calculates avalanche runout distance to predict whether an avalanche can reach a road and uses remote sensing to map and model snow depth distribution. This effort will explore new tools which include UAS data combined with fixed ground-based systems. Ultimately, they hope to build simulations to support decision makers who need to open or close roads. Given the close relationship of this project to the goals of the NPRA, this effort should be monitored by the NPRA.

The simulation developed by SLF highlights efforts to develop models of avalanche activity and risk. There are numerous examples in the literature dealing with the possibility of using Artificial Intelligence to better understand and predict avalanches (see for example, Maggioni et al. 2013; Chobin et al. 2019; Hafner et al. 2020; Kapper et al. 2023). While this complex activity is beyond the scope of this review, the data that is input into these models may be collected by UAVS and the AI output could support decision by roadway agencies.

Sensors and Cameras

This section is a review of camera and sensor technology that can be flown on UAV. It is designed to complement the information developed by sensors being tested and documented in the GEOSFAIR effort.

A detailed review suggested a range of sensors that may have value on UAS in the Cryosphere (the frozen component of water) (Gaffey and Bhardwaj 2020). Their list includes multispectral, hyperspectral, microwave, thermal/night imaging, lidar and photogrammetric technology. This list guides the literature review below.

Digital Images

A review by Kucharczyk and Hugenholtz (2021) of 635 articles related to remote sensing of natural hazard-related disasters using small UAS noted that most studies (87%) used common RGB (Red Green Blue) cameras. They found this use of camera was logical:

> “since RGB cameras: (i) are supplied with consumer-level drones, (ii) are used for the highly popular structure-from-motion photogrammetric technique, and (iii) have been found to be the most popular sensor for drone-based remote sensing.”

In addition to using photogrammetry software, these digital images can be used for direct viewing.

Direct Viewing

While little literature has been found of the uses of digital image for hazards monitoring, interviews with avalanche experts indicate there is value in looking at video and still images of avalanche release zones (Belz and McCormack 2021). Simply viewing a digital image can provide an expert with a better assessment of the avalanche risk or for other natural hazards. Risk assessment for snow avalanches includes elements such as looking for recent avalanche activity, cracks in the snow, the type of terrain and other direct visual features. For other natural hazards, such as rock falls or mud slides, experts can extract similar useful information.

And additional benefit, as noted by an avalanche forecaster at the Washington State Department of Transportation (Belz and McCormack 2021), is UAS images can be used for public information such as in blogs to convey the scale of a problem and help demonstrate, for example, why a roadway is closed due snow that slid over a roadway.

Infrared and Thermal Cameras

Both infrared (IR) and thermal cameras can be carried on UAS. IR cameras use infrared light (heat) to illuminate an area with the infrared energy reflected to a camera and processed to create an image. For example, one study used a UAV-mounted thermal infrared (TIR) imaging system to successfully capture snow covered surface temperatures surfaces (Johnston et al. 2021). Thermal imaging systems are passive and use mid- or long wavelength IR energy and sense differences in temperature (Teledyne Flir undated). Because thermal cameras do not see reflected light, they are less affected by fog, haze, or dust. However, the accuracy of this technology may require a calibration process (Pestana, 2019), having ground control points and a suitable flight altitude and flight geometry (Rossinei et al. 2023), and perhaps the even the correct angle of camera on the UAS (Lee and Lee 2022).

While UAS carrying an infrared camera are used in a wide range of applications (such as search and rescue) little was found in the literature related to avalanche risk assessment using this technology. One 2018 study used IR on a UAS to provide temperature of an avalanche flow to support analyzing the flow's structure, but this was after an avalanche had occurred (Nishimura et al. 2018).

A study applying photogrammetry (Structure from Motion or SfM) to snow surfaces suggested near-infra camera on drones could be used to show grain size of snow and to improve SfM images but did not detail how this would improve avalanche assessment (Bühler et al. 2017).

Handheld thermal cameras have been applied to explore snow pit differences and find weak layers leading to better information on avalanche risk (see for example, Shea et al. 2012) but the results are not definitive, and it is difficult to see how this could be applied on UAS in flight. Other types of snow analysis related applications of thermal cameras that might address avalanche risk were not found in the literature. Thermal cameras can see through fog and snow (but the distance they can see is reduced by these atmospheric conditions) (Teledyne Flir undated) so it is possible thermal images would support mapping of snow surfaces in difficult weather.

Multispectral and Hyperspectral Imaging

Multispectral imaging combines two to five spectral imaging bands into a single optical system and can measure radiation from a surface or object. This often includes thermal imaging covering parts of the infrared and ultraviolet spectrum. Hyperspectral imagery has narrower bands (10-20 nm) and could have hundreds or thousands of bands (Specim undated).

Multispectral imaging technology has been proposed for use on UAS for field-based cryospheric research (Gaffey and Bhardwaj 2020) and has potential to support more accurate snow surface models. It been used on a UAS to map snow surface properties at high resolution and:

> "the maps showed spatial variability and coherent patterns in the freshly fallen snow." (Skiles et al. 2023).

Data collected in this study included snow surface properties, snow grain size, and albedo. Other studies (for example, Sproles et al. 2020; Mullen et al. 2022) have also examined albedo measurements from UAS, and considered issues related to terrain correction for satellite validation and the spatial variability of albedo at smaller scales in complex alpine terrain.

Another study successfully used multispectral images to map different snow and ice types on a glacier (Rossini et al. 2023). As with the thermal camera, calibration, flight planning and ground control was necessary for accurate results. The integration of thermal and multi-spectral images in this study supported the mapping of both the surface temperature and surface type which may be of value for assessment of snow and perhaps mud slopes.

One of the results obtained by Adams et al. (2017) using a UAS to collect snow depth data acquired images in near-infrared (NIR) wavelengths to generate maps. They reported that for poorly illuminated snow surfaces, the NIR imagery provided considerably better accuracy than the visible imagery. This result is promising in suggesting multispectral imagery in infrared wavelengths can be used for snow depth mapping for avalanche assessment.

A study in Sweden in alpine terrain used UAS flying a multispectral camera to collect 3D images for SfM processing of images (Maier at al. 2022). This use of multispectral images in combination with SfM was found to:

> "be capable of producing high-resolution 3D snow-covered surface models (7 cm/pixel) of alpine areas up to eight hectares in a fast, reliable and affordable way."

Nothing was found in the literature that directly discusses the use of multispectral imaging to support snow avalanche assessment.

A few articles exploring hyperspectral imaging on UAVs to assess snow conditions were found. Gaffey and Bhardwaj (2022), in their broad UAS and cryospheric survey, noted the use of this type of camera to calculate snow albedo (as did Skiles et al. 2023) and certain aspects of snow and glacier facies and debris cover as well as for geological mapping. The article also noted hyperspectral cameras are becoming smaller and more practical for use on UAVs.

As with multispectral cameras, nothing was discovered in academic literature that discussed the use of hyperspectral images specifically for snow avalanches.

Photogrammetry

As seen in the projects covered in Appendix 1, the NPRA is a leading organization in the exploration of the use of SfM or photogrammetry to evaluate avalanches that threatened roads. Structure from Motion (SfM) used 2-dimensional digital images to reconstruct the 3-dimensional structure of terrain. By taking a series of overlapping digital images, and stitching them together using SfM software, 3-D point clouds similar to lidar output can be produced. This technique can be used to create high resolution surface models (including digital elevation models) with consumer grade digital cameras. The NPRA studies found that SfM on UAS was a usable tool for avalanche assessment. However, the accuracy of the SfM depends on the light conditions and the ability to geolocate the images typically using ground control points or correction by Real Time Kinetics (RTK).

Photogrammetry has considerable potential since it requires only a consumer grade camera and can map snow surface conditions and, with a baseline survey, can measure snow depth both of which are valuable for avalanche assessment. The concurrent, real time camera views of the snowpack are also valuable to the avalanche staff.

This image processing technique replicates lidar but with much less costly equipment. And as with lidar, this technology has been used to map snow. Other research efforts have determined that:

> “SfM is a promising new photogrammetric methodology, which enables the collection of geospatially accurate and high-resolution data, useful in avalanche dynamics modeling and snow depth spatial variability studies” (Eckerstorfer et al. 2015).

This technology has been applied for snow analysis in several studies with promising results when applied in a research setting (see for example, Bühler et al. 2016; Cimoli et al. 2017; Fernandes et al. 2018; Goetz and Brenning 2019; Gaffey and Bhardwaj 2020).

Cimoli et al. (2017) used SfM and noted:

> “Of the resulting snow depth maps with spatial resolutions between 0.06 and 0.09 m, the average difference between the UAV-estimated and conventional snow probing depths varied within an acceptable range of 0.015 to 0.16 m.”

Goetz and Brenning (2019) found that UAV derived:

> “snow depths as shallow as 1 to 5 cm could be detected with high confidence for most of the study area.”

Masný et al. (2021) used a small fixed-wing UAS with SfM to map snow depth. They covered a larger area (1.2 km^2) in a mountainous region in Slovakia that has numerous snow avalanches. The fixed wing aircraft allowed for quickly mapping a larger area. They found that different filtering modes for the point cloud had no impact on the results, but that vegetation did influence the results. The researchers also noted the importance of real-time kinematic positioning (RTK) when operating without ground control points.

In their detailed survey of the use of UAS to understand field-based cryospheric research, Gaffey and Bhardwaj (2020) conclude that UASs have emerged as a viable and inexpensive option. Their review explored numerous recent applications with measuring snow cover one of the most common usages of UAS. Given its frequent use in the cryosphere, SfM was evaluated, and the report determined that snow is challenging for SfM algorithms “because of the high reflectance of homogenous surfaces and lack of contrast.” The report also stressed the importance of ground control points. Gaffey and Bhardwaj’s review, however, did not mention the use of UAS or sensors for avalanche monitoring and the examples cited were research-based and not designed to support routine operational snow conditions data collection as required by roadway owning agencies.

Another study conducted an evaluation of the SfM snow depth distribution maps over an experimental five-hectare site in Spain (Revuelot et al. 2021). The evaluation tested different commercial UAS and collection methodologies and used both fixed wing and multi-rotor uncrewed aircraft. Three different ground control methods (fixed points, an Iterative Closest Point (ICP) algorithm, and RTK-GPS positioning) were examined. Data was collected under contrasted snow surface characteristics and at different altitudes. Lidar data was used to develop ground truth snow depths. The finding showed, for the best case, a Root Mean Square Error (RMSE) below 0.23 meters for snow depth and maximum snowpack volume deviations were less than 5%. Different flight altitudes did not show significant differences in the snow distribution maps. The study concluded:

> "that under good illumination conditions and in relatively small areas, affordable commercial UAVs provide reliable estimations of snow distribution compared to more sophisticated and expensive close-range remote sensing techniques. Results obtained under overcast skies were poor, demonstrating that UAV observations require clear-sky conditions and acquisitions around noon to guarantee a homogenous illumination of the study area."

A study in Switzerland evaluated the strength and weakness of collecting snow depth measurement using photogrammetric mapping techniques on different platforms including the use of small UAS over a 3.9-kilometer square area at 2350 meters height (Eberhard et al. 2021). The photogrammetry derived measures were compared to manual snow depth measurements. The report concludes that UAS images were "an economical and flexible method for mapping snow depth with high accuracy."

As noted above, the British Columbia Ministry of Transportation and Infrastructure (2020) commissioned one of the few studies found to specifically explore the use of UAS to support roadside avalanche data collection. The researchers tested different UAS and explored the use of different SfM processes to understand snow-covered surfaces and estimate snow depth. The study found that multirotor UAS (as opposed to fixed rotor) were the most practical as part of an avalanche program, but a major constraint was flight duration. The report also concluded that the snow depths measurement accuracy varied considerably depending on the methods used. Sole reliance on a built-in Global Navigation Satellite Systems (GNSS) receiver on the aircraft led to unacceptable inaccuracy, but this was greatly reduced using Ground Control Points. The most accurate measurement of snow depth was obtained using Post Processed Kinematic (PPK) techniques (a GPS correction technology).

LIDAR

The NPRA is also a leading organization in evaluating the use of lidar for avalanche assessment (see Appendix 1, Solbakken et al. 2020). Lidar, which stands for Light Detection and Ranging. Lidar is a remote sensing 3D scanning technology that uses light in the form of a pulsed laser to measure variable distances to the Earth and to develop a point cloud with each point holding information and representing one laser scan. The NPRA's test determined that lidar could create high precision measurement snow and map snow surfaces and has become increase feasible as the lidar technology has become less expensive and more suitable for use on UAS. Unlike SfM, lidar can be used in dark and low light conditions but has limitations in fog, snowy, or rainy weather because the moisture in the air diverts the lidar laser impacting data quality (DJR Enterprise 2022). Like SfM, useful lidar data requires considerable processing power and, depending on the level of accuracy required, possibly ground control points.

Lidar designed for UAS are commercially available and researchers have used lidar on UAS to look at the snow surface and the distribution of snow for more than 10 years (Bøggild and Sigernes 2015; Prokop and Singer 2016). The later study noted:

> "Overall we can conclude that UAV borne laser scanning presents a useful alternative to existing methods for spatial snow surface/depth mapping."

A 2017 Italian study compared lidar readings to manual probing and found that lidar "represent a competitive choice among existing techniques for high-precision high-resolution remote sensing of snow" (Avanzi et al. 2017). Other studies have found that lidar can provide usable snowpack information, but these studies collected data in more ideal research (as opposed to an operational) settings (Marks et al. 2018). This use of lidar for snow depth measurement typically requires a bare earth baseline survey when the snow is absent. Lidar can also be used to survey the surface of the snow to look for features that indicate avalanche hazards such as cracks in the snow.

Sullivan et al (2023) explored UAS flight speed while using Lidar to estimate snow depth and explored the tradeoff between speed and data return quality. Their effort was focused on mixed landscapes (open fields and forests) and they suggested different speeds for different landscapes. This finding suggests there may be an opportunity for the NPRA to develop optimal flight speeds for collecting snow depth data in avalanche areas.A recent article suggested an interesting approach by using the lidar that is a feature on an iPhone 12 Pro. The phone was mounted on a consumer grade drone (Figure 4) and used with 3D Scanner app to map snow depth (King et al. 2023).

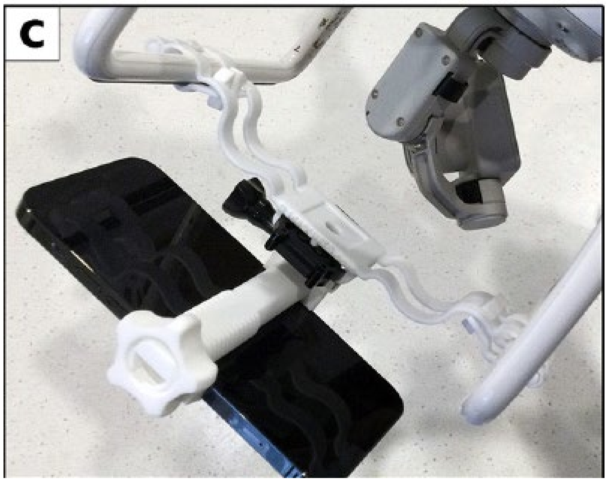

Figure 4. iPhone on a Commercial UAS used for Snow Depth Measurement (King et al. 2023).

This approach was notably low cost and the researchers collected snow depth data accurately to 3 cm and noted their results were similar in accuracy of more expensive lidar systems. In conclusion, the authors noted:

> "the accessibility of the iPhone combined with the simplicity of the drone controls results in little necessary training, allowing for novice-level operators to perform snow depth scans."

Tools based on smart phones are evolving and these advances may make it easier for the NPRA staff to collect snow data throughout their area of responsibility without using costly tools or requiring extensive training.

Lidar and Other Natural Hazards

A wide-ranging study of UAVs used for remote sensing and natural hazards notes that only a few efforts used lidar on UAS (Kucharczyk and Hugenholtz, 2021). This may be because lidar, until recently, has been too expensive to risk flying on a UAS. Application noted for UAS and lidar include after floods, wildfires, and earthquakes.

Given that lidar on UAS can provide detailed maps of terrain and water bodies, it is also a valuable tool for assessing other types of natural disasters. Lidar on UAS is useful for flood monitoring, mapping, and detection activities (see for example, Iqbal et al. 2023). Lidar technology can also help create flood hazard maps. In British Columbia, UAVs with lidar was used to survey roadways at 20 sites after severe flooding. This information was used to survey damage and guide the scope of repairs in support reconstruction projects (Karamuz et al. 2020).

In a similar manner, the NPRA could utilize UAS and lidar to map after rockfall hazards (see for example, Utlu et al. 2021) and to assess rockfall risk (Albarelli et al. 2021) including above roadways (Cunningham et al. 2020; Markus et al. 2023). The same holds true using lidar on UAS for landslide mapping and assessment above roads (see for example, Steward 2022).

Ground Penetrating Radar

Ground penetrating radar (GPR) has been successfully used on UAS and has been tested by the NPRA (Appendix 1). The NPRA's tests indicate this technology has promise but still has limitations related to effectively collecting, processing, and interpreting the data. GPR generates pulses of electromagnetic radiation that propagate in the subsurface and gets reflected to the antenna when reaching snow surface, snow layers of different densities and snow-ground interface. After processing of the recorded data, this allows to create an image of layers or objects below the ground or snow surface (JBUAS undated). The appropriate flight height of the radar above the ground (or snow surface) needs to be carefully chosen to get a good compromise between flight safety and data quality. The spatial resolution and swath of radar is related to the height so when comparing data it is necessary to know these parameters because otherwise a higher flight path looks "smoother" than reality, due to the averaging effects. The signal to noise ratio of the data is also decreasing when the flight altitude increases

One of the first mentions of GPR on a UAS used for avalanche assessment is by Jenssen et al. (2016) in Norway. They simulated a UAV flight and "showed the potential of an airborne UWB radar in detecting distinct snow layers" in support of avalanche risk assessment. Later tests by Jenssen using a UAS noted this technology has great potential for sensing of snow properties but noted on-going technical challenges linked to antenna design and data ambiguities (Jenssen and Jacobsen, 2020).

A 2022 review of GPR on UAVs highlights the possibility of this type of sensor and cites examples exploring snow and ice (Grathwohl et al. 2022). This technology can measure properties of and spatial variability in the snowpack. For example, this article mentions applications of GPR employed on UAVs and used for snow depth and snow coverage (Valence et al. 2002; Vergnano et al. 2020; Jenssen et al. 2020). However, many of these applications were not in mountainous environments suggesting the data was collected in ideal conditions. Information on the use of this technology for avalanche assessment and monitoring was not found. There are a handful of studies that evaluate the use of GPR to find avalanche victims (Janovec et al. 2022) but this is likely not an activity undertaken by most roadway agencies.

Limited information was found using this technology for avalanche assessment particularly on an operational level. One Norwegian group developed systems to

> “remotely detect layers in snow or ice that tend to crack or break under certain conditions and measure snow depth with a correlation coefficient of 0.97 compared to in situ depth probing”. (Jenssen and Jacobsen 2020).

Interestingly, one challenge found was the radar system accuracy was hard to confirm because the manual depth measurements used for a control had a coarse spacing compared to radar data.

A recent study in Austria used GPR on a UAS aimed to obtain radar data of an area’s internal snowpack layering structure (Siebenbrunner et al. 2023) with the goal of collecting snowpack layering data over larger area without human exposure to avalanche areas. The preliminary results:

> “indicate the success of the UAV’s flight performance and the accuracy of the GPR data in determining the snow depth and detecting the most prominent layers of the snowpack.”

The main advantage of using radar was the ability to collect data at scale allows for a more effective assessment of an area. However, the authors noted that their process was not yet mature enough for operational applications.

A 2023 study by Abushhakra et al. used Frequency Modulated Continuous Wave (FMCW) radar on a small UAS flying at 75 meters altitude and found that:

> “The radar mapped air-snow and snow-ground surface interfaces as well as the snow internal layers with snow depth exceeding 2 m in areas covered with 15-25 m tall trees. In addition, the radar-generated snow thicknesses are within ±10 cm of in-situ measurements.”

This test, however, was conducted on flat ground with light winds emphasizing water resource management. The radar footprint is a function of the flight altitude and beam angle. This means that the resolution and swath is related to the flight height – so when comparing data, you need to know about these parameters as well. Otherwise, a higher flight path looks “smoother” than reality, due to the averaging effects of the footprint size.

A study by Dupuy et al. (2024) evaluated the use of UAV-borne GPR systems to derive large-scale information on snow depth and snow properties including water equivalent, density and stratigraphy. Their effort explored the potential and limitations of this technology and made observations involving effective flight speed and altitudes, antenna, and data analysis.

OTHER TECHNOLOGIES

This section covers other, more speculative, technologies that could be used with UAS to support avalanche assessment.

Snow Profile Probes and Drills

A 2021 study by Meckl reviewed different field tools (including snow pits, block tests, and penetrometers) for snow layer analysis and explored the possibility of using a UAV to create a snow profile for avalanche prediction particularly in areas risky for humans. The author suggests dropping a recording penetrometer or snow pen from a UAS and recovering the device with a winch and cable to obtain snowpack stratigraphy. He noted the aircraft would need to be able to handle a payload of around 5 kilograms.

A test in Greenland tested the use of a UAS to autonomously retrieve ice samples off icebergs (Carlson et al. 2019). Their system used a commercial off the shelf (DHL brand) multi-rotor UAS with a custom-built coring drill hanging under the aircraft (Figure 5).

Figure 5. UAS with an ice coring drill (Carlson et al. 2019).

The system had interesting features including three lidar modules on the aircraft to assess the surface before landing and to track the progress of the drill and a quick release if the drill became stuck in the ice. The system had a number of initial problems and redesigns and was not fully successful, but the authors concluded this study:

> “has demonstrated the potential for unmanned aerial drone systems to aid in ice sampling operations and the prototype demonstrated here paves the way for the development of more capable and fully autonomous systems.”

Research and applications on the use of UAS to collect data autonomously using probes or drills is certainly worth following for NPRA’s avalanche assessment effort given that snowpack layering provides important avalanche risk data.

Explosives delivery by UAS

A test in North America demonstrated that small UAS could accurately drop dummy explode charge into above road avalanche release zone suggesting this approach could have value for triggering artificial releases under operational conditions (McCormack and Stimberis 2010).

A NPRA effort explored the use of explosives carried buy UAS for artificial releases (Statens vegvesen 2019 *in Norwegian*). The effort noted this approach may have the most promise for opening closed roads for the summer. Their report recommends the NPRA purchase this type of service but ultimately the NPRA maybe be able to do so in house.

A commercial Italian company has developed UAS based system to drop charges to trigger artificial research of avalanches. The system is a multirotor aircraft with an explosive delivery system underneath. (Sniper Technology Website, undated).

Another US based operation "Mountain Drones" also explored dropping explosives to trigger an artificial release (Callaghan 2022) and used UAS built-in LED lights for visibility in whiteout conditions and a proprietary climate-controlled, waterproof housing for the electronics. Ultimately the company turned towards the larger, and more lucrative application of measuring snow water equivalence using Frequency-Modulated Continuous Wave Radar on a UAS (Robison, 2016). Operational applications of a system to deploy explosives from a UAS were not found.

UAS Carried Avalanche Sensors

The Washington State Department of Transportation, the University of Washington (including McCormack) have developed a prototype low-cost avalanche sensor that can be deployed by use of UAS to inaccessible slopes above roadways to provide direct snowpack information to support the assessment of avalanche risk. This sensor will provide remote temperature and snow movement information (using a GPS and/or acceleration sensors) on the snowpack in support of assessing avalanche risk and avalanche activity. The device has a battery designed for operations over a winter and can communicate over 300 meters to a signal receiving tower via Wi Fi network or a cellular connection. The sensor is designed to be recovered (after a winter) by a UAS but will be low cost (around 1500 NOK) so a network of multiple sensors can be used in an avalanche release zone and an occasional loss of a sensor is acceptable.

UAS AND NATURAL HAZARDS / DISASTER MANAGEMENT

The UAS used by the NPRA have additional value as tools for remote sensing in support of disaster management and natural hazards assessment (see for example, Daud et al. 2022). A review by Kucharczyk and Hugenholtz (2021) noted that small UAS have expanded the toolkit for disaster management activities and noted "numerous papers" have explored the use for UAS for both pre- and post-disaster assessment. They found 635 articles looking at UAS used for disaster mitigation, preparation, response, and recovery including events relevant to Norway: landslides, mud flows, rockfall, earthquakes, floods, and windstorms. (Avalanches and snow event were not mentioned in this review). The applications of the UAS typically were on a case-by -case basis and noted there were not many standardized approaches to using UAS for disaster management. The review explored the sensors used which are mainly mounted on multirotor drones. The most common sensors used on the UAS were RGB cameras (87%) followed by thermal cameras (4%), video cameras (4%) and multispectral cameras (3.5%). It was notable that lidar was only mentioned in 2% of the article and photogrammetry was mentioned only in conjunction with use of RGB cameras.

One review of UAS for natural hazards assessment that may be relevant to NPRA operations is an article exploring the use of UAS related to railroad infrastructure (Askarzadeh et al. 2023). This article, which reviews 47 studies, suggests that UAS can inspect a rail network to look for problems and support "situational assessment in emergencies and crisis management during a natural catastrophe" and to evaluate risks from natural hazards. The technology used on the aircraft is the same as used by the NPRA for snow assessment (cameras, thermal camera, and lidar). This suggests that the same approaches would be of value for road networks and that the NPRA may want to monitor railroad-based applications of UAS.

SUMMARY AND RECOMMENDATIONS

This review suggests ideas and points to studies of relevance to the NPRA's use of uncrewed aerial systems (UAS) for roadside snow avalanche monitoring and assessment, and by extension, other natural hazards that impact the Norwegian roadway network.

One observation, after looking at hundreds of sources, is that the NPRA is probably the leading single organization internationally in terms of past and planned research evaluating the use of UAS for assessing and monitoring roadside avalanche risk. As seen in Appendix 1, which reviews NPRA's projects since 2014, this organization has explored the use of UAS in winter weather and in rugged terrain and has, or will through the GEOSFAIR research effort, evaluate a range of sensor and camera technologies.

Specific recommendations based on this state-of-the-art review are:

- Photogrammetry (Structure from Motion or SfM) has been shown by both the NPRA and other studies to offer usable data on snowpack depth and snow surface conditions. Given the low-cost nature of collecting SfM data using images from commercial off-the-shelf digital cameras, the NPRA should continue to use and explore the limits of this technology. What the literature did not provide guidance on, was information on how to create SfM maps on a routine, operational basis in the dark or low light conditions that are common in Norway in the winter and that reduce the usability of SfM. One interesting area that might address this limitation, and that will be worthwhile for the NPRA to evaluate, is the use of infrared or hyperspectral images with SfM software to build snow surface maps and quantify snow depths in low light conditions.
- As with photogrammetry, the NPRA has shown that lidar can provide useful snowpack information. This may ultimately be the main source of UAS-derived snowpack information for avalanche assessment since the cost of lidar sensors mountable on UAS are becoming increasingly affordable and accessible (including lidar on iPhones) and this technology works in all light conditions but has limitations in snowfall, rain, and fog. As with photogrammetry, there is limited information on using this technology on a daily operational basis to collect information to support keeping roads open. The NPRA may want to consider developing UAS operational protocols for flying lidar sensors as well as supporting software for processing the images to make the resulting maps easier to create by staff with a range of skills. This area is being partially addressed by GEOSFAIR.
- Several research efforts have shown that ground penetrating radar (GPR) on UAS has promise because it can cover wide areas and can provide snow layering (stratigraphy) information which is important for avalanche forecasting. However, challenges related to data collection, such operating at an appropriate height above the snow, and with data processing need to be addressed before GPR can provide usable data on a routine, operational basis. The NPRA should continue to monitor advances with radar technology and to conduct field tests.
- Studies cited in this report have looked at flying in difficult conditions and dealing with situations such as icing and reduced battery life and flight duration due to cold. These reports may offer support and ideas for the NPRA as they plan to use UAS on a routine operational basis to assess avalanche risk in all conditions. In addition, a few transportation agencies have

formalized the procedures for operating UAS by their staff. If the NPRA desires to more routinely use UAS, these sources could provide a usable operational framework. In addition, several studies have a systematic approach to addressing flight limitations due to weather and terrain and these approaches could be used as basis for the NPRA to develop systems or rules for flying in different weather conditions, perhaps in support of or for training new pilots.

- The studies clearly indicated that the technology behind UAS operations is advancing, and this will result in longer flight duration and better software to deal with difficult flying conditions. The NPRA will want to follow this area and consider how artificial intelligence (AI) and perhaps anti-icing technologies can make UAS more useful in a wider range of weather conditions and terrain.
- Several studies have looked at using AI and other tools to process the data from UAS. This is an area that should be of interest to the NPRA as they develop decision support tools that help make more effective and rapid decisions to open or close roads under threat of snow avalanches. The same, increasing more capable, AI technology may also be used to develop models that can simulate and predict avalanche risk and the results can support roadway agencies' decisions about road openings and closures. These models likely will utilize data collected by UAS and this entire process should be relevant to the NPRA.
- One area that is promising for NPRA, and is being explored by GEOSFAIR, is the ability of UAS to fly autonomously without direct human control. This opens many opportunities to collect data on avalanche release areas remotely, perhaps using permanently installed UAS garages to store the UAS and recharge their batteries. This will support rapid collection of data since NPRA employees will not have to travel to areas of concern.
- Beyond line of sight (BLOS) operations are related to autonomous flight (no human pilot or out of sight of a human pilot). The ability to make such BLOS flights may depend on regulations but the see-and-avoid technology, transponders or UAS relays should make BLOS safer and more feasible to regulators. BLOS could notably enhance the collection of avalanche risk data and the NPRA should monitor this area.
- Technology using a UAS's ability to drop and pick up in-snow sensors or use probes or drills that provide autonomous and direct snowpack information, particularly in areas dangerous for humans, should be monitored by the NPRA.
- The same UAS and camera and sensor used by the NPRA to evaluate avalanche risk can be deployed for other transportation agency functions. This includes use of UAS for infrastructure inspection and mapping but also to look at other natural hazards including land and mud slides, wildfires, and floods. The most likely application will be direct viewing areas of interest with cameras, photogrammetry (structure from motion), and lidar. It is likely that the experiences of the NPRA geologist operating UAS for monitoring snow avalanches will make evaluation of other natural hazards more common and effective.
- This review noted that railroads are an active user of UAS to monitor their infrastructure and to assess risks. Given that railroads operate large transportation networks similar in scale to roadway networks, this suggests that the NPRA may want to monitor railroad-based applications of UAS.

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APPENDIX 1: NPRA'S RESEARCH ON UAS AND AVALANCHE RISK MONITORING

This section provides an over the NPRA past research into use of UAS to support roadside avalanche monitoring and risk assessment. Studies and projects that the NPRA has completed in the past and is currently researching suggest areas of future interest and research.

The following table provides an overview of the series of NPRA's field tests and demonstrations exploring the use of UAS to support roadside avalanche monitoring and risk assessment.

Test	Goal	Findings
Trollstigen (2014)	Explore if digital images from UAS can support avalanche monitoring, evaluate UAS operations in mountain terrain	Incomplete findings due to equipment failures and weather that limited flights
Bjorli (2016)	Demonstrate UAS's ability to operate in winter weather and in mountainous terrain	• Some UAS can operate in winter conditions • Camera quality and sensor technology critical to the usefulness of UAS for avalanche monitoring
Andøya (2018)	Evaluated the ability of ground penetrating radar (GPR), photogrammetry (structure from motion or SfM), and digital cameras to detect snowpack characteristics relevant for avalanche assessment	• GPR output could identify snow layers but required challenging post-processing to be useful • Digital camera images were usable to avalanche staff • SfM data could potentially map surface conditions and measure snow depth
SfM Test (2019)	Explored using SfM data from UAS cameras to model avalanche slopes	• With the correct flight software and ground control points, accurate terrain maps could be created which support the assessment of avalanche risk
Trollstigen (2021)	Evaluate the usability of lidar sensors on UAS for snow avalanche monitoring	• Lidar data has the precision and accuracy to be used for monitoring avalanche risk • Results, at times, showed inaccurate or sub-optimal results, and systematic errors suggests the data collection process to be correctly conducted
GEOSFAIR Fonnbu (2022)	Explored the flight operation of UAS above snow, evaluated technologies including digital cameras, lidar, GPR, SfM, and multi-spectral cameras to collect snowpack data	• Sensors provided promising datasets about the snowpack characteristics and terrain. • Operation of the UAS flight planning, communications systems, flight controls, and automated flights worked. • Sensor use included equipment failures, difficulties operating UAS at altitude and speeds suitable for collection of data, some manufacture-caused breakdowns, and complex, and time-consuming data processing.
GEOSFAIR Fonnbu (2023)	Explored the flight operation of UAS above snow, evaluated technologies including digital cameras, lidar, and SfM.	• Lidar and SfM provided usable data about the snowpack characteristics and terrain. • Operation of the UAS flight planning, communications systems, flight controls, and automated flights generally worked.

Test and Demonstrations

The following section provide details about each of the NPRA's test and demonstrations as well as noting resulting report and articles.

Trollstigen – 2014

In 2014, the NPRA supported a research effort to fly a small quadcopter UAS owned by the Norwegian University of Science and Technology (NTNU) above the Trollstigen road (Fv 63) to evaluate if digital images collected by a UAS camera could provide details that might support avalanche monitoring and to also explore the operation of a UAS in steep terrain (Figure 1). This effort had limited success because of equipment failures and gusty winds that limited operational abilities. This test, as well as findings from similar UAS flights by organizations in other countries, indicated that a challenge with operating UAS to support the NPRA's avalanche program was the uncertainty about the ability to consistently fly in the steep terrain and the winter weather that generates roadside snow avalanche risks.

Figure 1. NTNU's Aircraft at the 2014 Trollstigen Test.

Bjorli – 2016

In response to the questions about the ability to fly unmanned aircraft in areas and conditions that generate avalanches, the NPRA sponsored a 3-day test in February of 2016 at Bjorli in central Norway (Figure 2). The NPRA circulated a tender and invited and funded vendors to demonstrate the ability of their UAS's to operate in winter weather and in mountainous terrain in support of snow avalanche monitoring. The six participating vendors flew nine multi-rotor, rotary-wing, and fixed wing aircraft on four increasingly difficult missions ranging from flights over a nearby road and bridge to a 2.3-kilometer flight to a 1,300 meter mountain to inspect avalanche features. These missions were designed to replicate the NPRA's operation needs.

Results indicated that there was no single UAS could meets all the road administration's avalanche monitoring needs, but UAS could be used in winter conditions. A conclusion was that camera quality and sensor technology were critical to the usefulness of UAS for avalanche monitoring. The photo and video quality general were good, and several were exceptional suggesting UAS with cameras could partially replace the need for NPRA observers to travel into dangerous avalanche assessment areas. The project concluded that NPRA should continue to monitor sensor technology.

Figure 2. UAS Vendors and NPRA's Project Team at Bjorli.

Documentation:

- McCormack, E. et al. (2016a) Evaluating Unmanned Aircraft Systems for snow avalanche monitoring in winter weather and in mountainous terrain, Project report for Norwegian Public Roads Administration, May. https://www.vegvesen.no/dokument/basis/fil/17351154

- McCormack, E. et al. (2016b) Unmanned Aircraft for Roadside Avalanche Monitoring, Nordic Road and Transport Research, December 2, www.nordicroads.com.

Andøya – 2018

A test at Andøya, Norway in April of 2018 was motived by the Bjorli test and was designed to explore the use of sensors on unmanned aircraft. The research team, reviewing other research efforts, determined that sensors carried in commercially available UAS could potentially provide useful information about snowpacks characteristics and avalanche risk. Measuring snow volumes or depth and detecting weak layers under the snow were of particular interest to the NPRA staff.

The NPRA team invited a vendor and two research organizations to the Andøya test. The test evaluated the ability of ground penetrating radar (GPR), photogrammetry (structure from motion or SfM) and digital cameras to detect characteristics of the snowpack that are relevant for avalanche hazard assessment. The GPR sensors were also tested for their ability to detect humans and vehicles buried in snow (Figure 3).

The test found that GPR output could identify snow layers important for snow avalanche hazard monitoring, but the raw GPR output was challenging to interpret and required post-processing to be most useful and this technology would need further development before it was usable by NPRA staff.

Figure 3. A UAS Carrying Ground Penetrating Radar During the 2018 Test at Andøya

Digital cameras on UAS were used to view surface features of the snow and this visual output was the most usable to the avalanche experts at NPRA since the other sensor technologies tested required post-processing. The use of SfM data (photogrammetry) derived from digital cameras can potentially map snow surface conditions and measure snow depth both of which are valuable for avalanche hazard assessment. SfM used both before and after snow fall could provide valuable data about snowpack depths and snow volumes. It was recommended that photogrammetry (SfM) surveys on small UAS be further explored by the NPRA.

Documentation:

- McCormack, E. et al. (2018a) Evaluating Sensors for Snow Avalanche Monitoring on UAS, Findings from Andøya, Norway, Statens vegvesens rapporter Nr 615, September 12, http://hdl.handle.net/11250/2564216
- McCormack, E., et al. (2018b) Testing unmanned aircraft for roadside snowpack avalanche evaluation, Nordic Road and Transport Research, August 9, www.nordicroads.com.
- McCormack, E. and Vaa, T. (2019). Testing unmanned aircraft for roadside snow avalanche monitoring. Transportation Research Record, 2673(2), 94-103.

SfM Test – 2019

Because of the promise of SfM, an NTNU student, Emil Solbakken, was supported by the NPRA and Norwegian Geotechnical Institute (NGI) to conduct a field investigation using SfM to model avalanche slopes. Test were performed by at Grasdalen in western Norway, in September 2019 and in Lavangsdalen, in October 2019 (Figure 4). The UAS-based SfM survey on the Sætreskarsfjellet avalanche path resulted in an accurate three-dimensional digital surface model. The model was compared to data from a previously acquired lidar survey of the same path. The test concluded, with the correct UAS flight software and with ground control points, accurate maps of the terrain could be achieved which could support the assessment of avalanche risk.

Figure 4. Testing SfM to Map an Avalanche Release Zone at Grasdalen in 2019

Documentation:

- McCormack E. et al. (2020) Photogrammetry and Drones for Avalanche Monitoring, Norwegian Public Roads Administration, https://hdl.handle.net/11250/2655350.
- Salazar, S. et al. (2020). Airborne Structure-from-Motion modelling for avalanche and debris flow paths in steep terrain with limited ground control. In EGU General Assembly Conference Abstracts (p. 20529).
- Solbakken, Emil (2019). Snow surface mapping and change detection in avalanche release areas using a consumer-grade UAS and SfM photogrammetry, Master's thesis in Geology. NTNU-Norwegian University of Science and Technology Department of Geoscience and Petroleum, http://hdl.handle.net/11250/2631360

Trollstigen – 2021

The NPRA, funded by their Borealis technology testbed, sponsored a 3-day field demonstration in October 2021 at Trollstigen (fv 63), Norway to evaluate the usability of lidar sensors on UAS for snow avalanche monitoring. Lidar is an attractive option for exploring snowpacks, particularly in northern latitudes, as it can be used in low light or dark conditions which limit the usability of SfM tools (Figure 5). After a tender was circulated and seven vendors were selected, these vendors and the NPRA flew over field sites of varying complexity and collected data using lidar sensors. The resulting datasets were analyzed for accuracy and for usability for avalanche hazard assessment.

The demonstration found that, in general, the lidar data was within a level of precision and accuracy that could be used for monitoring of the snowpack and avalanche risk. The data could (when combined with bare earth data) be used to determine snow depth and snow volume, and with repeated flights, could also track changes in the snowpack. The lidar returns also provided usable information on the surface of the snowpack and of the surrounding terrain (Figure 6).

Figure 5: UAS with a Lidar Mounted Underneath at the 2020 Trollstigen test.

The demonstration highlighted room for improvement in the collection of UAS lidar data. Even the lidar professionals at this demonstration, at times, produced inaccurate or sub-optimal results and some results showed signs of systematic errors. This suggests a successful lidar data collection operation will require detailed knowledge of the technology, good referencing systems, extensive testing, and well thought out survey workflows.

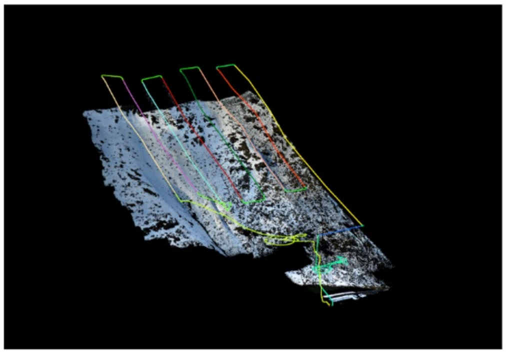

Figure 6: Lidar Results and UAS Flight Path from the 2020 Trollstigen Test (Orbiton).

The use of UAS for avalanche monitoring on an operational level depends on the ability of the aircraft to fly and to collect data in a range of weather conditions in rugged terrain, so there is some uncertainty on how well lidar data can be collected routinely and operationally in all situations.

Future steps are suggested which include continuing to evaluate lidar on small UAS for routine NPRA operations, with additional research needed to explore the economics of lidar. In particular, the NPRA will need to decide if losing an aircraft with a costly lidar sensor is acceptable: although this may change as the cost of lidar sensor is dropping. Related research should explore if UAS routinely operated by NPRA staff trained primarily as geologists can accurately and economically capture snow conditions data in a timely manner.

Documentation:

- McCormack, E. (editor) (2022). Lidar Carried on Unmanned Aircraft to Support Roadside Snow Avalanche Monitoring, Norwegian Public Roads Administration.

Figure 7: UAS Test Flight at NGI's Avalanche Research Station (Fonnbu) in 2022.

GEOSFAIR Fonnbu – 2022

The NPRA, in 2020, along with SINTEF and NGI, successfully completed an application to the Research Council of Norway for a 3-year 1.9 million NOK effort to develop effective methodologies for integrating uncrewed aircraft systems to collect data into the present NPRA decision support system for geohazard risk assessment. The effort, known as GEOSFAIR (Geohazard Survey from Air) primarily focuses on snow avalanches.

The GEOSFAIR effort has three field tests scheduled. The first was completed in March of 2022 at NGI's avalanche research station at Strynefjellet (Figure 7). This test explored the flight operation of UAS as well as evaluating sensor technologies including digital cameras, lidar, GPR, SfM, and multi-spectral cameras.

The test showed that operational limitations, mainly due to equipment malfunction but also due to operators' learning curves will need to be addressed if UAS technology is routinely used by the NPRA. The data from the sensors used at this are still being processed and evaluated.

Documentation:

- NGI (2023). Field test activity report - Fonnbu March 2022. Report no. 20210309-01-R, https://hdl.handle.net/11250/2999621 GEOSFAIR Fonnbu – 2023
- Salazar, S., Frauenfelder, R., Humstad, T. and McCormack, E. Geohazard Monitoring by UAS, The future Technology for Remote Decision Support, GEOSTRATA, April/May 2023, pp 48-54

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