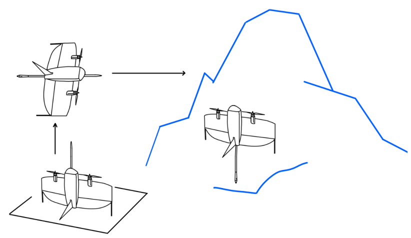
AVATARS: Aerial Vehicles for Avalanche Terrain Assessment and Reporting Systems



Columbia University Space Initiative

NASA's Gateway to Blue Skies Competition

2024: Advancing Aviation for Natural Disasters

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Abstract

Avalanches account for nearly 30 of the natural disaster deaths in the United States each year. Additionally, avalanches cause millions of dollars in property damage and put many avalanche professionals such as forecasters and first responders at risk. Avalanche preparation efforts focus on forecasting; distributing predictive warnings about danger allows individuals and organizations to make informed decisions regarding their own safety. However, these hazard maps are limited by a severe lack of data due to the time-consuming and dangerous nature of taking measurements and a general lack of certainty surrounding snow models.

An unmanned aerial system is proposed to drastically increase the amount of available data and revolutionize the future of avalanche forecasting and modeling. New advancements in Tailsitter VTOL UAV technology allow for the rapid aerial surveying of an entire mountainside, allowing professionals to gauge snow depth from digital elevation modeling (DEM) and identify other markers of avalanches. Snow probes, designed to take rapid snow profile measurements, can be deployed from the UAV in order to measure dozens of snowpack measurements across a slope in the same time it would take an on-ground professional to canvas one location. The increase in data will greatly improve the accuracy and availability of daily avalanche forecasts and advance the long-term goals of avalanche and snow models. The system is demonstrated to be implementable in statewide avalanche organizations by 2032. While previous proposals have discussed the utility and feasibility of such a system, this paper clarifies the intended use cases, conceptualizes a design for the system, and outlines a plan for integration of the system into existing organizations.

I. Natural Disaster Assessment

A. Avalanche Risk and Impact

An avalanche is a rapid flow of snow, rock, or ice down a slope. In the United States, an average of 28 people die in avalanches every year, with 90% of these deaths caused by human-triggered avalanches (FEMA, Page et al., McIntosh et al. 2007, McIntosh et al. 2019). Additionally, annual economic losses due to avalanches amount to millions of dollars in property damage, snow removal, road closures, and rescue costs (FEMA).

Avalanche preparation efforts focus on predicting the likelihood an avalanche will occur during a given time range in a specified area. Avalanche forecasting, or the evaluation of avalanche hazards, is used to advise the public to avoid dangerous areas, determine locations for road closures, and identify regions for further investigation. Avalanche forecasters reduce avalanche-induced fatalities and property damage by developing and communicating daily avalanche forecasts (FEMA, Etter et al.).

These forecasts are communicated to the public and other stakeholders through easy-to-interpret *hazard maps*, which rate the danger of a given region on the exponential North American Public Avalanche Danger Scale from a level of one (low risk) to five (extreme risk) (Statham et al. 2010). In order to determine the risk level, forecasters examine a complex array of data to evaluate the spatial distribution and sensitivity of snow, determining the likelihood and potential magnitude of avalanche activity (Statham et al. 2017).

The mechanics of snow can describe how avalanches propagate, therefore avalanche professionals measure the structure of snow for predictive purposes. The primary measurement type for recording snow structure is the snow profile. As outlined by the American Avalanche Association, snow profiles are typically obtained by digging a *snow pit* at least one meter into the ground and recording snow hardness, layering, and grain size (American Avalanche Association) *[Figure 1]*. Additional identification of specific features, such as surface hoar, give further insight into where events will occur.

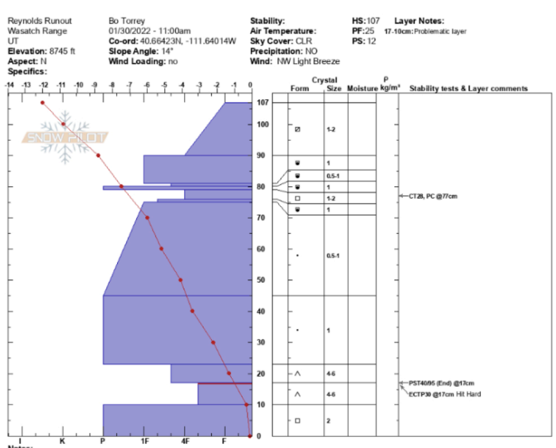


Figure 1: Sample Snow Pit Measurement ("Full Snow Profile")

However, snow pits are both time-consuming and burdensome to dig: a full-time avalanche professional could expect to dig at most five pits a day, so many high-impact regions are sparsely sampled if at all. Additionally, each profile is effectively a point measurement since it only measures vertical as opposed to horizontal variation. Oftentimes, a snow profile in one location contains conflicting information from a profile taken 15 feet away on the same slope. Furthermore, snow profile metrics are highly variable depending on the measurer: snow hardness, for example, is measured via a "hand test," where pushing "one finger in glove" into the snow with "moderate effort" signifies a snow hardness of medium (American Avalanche Association). This subjective method of data collection makes it difficult to standardize measurements, and only an experienced subset of professionals can collect reliable data. For these reasons, it's difficult to generate a confident map for any area larger than several square meters, let alone an entire slope or mountain.

Beyond snow profile measurements, avalanche professionals frequently utilize visual observation to identify where avalanches may form and where previous avalanches have occurred. However, professionals are limited to regions they can safely survey by foot, ski, or vehicle. Due to the inability to observe all regions, the majority of past avalanches – and the warning signs of future ones – go unnoticed.

The organizational structure of avalanche forecasting varies by location, yet usually involves communication between avalanches professionals including forecasters at avalanche centers, industry professionals including ski guides, and representatives from government agencies like the Department of Transportation. Some states, such as Colorado and Utah, have one centralized avalanche organization which controls forecasting. Other states without a centralized avalanche organization operate under a scheme of several regional forecasting centers. Avalanche professionals engage in a high-risk career: the 2020 Census of Avalanche Professionals reported that nearly half of workers had been caught in an avalanche on the job. Forty percent of professionals reported work-time injuries, with the majority of injured professionals either losing work time or needing a career change (Warren et al.). Decreasing the unnecessary time professionals spend in high-risk areas would lessen likelihood of injury (Johnson et al., Greene et al).

B. The Future of Avalanche Prediction

There exists a critical need to drastically increase the amount of avalanche prediction data. During the 2022-2023 season, the Utah Avalanche Center reported a total of 2,454 observations from 131 professionals and crowdsourced observers (“Annual Report”). However, given that most of these observations were verbal reports of avalanche sightings and that most specific data points represented point measurements, professionals agree there is an extreme lack of quantitative data available. Additionally, avalanche science itself is currently limited: gaps in understanding of snow mechanics and how it affects avalanche propagation make it such that the predictive abilities of avalanche forecasters cannot catch up to the demonstrated need for accurate, timely avalanche forecasts.

To attempt to address this problem, some statewide avalanche centers maintain their own snow models. One open-source example of this is the model *Snowpack* run by the Colorado Avalanche Information Center (“Snowpack”). However, these models are limited by the data currently being recorded; discussions with forecasters at these centers illustrated that critical information, such as an accurate understanding of snow depth, is preventing the full utilization of models. Additionally, as climate change increases the unpredictability of snow and weather patterns, our understanding of avalanche behavior will become even less clear (Strapazzon et al., Lazard and Williams, Mock et al., Peitzsch et al. 2021). Avalanche models must answer the question of how we can understand avalanches in the present as well as predict avalanches in the context of a changing climate.

II. Use Case and Proposed Solution

A. Problem Statement and Identified Need for System

The lack of avalanche prediction data is the largest limiting factor in developing effective avalanche forecasts (Schweizer and van Herwijnen, McClung). Due to the difficulty of digging snow pits as well as the human danger and variability inherent in snow profiling, standardized methods to augment data would greatly improve the abilities of avalanche forecasting (McClung). Because avalanche risks must be evaluated and distributed in a matter of hours in order to ensure the safety of all stakeholders involved, avalanche experts call for rapid technological development to better understand the current science of avalanches as well as prepare to distribute accurate forecasts for a changing future.

Thus, we identify a critical need for an aerial system which can measure key avalanche indicators efficiently and safely. First, this system should advance avalanche forecasting needs on a day-to-day basis, allowing for daily forecasts to be more accurate and survey broader regions. Second, the system should contribute to the longer-term advancement of avalanche science. By increasing the flow of data to operating avalanche models and research efforts, professionals will be better able to understand how avalanches work and how to accurately predict them.

B. Emerging Technologies

1. Snow Probe

One state-of-the-art technology in snow profile collection is the digital snow penetrometer, which measures relative hardness between snow layers ("Snow Data"). As someone inserts the penetrometer into the ground, snow structure is measured through force and optical sensors on the tip. While penetrometer technology has existed for decades, in the past five years lightweight probes like the Snow Scope Probe by Propagation Labs and the Lyte Probe by Adventure Data have become available. These probes measure hardness at high resolution and transmit snow profiles to an app-based UI in seconds via Bluetooth. Typical hand profiles include five to fifteen measurements total over two meters dug; the Snow Scope probe operates at a resolution of one measurement per millimeter of depth *[Figure 3]*. Current models range from $1,500 - $2,000 and extend from 1- 1.5 meters into the snow [*Figure 2]* (Harmsen and Trovato, Johnson and Rothenbuhler).

Figure 2: Snow Scope Probe (Harmsen and Trovato)

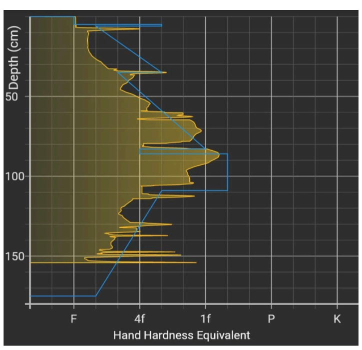


Figure 3: Resolution Improvements with the Snow Scope Probe (Harmsen and Trovato)

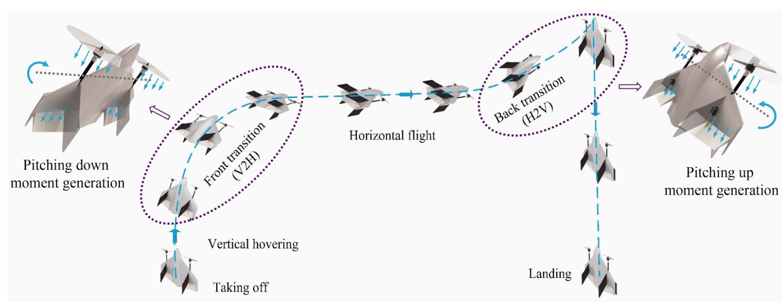


Figure 4: Typical flight stages of the Tailsitter VTOL UAV (Yang et al.)

2. Tailsitter VTOL UAVs

The "Tailsitter" drone model is a Vertical Take-off and Landing (VTOL) Unmanned Aerial Vehicle (UAV) that takes off and lands from a vertical orientation, but pitches forward to fly horizontally during flight with a fixed wing (Tal and Karaman 2021, 2022). Traditionally, multi-rotor UAVs have been popular for commercial use due to their vertical take-off capabilities and low cost, but require large inputs of power to generate lift. Alternatively, fixed-wing UAVs require less energy due to passively generating lift similar to commercial airplanes, and have frequently been utilized in the defense sector and longer commercial surveying missions. However, fixed-wing UAVs have previously been limited by large take-off and landing zones. Therefore, the VTOL Tailsitter design – essentially a hybrid between fixed-wing and multi-rotor UAVs – combines the best of both worlds, flying for longer and faster than multirotor UAVs, but also hovering and landing with precise control in small-range environments. Recent advancements in UAV stability and maneuverability have made the Tail-Sitter model a prominent choice for surveying and mapping over the past seven years, with commercial models now ranging from $11,000 to $20,000 [*Figure 4]* (Doddi, Akshat et al., Tal et al. 2023, Yu et al.).

C. Proposed System

1. Nominal Use-Cases

The proposed system is a combination of these two existing technologies: the hybrid Tailsitter VTOL UAV and a deployable probe *[Figure 5]*. The proposed system has two primary data collection uses. First, the UAV can conduct aerial surveying via an on-board camera for photogrammetry purposes, allowing for the modeling of snow depth over time as well as recording markers of surface characteristics. Second, the system measures snowpack hardness and temperature via deployment of a sensor-equipped probe during a hovering phase *[Figure 6]*.

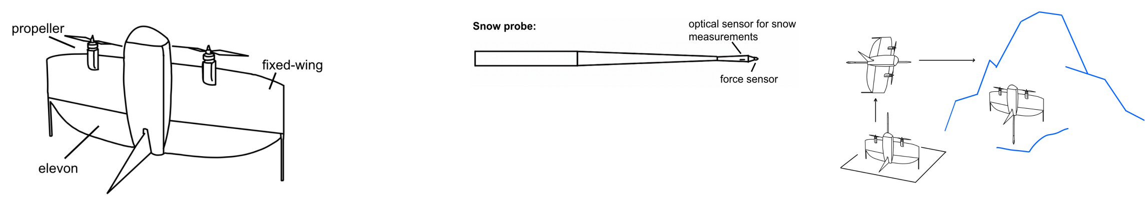


Figure 5 (from left): Hybrid Tailsitter UAV, Snow Probe, Combined System

Nominal Use-Case	**Objective**	**Methodology**	**Advantages**
1. Aerial Surveying	Aerial surveying aims to collect high-resolution imagery to monitor snowpack conditions, model snow depth, and identify past avalanches.	Flight paths are mapped by a Drone Pilot to cover a target area. The UAV payload is equipped with a camera. The UAV follows the flight path and stores photogrammetry on-board for later analysis.	Aerial surveying allows for the rapid avalanche monitoring over large or inaccessible terrain. With the capacity to cover 300 acres in a single flight, aerial surveying gives crucial information to professionals on a much more rapid schedule than satellite data imagery.
2. Probe-based Snow Profile Measurements	The probe deployment system will gather time-stamped snow profile data at specified points across the terrain. Photogrammetry data can also be recorded.	The UAV payload will be equipped with a retractable probe system. The Drone Pilot will hover the UAV over a location of interest, then lower the system until the probe is inserted into the snow. Measurements are stored on-board for later analysis.	The probe system creates snow profile measurements in a matter of minutes as opposed to hours for hand-dug pits. Additionally, probe measurements can be taken in regions that are unsafe for professionals to access by foot.

Figure 6: Nominal Use-Cases

2. Design Considerations

In creating this system, we prioritize two key design tenets. First, the system must safely launch, collect measurements, and land successfully in cold-weather conditions. Second, the system must closely integrate with existing Tailsitter UAV models and follow a modular design ideology. The UAV and snow probe technology may evolve, therefore components of the system must be interchangeable, and forthcoming software developments must be able to be incorporated.

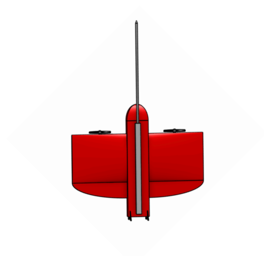
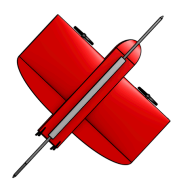
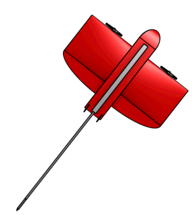
The aerial-surveying use-case is already widely accepted. We investigated several commercially-available Tailsitter UAVs for the surveying use-case with a selection criteria of reasonable cost, large payload capacity, transportability, high function in low to freezing temperatures, and ease of handling. We identified several promising models including the WingtraOne Gen II UAV, AeroVironment Quantix Mapper Drone, and Cobra VETAL Drone (“WingtraOne,” Quantix Recon,” “VETAL Drone”). These models are already designed to house cameras with surveying capabilities to 0.5 inches of horizontal resolution and 1.2 inches vertical resolution in similar use-cases such as polar surveying. Additionally, these UAVs are optimized for aerodynamic efficiency especially during horizontal flight (Bliamis et al., Tal and Karaman 2022, Dyatmika et al.). The integration of the probe must not block the surveying camera or disrupt the aerodynamics and stability of the system.

In order to take accurate, repeatable measurements, the probe must be inserted into the snow at a vertical angle (± 5°) at a rate of around 1 - 3 meter per second to a depth of 1 - 1.5 meters. Thresholds written into the software return a snow profile reading only if these conditions are met (Harmsen and Trovato, Johnson and Rothenbuhler). The functional components of the probe are contained in a small sensor bullet at the tip. The bullet is attached to a lightweight, rigid pole: existing models use a “ski-pole” or folding set-up, however the bullet can be mounted to any pole configuration that maintains needed rigidity. Lightweight, rigid materials such as fiberglass or aluminum alloy should be considered.

3. Preliminary Design Conceptualization

a) Hardware

Figure 7: Probe Deployment Modes

Mode One: Take-Off and Landing	Mode Two: Horizontal Flight	Mode Three: Snow Profile Collection
		

Design efforts should focus on integrating the functionality of the probe while maintaining the existing aerial surveying capabilities of the system. We identify three essential probe deployment modes *[Figure 7]*. The first mode is the forward extension of the probe during take-off and landing. Take-off and landing is significantly slower than horizontal flight; therefore the aerodynamics and stability are not significantly disrupted. Furthermore, the vertical orientation means that the center of gravity of the drone is not altered. Once horizontal flight is enacted, the probe will automatically move to the second mode where it is centered on the body. This maintains the original Tailsitter center of gravity and minimizes aerodynamic disruption during flight up to 35 miles per hour. Finally, during probe-based snow profile measurement, the Drone Pilot will switch the UAV to hovering and activate mode three which moves the probe towards aft extension. Then, the Drone Pilot can manually control the descent of the UAV to be inserted into the snow at the specified speed and angle.

In the third mode, the probe or entire system could be damaged in the case of rock or ice layer. If the probe’s force sensor measures too much resistance or an incorporated accelerometer measures that the probe has stopped its motion, a signal could be transmitted to automatically move the UAV upwards and send an error message to the controller to avoid damage. Additionally, a release mechanism may be included such that if the probe is hooked on something, it may be dropped and geotagged for potential later recovery. Further development must investigate the best probe deployment mechanism, such as a rack and pinion, ball screw, or motorized actuator system. Keeping the probe as a long tube will likely maintain better rigidity than a collapsible system, although telescoping or other models may also be considered.

b) Interfaces

Communication between the aerial vehicle and the on-ground Drone Pilot is controlled via a two-way radio link. The UAV communicates information, including sensor data and GPS coordinates, to the Pilot's controller (such as a tablet), and the Pilot can send instructions back to the UAV and manually override any automatic settings. Photogrammetry data is typically geotagged and stored on board; a similar system can be used to wirelessly transmit and cache snow probe data until return to base (Vasylenko and Karpyuk, Mototolea). These measurements can also be sent to the Drone Pilot in real time for evaluation but will be recorded on-board in case of temporary loss-of-connection. Post-flight, the Drone Pilot and other professionals can transfer the data to a laptop or external drive in the field.

Additionally, it is critical that the system and launchpad it interfaces with are transportable and lightweight. The WingtraOne Gen II UAV, for example, weighs less than 10 pounds, fits into a small car, and comes with a soft-shell carrying case with backpack straps ("WingtraOne").

III. Implementation

A. Overview of Operations

1. Operational Phases

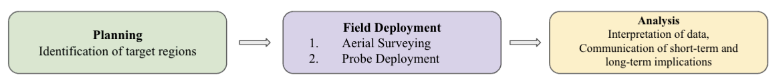


Figure 8: The Three Phases of AVATARS Operations

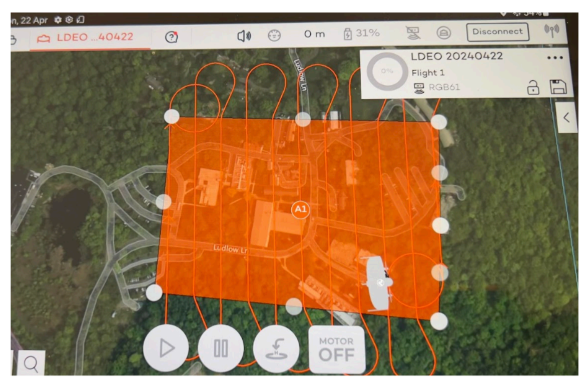


Figure 9: Flight Path Planning (Courtesy of Lamont-Doherty Earth Observatory)

The operation of AVATARS will occur in three phases: planning, field deployment, and analysis [*Figure 8*]. During the planning phase, professional forecasters will identify regions of interest that could benefit from additional data collection. Once avalanche professionals have identified a region of interest, an open-source flight planning software such as qGroundControl can be used to develop a flight plan that the UAV may autonomously follow *[Figure 9]*. A feature in the software must allow for users to select specific mapping capabilities for the probe deployment use-case, since the UAV must transition to its bicopter mode to enable the third probe mode *[Figure 7]* until the Drone Pilot manually takes over in order to lower the vehicle and insert the probe into the snow. A small camera at the base of the UAV allows for the Drone Pilot to observe this process on the controller. Once this system has been tested and successfully utilized, it would be possible to consider adaptive flight-path planning, where an algorithm analyzes measurements on-board and autonomously determines where to travel and take the next measurements during flight.

During the field deployment phase, the two nominal use-cases serve distinct purposes. The aerial surveying use-case creates a model of snow depth of a region and aids forecasters in visually identifying surface markers of impending avalanches, like fracture patterns, as well as remnants of past avalanches. The UAV can be deployed in the summer months to build a Digital Elevation Model (DEM) of the terrain.

Then, within the winter months, aerial surveying will allow for snow depth to be recorded across that terrain via structure-from-motion techniques. Currently, forecasters measure snow depth through snow gauge placement; the aerial-surveying use-case systematically measures this across an entire region of interest. Additionally, the probe-deployment use-case characterizes structure through comprehensive snow profiling with many measurements across a slope.

Within the analysis phase, forecasters must interpret the data. Since both use-cases measure data types that are already utilized, forecasters are already skilled at interpreting aerial surveying and snow profile measurements. However, the greater amount of data will allow for interpretations to be more confident, accurate, and cover a greater region. It is important to note that the system is not intended to replace the on-ground operations of avalanche professionals, as professionals can conduct further snow stability tests and take finer observations at regions of concern.

Each center where AVATARS will be implemented must develop a Data Management Plan. Discussions with avalanche centers led to the conclusion that many larger centers, such as the Colorado Avalanche Information Center, utilize computer clusters in order to run models, whereas regional avalanche centers are limited to storing data on desktop or laptop computers. AVATARS may be first integrated into the operations of larger avalanche centers for this reason.

2. Risk Management

A successful AVATARS mission is defined by the full recovery of the system and collection of accurate, repeatable data. Potential hazards to the system may be critical (such as those resulting in loss or destruction) and non-critical (such as probe data not properly recorded). During the development of AVATARS, a comprehensive risk assessment must be conducted with professionals to determine all risks associated with both the system and the environment in which it will be deployed (JARUS, Ancel et al.).

There exist numerous concerns with flying UAVs in cold-weather environments. Tailsitter UAV models utilize rechargeable lithium-ion batteries which have reduced capacity in sub-freezing temperatures. A survey of lithium-ion battery usage in similar environments suggests a maximum flight time of 15 - 20 minutes for each deployment with hovering and a maximum flight time of 30 - 40 minutes for a surveying mission without hovering (Bisht et al., Ma et al., Luo et al). However, with cruise speeds upwards of 35 miles per hour, a remote pilot can quickly return the UAV to the base and swap the batteries. Since batteries are kept insulated on the UAV, battery failure is expected to more commonly occur on-ground. Precautions such as storing batteries on the inside of one's jacket until flight have successfully maintained battery lifespan on previous cold-weather missions. However, in the case of low battery, Return-to-Home mode is triggered on the UAV resulting in a non-critical mission failure. Additionally, due to current line-of-sight regulations, pilots must be in sight of their vehicle at all times. If a sudden failure occurs, presumably the drone would be easily recoverable due to the restrictions on distance.

It is not advisable to fly any model of UAV in inclement weather such as snow, rain, or high winds (Gao et al.). Built-in safety features exist for poor weather: for example, the WingtraOne Gen II UAV will automatically return to home with wind over 27 miles per hour ("Technical Specifications: WingtraOne"). It is the drone pilot's responsibility to limit flights to clear days without active precipitation. However, turbulent mountainside weather such as wind gusts must be researched in the context of this system. A wind gust while the UAV is hovering to collect measurements for the probe deployment use-case could knock over the system and result in catastrophic failure via loss of the UAV.

Another major threat posed to UAVs is icing. Ice build-up, occurring when water droplets are present in the air, can increase drag, reduce lift, and add extra weight (Lindner et al., (Bernstein et al., FAA "Pilot Guide). The risk of icing can be mitigated by including temperature and humidity sensors which send the drone to Return-to-Home mode during risky conditions, and future modifications could explore de-icing systems. However, even in desirable conditions snow or ice may accumulate on the probe system. Methods such as pulsed Joule-heating, in which short pulses of current are sent through a wire, should be explored to help eliminate precipitation build-up (Li et al.).

Finally, the UAV is constrained by connectivity limitations. Data telemetry between the vehicle and controller typically operates within a range of 10-20 kilometers which is sufficient for line-of-sight flying. If the aerial vehicle exits the specified range or there is a disruption in connection, then Return-to-Home is automatically triggered (Vasylenko and Karpyuk, Mototolea). While these safety measures implemented in existing models increase the likelihood of a successful flight, it is necessary that the testing phase focuses on how the risk of catastrophic loss-of-control – due to either pilot error or software/hardware failure – can be best mitigated.

B. Integration into Existing Operations

1. Stakeholder Involvement and Projected Improvements

In locations including Colorado and Utah, one avalanche center with a team of 10 - 20 forecasters oversees avalanche forecasting operations for the entire state (*CAIC, UAC).* In other states, smaller avalanche centers control regions of the state ("U.S Avalanche Centers"). We foresee the initial rollout of AVATARS in statewide avalanche organizations first, where one or two professionals are first trained in the usage of the system and can deploy the system in regions across the state. After the initial rollout, AVATARS can be implemented into regional avalanche centers.

Avalanche professionals are necessary at all stages of the AVATARS lifecycle, through identifying regions of interest, deploying the system, and analyzing the data. The field deployment of the system is intended to supplement field operations of professionals. By identifying snow structure through aerial surveying and snow profile measurements, the system can point to areas that require further testing. Instead of just conducting tests in randomized locations, forecasters can pinpoint areas of concern. However, the system may replace forecasters in high-risk, dangerous regions. An additional component that avalanche professionals must lead is scientific communication: the data collected by our system is not valuable unless professionals can distill that information into hazard maps and short warnings that can be distributed to the public.

Some avalanche professionals already utilize quadcopter drones to a limited extent to survey regions, but experience very short flight times and slow speeds. With AVATARS, forecasters could take an aerial survey of an entire mountainside and collect 15 probe measurements in a matter of minutes, all while cutting out the dangers of traversing areas of high avalanche risk on skis or by foot.

2. Training

The Federal Aviation Administration outlines that all remote pilots must be certified or under direct supervision of a certified individual. Certification consists of an online training program and exam ("ARC"). Additionally, companies which sell hybrid VTOL UAVs typically include training programs which ensure proper use of the specific technology.

However, even with training and certification protocols, an analysis of human factors in UAV flight determines that the majority of UAV accidents come from decision-making errors (Grindley et al., Cardosi and Lennertz, Wang et al., Safany and Bromfield). Training specific to the avalanche environment and the AVATARS system must be developed. We envision each forecasting center having one person who oversees AVATARS operations and acts as a point-of-contact with UAV professionals to develop training opportunities for the avalanche use-case. This person can facilitate the onboarding process of professionals who use the system and ensure proper protocols are followed.

C. Cost and Return on Investment

Item	Tailsitter UAV & Controller	Lithium-Ion Batteries (3 pairs)	Snow Probe	Camera (20-50 MP)	Total Cost per Unit
Cost	$11,000 - $20,000	$1800 - $2400	$1000 - $2000	$1000 - $4000	$14,800 - $28,400

Figure 10: Projected Hardware Costs

With a projected cost of $14,800 - $28,400 per UAV system and additional costs required for testing, training, and integration, AVATARS is a substantial investment for private and public stakeholders *[Figure 10]*. However, AVATARS will save money on lost lives, injury, forecasting, personnel, and transportation costs: over the past three decades in Colorado, for example, loss of life estimates due to avalanches total to $2.25 billion and property and road damage over $500,000 (Colorado "2022-2023 Annual Report", Colorado DHSEM). Additionally, each search-and-rescue mission can cost more than $50,000 and jeopardizes the lives of first-responders. For each avalanche center, the primary revenue contributions come from public tax, government organizations including the Department of Transportation and U.S. Forest Service, and private donors and partnerships (Idaho, Washington, Utah "Annual Report 2022-2023", Colorado "2022-2023 Annual Report"). Each of these stakeholders, as well as the lives of individuals, will benefit from better avalanche prediction through increased safety and knowledge about a fundamentally misunderstood disaster. Since AVATARS will be integrated into existing avalanche data collection operations, operational costs should not be a major increase over existing practices. For additional funding, partnerships with private organizations should be considered. Companies such as Vail Resorts, which operated 37 ski mountains with a net profit of $347 million for the 2023 fiscal year, may consider investing in new technologies which promote safety in recreation (Vail).

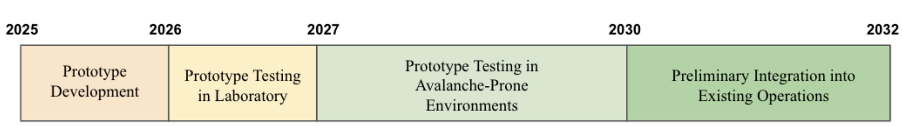
IV. Path to Deployment

A. Technology Readiness

AVATARS combines two critical components currently at a technology readiness level of nine: the Tailsitter VTOL UAV and snow probe attachment. With similar UAVs utilized for polar surveying, flash flood prediction, and soil collection, and snow scope probes emerging as a state-of-the-art tool for snowpack data collection, both systems are independently proven to be effective in operational environments (Rehan et al., "WingtraOne", "Snow Data").

While aerial surveying can be carried out with existing technologies, the probe deployment involves integrating a probe equipped with sensors into housing on the UAV payload *[Figure 5]*. A survey of TailSitter UAV testing, development, and integration allows us to estimate a technology readiness level of 4-5, with most components validated in winter environments (Akshat et al., Doddi, Lin and Shao). Due to the high technology readiness of individual components, we foresee rapid development of the joint system. A preliminary plan for testing would include one year for prototype development, one year for prototype testing in a laboratory environment, three years for testing in a cold-weather environment, and two years for preliminary integration for a roll-out date of 2032 *[Figure 11]*.

Figure 11: Timeline for Deployment



B. Barrier Analysis

There exist several barriers before the proposed system can be implemented into existing practices; we emphasize the need for their further consideration on the path to deployment.

1. UAV Regulations

The Federal Aviation Administration (FAA) regulates commercial drone use. Key components of commercial UAV regulations include a weight limitation of 55 pounds, travel limited to 100 mile-per-hour ground velocity, and a maximum altitude of 400 feet above ground ("ARC", "Small UAS"). Since the proposed system operates under these constraints and our data collection probe is passive (it does not alter the environment), we do not anticipate major barriers due to FAA regulations. However, geographical restrictions on UAV usage around populated or federally protected areas may affect usability in some regions.

2. Security and Privacy Considerations

The WingtraOne Gen II UAV and similar Tailsitter VTOL UAVs are cleared by the Defense Innovation Unit as a certified Blue UAS, verifying security measures on the vehicle ("Blue UAS"). However, care must be taken to ensure the privacy and security of individuals and local residents, especially due to photogrammetry data being recorded (Tang).

3. Human Safety and Environmental Disruption

Safety considerations must be implemented both in testing and in use to ensure the safety of all stakeholders involved. Additionally, while the system is passive and minimally invasive, research must be conducted on how it may disturb potentially fragile ecosystems.

4. Acceptance

Drone technology, and especially hybrid VTOL technology, is relatively new. Public acceptance, as well as the acceptance of new technology by avalanche professionals, must be considered when implementing aerial systems that alter existing practices. Since most avalanche organizations serve a dual purpose of distributing forecasts and providing avalanche education, we foresee many opportunities to connect general stakeholders and avalanche professionals to increase acceptance and understanding.

C. Conclusion and Key Findings

A review of the current state of avalanche danger finds that fatal avalanches are most often human-triggered. Preparation for minimizing avalanche danger requires professionals to distribute accurate and timely avalanche forecasts. Unmanned aerial systems such as the Tailsitter VTOL UAV have the capacity to augment the amount of data, standardize existing data collection methods, and improve data resolution. An aerial surveying use-case allows for hundreds of acres of mountainside to be observed in a single trip, and a snow probe deployment use-case allows for tens of snow profile measurements to be taken across a slope. This will greatly improve the accuracy and availability of forecasting on a daily time scale and will advance the field of avalanche science through the contribution to avalanche models. The technologies required for the system have proven successful in the operational environment and the architecture of existing statewide avalanche organizations has the capability to implement AVATARS with minimal adjustment; therefore, we anticipate that the system could be implemented by 2032.

In conclusion, avalanches are deadly, costly, and vastly underpredicted. AVATARS would drastically increase the amount of aerial and snowpack data available to avalanche professionals, allowing us to confidently understand avalanche risk and gain insight on a misunderstood natural disaster. AVATARS has the potential to save hundreds of lives and millions of dollars with a system costing less than $30,000.

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