Recent emergence of unmanned aerial vehicles for cryosphere research

Clare Gaffey[1], Anshuman Bhardwaj[2]

[1]Graduate School of Geography, Clark University, Worcester, Massachusetts, USA, cgaffey@clarku.edu
[2]Division of Space Technology, Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Luleå, Sweden , anshuman.bhardwaj@ltu.se

Introduction

Unmanned Aerial Vehicles (UAVs) have emerged as a viable and inexpensive option for studying cryospheric components at unprecedented spatiotemporal resolutions. UAVs are adaptable to various cryospheric research needs in terms of providing flexibility with data acquisition windows, revisits, data/sensor types (multispectral, hyperspectral, microwave, thermal/night imaging, Light Detection and Ranging (LiDAR), and photogrammetric stereos), viewing angles, flying altitudes, and overlap dimensions. Thus, UAVs have the potential to act as a bridging remote sensing platform between spatially discrete in situ observations and spatially continuous but coarser and costlier spaceborne or conventional airborne remote sensing. In recent years, a growing number of studies using UAVs for cryospheric research have been published. This paper reviewed 103 studies that incorporated UAVs in cryosphere applications between 2014 and 2019. Our aim is to summarize efforts and promote successful continued incorporations of UAV-collected data.

Search Methods

The papers included in this review were found by utilizing the Clark University Library online discovery tool and Google Scholar to search for several combinations of keywords such as “Arctic”, “Antarctica”, “UAV”, “UAS”, “unmanned aerial”, “drone”, “polar”, “glacier”, “permafrost”, “ice sheet”, “snow cover”, and “glaciology”. Beyond the word searches, we followed papers referenced in published studies that would also be applicable to the criterion. Materials including peer-reviewed articles, conference proceedings, theses and dissertations utilizing UAVs for cryospheric research were consulted.

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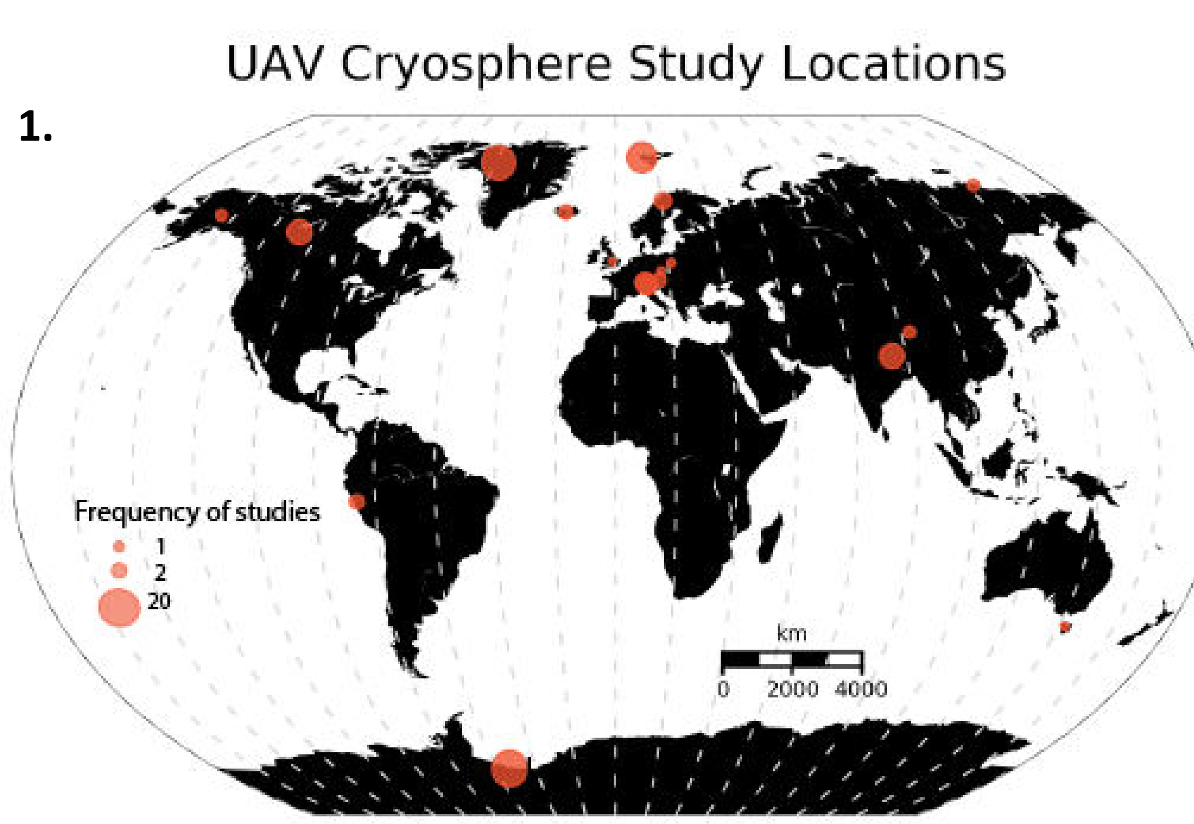

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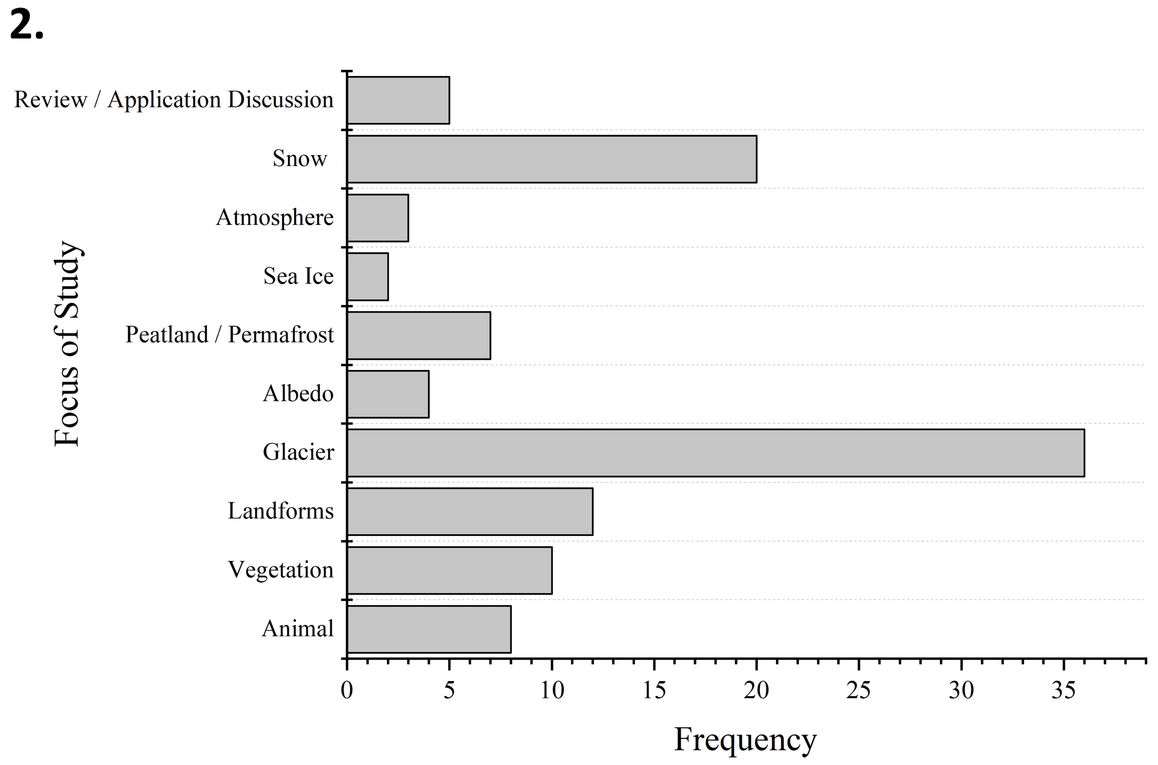

Challenges and Recommendations for UAV Remote Sensing

UAS can be a great, accessible tool for any researcher. However, pre-flight planning is crucial for a successful mission. Hazards that can be introduced during data collection include losing GPS, rapid voltage drop, communication loss between the ground station and vehicle, unanticipated weather interruptions, user and mechanical failure. Planning ahead is necessary to limit the impacts of environmental, mechanical, and human influences.

Tips for a successful flight and resulting orthomosaic:

- Keep batteries heated and unexposed prior to launching the UAV.
- Ensure 80-85% image forward– and side-lap.
- Consider options for Ground Control Points (GCPs) early. Apply GCPs in a triangular mesh grid. If using five or less GCPs then consider supplementing with on-board Post-Processing Kinematic and Real-Time Kinematic technology or relative referencing by matching features with prior datasets.
- Environmental illumination is a challenge for homogenous snow surfaces, a way to remedy the influence is to properly set the camera exposure time and store imagery in RAW format using the full bit depth of the sensor (usually 10 to 14 bits).

Table 1. Summary of application studies of UAVs in cryospheric disciplines. . The articles mentioned here were published online between 2014 and 2019.

Study	Location	UAV platform	Highlights
Lucieer et al. (2014)	Windmill Islands, Antarctica	MikroKopter OktoKopter	Performed a single flight to capture micro-topography (bryophytes and lichens) of moss beds.
Turner et al. (2014)	Windmill Islands, Antarctica	MikroKopter OktoKopter	Flew multiple sensors to investigate physiological state of moss ecosystems including a visible camera (1 cm/pixel), a 6 band multispectral camera (3 cm/pixel), and a thermal infrared camera (10 cm/pixel).
Bollard-Breen et al. (2015)	McMurdo Dry valleys, Antarctica	Custom-built fixed wing	Used a UAV to identify cyanobacterial mats, estimate their extent and discriminate between different mat types. They were able to detect human disturbances on the mat and recommended using this technology to monitor human impact on the fragile ecosystem.
Goebel et al. (2015)	Cape Shirreff, Antarctica	Microdrone md4-1000, Aerial Imaging Solutions APQ-18, Aerial Imaging Solutions APH-22	Tested three UAVs and camera systems to compare performance in collecting abundance and disturbance information on a few penguin and seal population samples.
Vander Jagt et al. (2015)	Tasmania, Australia	Doidworx SkyJiB	Used imagery obtained from UAS in conjunction with photogrammetric techniques to resolve spatially continuous snow depths using snow-covered and snow-free RGB images.
Jonassen et al. (2015)	Weddell Sea, Antarctica	Multiplex and Mavionics custom Fixed Wings and a custom quadcopter	Used multirotor and fixed wing UAVs to collect stratified air samples and physical properties for atmospheric boundary layer profiling above sea ice.
Steiner et al. (2015)	Liring Glacier, Nepal	Swinglet CAM	Utilized updated meteorological and in situ measurements to model ice cliff backwasting with the aid of a DSM produced by previously published flights.
Cimoli 2015, Cimoli et al. (2017)	Longyearbyen, Svalbard	Walkera X350 Pro, DJI S900, custom-built octocopter	Sought to assess the feasibility of UAS SfM for depicting snow depth variability. Expected to fly at six locations but only one completed due to "UAS failure." Suggested pilots to be prepared to fly manually in Arctic locations.
Westoby et al. (2015. 2016)	Patriot Hills, Antarctica	Unspecified fixed wing	Orthomosaic and DSM produced by a UAV flight to aid in upscaling from patch scale sedimentological characterization and quantify short-term surface evolution of a moraine complex.
De Michele et al. (2015, 2016)	Val Grosina Vallu, Italy	SenseFly Swinglet CAM	Investigated UAV capability of detecting centimeter-resolution snow depth distribution compared to ground measurements for an alpine region.
Stuchlik et al. (2016)	Norden-skiöldbreen glacier, Svalbard	Custom multirotor	Created example products to demonstrate possible uses of UAVs including a RGB and IR orthomosaic of a proglacial river system. This is a proof-of-concept manuscript.
Buri et al. (2016)	Liring Glacier, Nepal	Swinglet CAM	Created a gridded cliff backwasting model including DSM produced from previously published flights.
Pederson et al. (2016)	Zackenberg, Greenland	Unspecified	Used a UAV-derived DSM to describe landscape features for investigating variations in snow distribution amongst vegetation types.
Boesch et al. (2016)	Brämabühl, Switzerland	Ascending Technologies (AscTec) Falcon 8	Investigated practical upgrades with the evolution of RGB + NIR sensor hardware and SfM software for UAV and manned aircraft for improved reconstructions of snow height in an Alpine area.
Ewertowski et al. (2016)	Norden-skiöldbreen glacier, Svalbard	Unspecified quadcopter	Used a UAV to produce a detailed map of complex flutings to supplement a study on the geomorphology of terrestrial margins within the foreland of a tidewater polythermal glacier.
Evans et al (2016)	Fláajökull glacier, Iceland	Unspecified quadcopter	A single UAV survey was flown to map submarginal landforms that have recently evolved (since 1989) at a glacier snout.
Tonkin et al. (2016)	Austre Lovénbreen, Svalbard	DJI S800	UAV imagery used to investigate the degradation of an ice-cored lateral-frontal moraine.
Harder et al. (2016)	Canadian Rocky Mountains and Saskatchewan	Sensefly eBee	Quantified snow depth using a UAV with RTK technology on different terrain types (prairie and alpine) and tested accuracy.
Vincent et al. (2016)	Changri Nup Glacier, Nepal	Sensefly eBee	Glacier surface mass balance is modeled combining UAV, terrestrial photogrammetry, satellite, and in situ measurements to investigate debris-cover influence using data from previously published flights.
Kraaijen-brink et al. (2016)	Liring Glacier, Nepal	Sensefly eBee	Collected optical RGB and thermal data on separate flights surveying a debris-covered glacier and compared to in situ and satellite sources.
Brun et al. (2016, 2018)	Liring Glacier, Changri Nup Glacier, Nepal	Sensefly Swinglet CAM, Sensefly eBee	Quantified total contribution of ice cliff backwasting to the net ablation of a glacier tongue via UAV-collected backwasting and surface thinning based on data from previously published flights.
Buhler et al. (2016, 2017)	Davos, Switzerland and Lizum, Austria	Ascending Technologies (AscTec) Falcon 8, Multiplex Mentor Elapor	Photogrammetrically estimated snow depth with UAVs on various surfaces including exposed alpine peak, sheltered valley area, and homogenous snow surfaces and discussed UAV performance in several scenarios
Rümmler et al. (2016, 2018)	South Shetland Islands, Antarctica	Mikrokopter MK ARF Okto XL	Recorded behavioral reactions to a UAV flown at different altitudes of Gentoo and Adélie penguins. Disturbance was visible when flown at a upper level of 30 m and 50 m above ground respectively.
Lambiel et al. (2017)	La Roussette rock glacier, Switzerland	SenseFly eBee RTK	Preliminary results of orthomosaics collected of a remote, difficult to reach, rapidly moving, and newly discovered rock glacier within the Valais Alps.
Dall'Asta et al. (2017)	Valtournenche Valley, Italy	Swinglet CAM, SenseFly eBee RTK	Discussed the performance of GCP and RTK derived UAV products for depicting displacement and characteristics of a rock glacier.
Telg et al. (2017)	Ny-Alesund, Svalbard	Manta fixed wing	Mounted on a UAV, collected several aerosol properties using a condensation nuclei counter, chemical filter sampler, three-wavelength aerosol absorption photometer, printed optical particle spectrometer, miniature scanning sun photometer, HC2 temperature and relative humidity probe.
Miziński and Niedzielski (2017)	Izerskie Mountains, Poland	Sensefly eBee and Swinglet CAM	Tested a novel method for on-demand snow depth mapping that omitted artificial GCPs though was found to be less accurate than including GCPs.
Phillips et al. (2017)	Kvíárjökull glacier, Iceland	Unspecified multirotor	Mixed methods study including terrestrial LiDAR, satellite, ground penetrating radar, and high-resolution maps from RGB flown UAV to analyze activity of a pulsing glacier.
Nehyba et al. (2017)	Norden-skiöldbreen glacier, Svalbard	Unspecified multirotor	UAV orthophoto and DSM supplemented QuickBird imagery to provide information on surficial deposits and associated landforms (i. e. fluvio-deltaic terraces) to support study on an ice-dammed lake.
Mustafa et al. (2017, 2018)	South Shetland Islands, Antarctica	Mikrokopter MK ARF Okto XL	Tested census techniques of penguin populations and found that NIR can be useful for distinguishing guano once vegetation signals are removed using NDVI, which has been helpful for identifying individual breeding pairs. Also reviewed wildlife responses to UAV activities.
Liang et al. (2017)	Tibetan Plateau, China	DJI Inspire 1 Pro	Three fractional snow cover mapping algorithms were tested on UAV and satellite data. A back-propagation artificial neural network model performed the best in the plateau's complex terrain.
Smith et al. (2017)	Kangerlussuaq, Greenland	Skywalker X8	RGB flight data that originally appeared in Ryan et al. (2015) provided catchment boundaries, surface drainage patterns, and snow cover for Rio Behar.
Busker (2017)	Langtang Glacier, Nepal	Sensefly eBee	A thesis using the flights previously provided by Kraaijenbrink to investigate methodology on measuring ice cliff backwasting.
Ader and Axelsson (2017)	Tarfala, Sweden	DJI Phantom 4	A thesis exploring the possibility of physically using UAVs for Arctic research. Includes interviews with UAV industry representatives and scientists, and test flights performed by unexperienced pilots as a measure of ease in applicability.
Lovitt et al. (2017)	Alberta, Canada	Aeryon Scout	UAV was used to reproduce ground elevations in peat land area and evaluate the role of vegetation and surface complexity.
Faulkner et al. (2017)	Summit, Greenland	Cryowing	Collected UAV-derived albedo over the Greenland ice sheet coincident with the MODIS sensor overpass for validation.
Bernard et al. (2017, 2017)	Austre Lovén glacier, Svalbard	DJI Phantom 3	Used UAVs to analyze ice, snowpack and moraine dynamics with hydrology through repeated UAV survey a few days apart to capture a quickly changing environment.
Ely et al. (2017)	Isfallsglaciären, Sweden	Custom hexactopter	Mapped a polythermal glacier for geomorphological characteristics including moraines, fans, channels and flutes.
Krause et al. (2017)	Cape Shirreff, Antarctica	Aerial Imaging Solutions APH-22	Flew a UAV to identify mass and body conditions of pinnipeds at target altitudes of 23, 30 and 45 m above ground level.
Malenovsky et al. (2017)	Windmill Islands, Antarctica	Custom-built octocopter	Collected hyperspectral high-resolution imagery to estimate moss bed health via machine-learning support vector regressions.
Dąbski et al. (2017)	King George Island, Antarctica	PW-ZOOM	Detect and quantified periglacial landforms such as scarps, taluses, a protalus rampart, solifuction sheets, bedrock outcrops, and more from an orthomosaic and DSM.
Jouvet et al. (2017)	Bowdoin Glacier, Greenland	Skywalker	Combined UAV and satellite imagery with ice flow modelling to analyze calving activity of a marine-terminating glacier.
Wigmore and Mark (2017)	Llaca Glacier, Peru	Custom-built hexacopter	Found heterogenous patterns of glacial volume change, surface velocities, and proglacial lake changes via a hexacopter designed for high-altitude missions.
Seier et al. (2017)	Pasterze Glacier, Austria	QuestUAV	Used a UAV along with electrical resistivity tomography for surface change detection of a glacier terminus. Provided a great example of careful accuracy assessment for UAV DSMs.
Gindraux et al. (2017)	Multiple glaciers, Switzerland	Sensefly eBee	Collected glacier DSMs in summer, autumn, and winter to investigate the accuracy of UAV-derived DSMs. Found that GCPs increase accuracy until a threshold is met and the presence of fresh snow decreases DSM accuracy.
Ryan et al. (2017)	Kangerlussuaq, Greenland	Skywalker X8	Obtained accurate fine-scale resolution of albedo over a sample of the Greenland ice sheet.
Scaioni et al. (2017, 2018)	Forni Glacier, Italy	SenseFly Swinglet CAM	Based on previously published flights, sought to understand precursory signals of an observed collapse of glacier tongue and discussed challenges of SfM applications for alpine glacier change.
Weimer-skirch et al. (2018)	Crozet Islands, South Indian Ocean	DJI Phantom 3	Assessed samples of eleven seabird species behavioral reaction to UAV flown within close vicinity at different altitudes. Found reactions above 50 m relative to individuals provided negligible impacts.
Lousada et al. (2018)	Adventdalen, Svalbard	Unspecified	Compared UAV flown RGB to aerial RGB + NIR imagery for identifying morphometric and topological features of ice-wedge polygonal networks.
Jones et al. (2018)	Isunguata Sermia, Greenland	Skywalker X8	Flew over the lower 16 km ablation area of a glacier at an altitude of 800 m to describe the structural, geomorphological and hydrological features of terminus.
Cooper et al. (2018)	Kangarussuaq Greenland	Unspecified quadcopter	UAV supplied a supplementary orthomosaic and DSM for study on cryoconite holes.
Yang et al. (2018)	Kangerlussuaq, Greenland	Skywalker X8	RGB flight data that originally appeared in Ryan et al. (2015) assisted in validating accuracy of supraglacial stream-river delineations from satellite imagery.
de Boer et al. (2018)	Oliktok Point, Alaska, USA	QuestUAV Data-Hawk and Pilatus	Described the UAV-enabled tasks performed under the US DOE Atmospheric Radiation Measurement program, including data collected on atmospheric aerosols, thermodynamics, and albedo over sea ice.
Fugazza et al. (2018)	Forni Glacier, Italy	Sensefly Swinglet CAM and custom quadcopter	Analyzed multi-year surveys to evaluate glacier thinning rate and for mapping hazards related to collapse event.
Jouvet et al. (2018)	Bowdoin Glacier, Greenland	Firefly 6 vertical take-off and landing hybrid UAV	Flown twice a day for twelve days over Bowdoin Glacier to monitor non-linear plume dynamics at the calving front.
Alfredson et al. (2018)	Trondheim, Norway	DJI Phantom 3	Subtracted a UAV DSM from a previously available DSM to estimate river ice thickness. Orthomosaic produced to map river ice for an ice jam and anchor ice dams.
Mather et al. (2018)	Leeden Tor, UK	DJI Phantom 3, Sensefly eBee	Evaluated methodologies for automated mapping of relict, sorted patterned ground characteristic of mature periglacial landforms using off-the-shelf fixed wing and multirotor systems.
Tan et al. (2018)	Scott Base, Antarctica	Unspecified multirotor	Preliminary results of an investigation into feasibility to utilize airborne radar onboard a UAV to map out snow depth on sea ice in Antarctica.
Gonzalez et al. (2018)	Tuktoyaktuk Coastal Plain, Canada	Unspecified	Preliminary results of quantitative morphological description of pingos (conical ice-cored hills) via UAV and satellite imagery.
Midgley et al. (2018)	Midtre Lovénbreen glacier, Svalbard	DJI S800	Compared a LiDAR topographic dataset to a UAV DSM to study moraine evolution and glacial landform response to climate.
Florinsky and Bliakharskii (2018)	Progress Station, Antarctica	Geoscan 201 fixed wing	Presented a novel approach for revealing hidden crevasses based on geomorphometric treatment of high-resolution glacier DSMs.
Bliakharskii and Florinsky (2018)	Progress Station, Antarctica	Geoscan 201 fixed wing	Based on the same flight that appears in Florinsky and Bliakharskii (2018), expands on crevasse identification and observations of a surface collapse event of Dålk Glacier.
Isacsson (2018)	Tarfala, Sweden	DJI Phantom 4** **Discussed the DJI Phantom 4 throughout the paper. One sentence stated the imagery used was collected by a DJI Phantom 3, we assume here this was a typographical error.	A sibling thesis to Ader and Axelssson (2017), investigated the performance of UAVs in mapping snow surface distance and snow layer depth estimation comparing Agisoft Photoscan and Pix4d reconstructions and various sensors.
Attalla and Tang (2018)	Tarfala, Sweden	N/A	A thesis that more thoroughly described engineering aspects of applying LiDAR and ultrasonic sensor on a UAV for measuring heights of ablation stakes. Sensors were tested in a lab setting and a UAV was not flown.
Adams et al. (2018)	Tuxer Alps, Austria	Multiplex Mentor Elapor	Twelve UAV flights of a snow-covered slope confirmed that both RGB and NIR UAV-derived DSMs provide highest accuracy under full sunlight conditions, while NIR provided more accurate snow DSMs under poorly illuminated conditions.
Luo et al. (2018)	Kunlun Mountains, China	DJI Inspire 1	Measured the thermal influence of power transmission poles and railroads on permafrost slopes via an RGB and IR-enabled UAV. They recorded variability of heat transfer that could create unstable foundations for the infrastructure. They recommend image overlap to be at least 90% for successful thermal mosaicking.
Barnas et al. (2018)	Manitoba, Canada	Trimble UX5	Opportunistically observed the behavior of three adult male polar bears and discusses the use and challenges of UAVs use for surveying polar bears.
Zmarz et al. (2018)	King George Island, Antarctica	PW-ZOOM	Flew a UAV beyond line of site to identify fauna, flora, and landforms to successfully monitor key elements of a polar ecosystem on the remote Penguin Island.
Rossini et al. (2018)	Morteratsch Glacier, Switzerland	DJI Phantom 4	Collected information on surface velocity, brightness, roughness, and DSM differencing of the ablation region of Morteratch Glacier.
Kraaijen-brink et al. (2018)	Liring Glacier, Nepal	Sensefly eBee	UAV was flown with both RGB and IR to improve UAV surveying potential for estimating glacial debris thickness via thermal signatures.
Kraaijen-brink 2018	Liring Glacier, Nepal	Sensefly Swinglet CAM	Two field campaigns flown to assess the magnitude of the downwasting of a debris-covered glacial tongue and the average glacier movement over the monsoon season.
Kim and Kim (2018)	East Siberian Sea	DJI multirotor (unspecified)	Proposed a method of detecting incorrect matches among images prior to correcting DSMs derived from UAV flown over sea ice.
Kizyakov et al. (2018)	Siberia, Russia	Unspecified	Mapped impact hollows resulting from gas emission craters in permafrost zones using a UAV.
Van der Sluijs et al. (2018)	Northwest Territories, Canada	A Sensefly, 2 Badatech, 2 DJI UAVs	Quantified permafrost thaw slump dynamics, estimated volumes of downslope sediment transfer and identified stratification features along a headwall.
Avanzi et al. (2018)	Belvedere glacier, Italy	Custom hexacopter	Compared snow depth measurements of UAV with a high-resolution MultiStation laser-scanner, found similar results within centimeter accuracy of spatial distribution of seasonal, dense snowpack.
Korczak-Abshire et al. (2018)	King George Island, Antarctica	PW-ZOOM	Based on the same flight data in Zmarz et al. (2018), this study further provided a census of local seabird and seal populations on Antarctic islands that would otherwise be difficult to access.
Fernandes et al. (2018)	Gatineau and Acadia, Canada	DJI Phantom 3	Investigates accuracy of multitemporal snow depth measurements over diverse microtopographic and vegetation cover terrain in relation to photogrammetric theory.
Schirmer and Pomeroy (2018)	Canadian Rocky Mountains	Sensefly eBee	Used SfM to develop maps of snow depth and snow cover to use as proxies for snow water equivalent, ablation rates, and snow cover depletion using data from previously published flights.
Cook et al. (2018) [98]	Western Greenland	DJI Phantom 2	Extracted still images from UAV-collected RGB video to obtain frequency, coverage, and geometric data of cryoconite holes.
Bash et al. (2018, 2019)	Fountain Glacier, Canada	MikroKopter	Measured daily and total glacial ablation via UAV reconstructions of a glacier. Later tested an enhanced temperature index model of glacier surface melt from this data.
Jenssen et al. (2018, 2019)	Multiple sites, Norway	Foxtech Kraken	Flew a radar to resolve snow stratigraphy and a dry snowpack and tested its capability of detecting a person buried under 1.5 m of wet snow.
Léger et al. (2019)	Seward Peninsula, Alaska	3DR Solo UAV	Vegetation and topography information collected by UAV was combined with additional sensors to analyze permafrost parameters.
Rohner et al. (2019)	Eqip Sermia Glacier, Greenland	Sensefly eBee	Compared satellite SAR, terrestrial radar interferometer, and UAV-derived velocity fields of a marine terminating glacier.
Lendzioch et al. (2019)	Šumava National Park, Czech Republic	MicroKopter ARF-Okto XL	Subtracted snow-free from snow-covered UAV-derived DSMs during different snow conditions for snow depth calculations in a forest environment and additionally related this to leaf area index.
Hendrickx et al. (2019)	Cliosses rock glacier, Switzerland	Custom DJI F550	Created multiple reconstructions of a rock glacier with identical inputs to test Agisoft Photoscan SfM variation among outputs.
Lamsters et al. (2019)	Greenland, Antarctica, Iceland	DJI Phantom 3, DJI Phantom 4, DJI Mavic Air	Discussed a collection of experiences and recommendations for using off-the-shelf DJI multirotors for DSM and orthomosaic production in polar environments.
Cook et al. (2019)	Western Greenland	Steadidrone Mavrik	Applied a novel supervised classification to a UAV-collected multispectral orthomosaic to map algae cover on the surface of the Greenland ice sheet.

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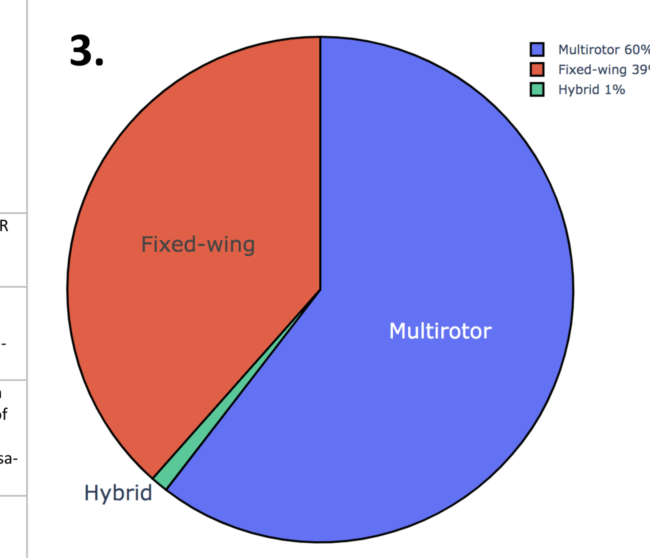

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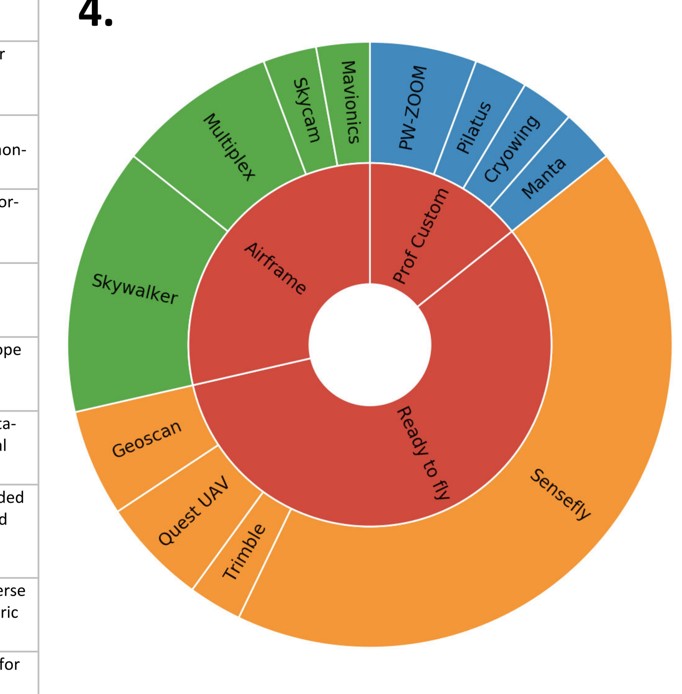

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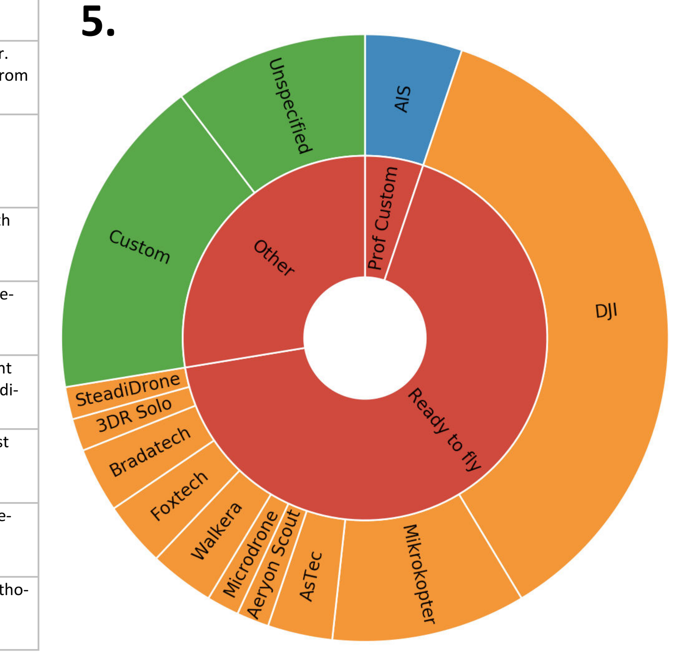

Figures

1.) Global distribution of the reviewed study sites. The point size indicates the relative number of UAV flights completed within the peer-reviewed journals, conference proceedings, and university degree theses published online between 2014 and 2019.
2.) Distribution of main topics of recently published studies utilizing UAVs for cryosphere research. This plot consists of the studies that were published as complete research articles in peer-reviewed journals and conference proceedings, or as university degree theses made available online between 2014 and 2019.
3.) The UAV hardware technology used by the studies. Percentages indicate the frequency of use surveyed from the studies. All platforms were included for studies that employed multiple UAV types.
4.) The preferred brands of fixed-wing vehicles used among the surveyed studies (N=35). Inner circles of each categorize the chosen platforms as ready to fly / off the shelf UAVs, if they were an airframe that requires some customization, or professionally customized UAVs.
5.) The preferred brands of multirotor vehicles used among the surveyed studies (N=58). Inner circles of each categorize the chosen platforms as ready to fly / off the shelf UAVs, if they were an airframe that requires some customization, or professionally customized UAVs. “AIS” is an abbreviation for Aerial Imaging Solutions. Multirotor category “Custom” includes studies that explicitly said they flew a customized multirotor.

Reference

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