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Abstract

Small Unmanned Aircraft Systems (UASs) are often suited to applications where the cost, resolution, and/or operational inflexibility of conventional remote sensing platforms is limiting. Remote sensing with small UASs is still relatively new, and there is limited understanding as to how the data are acquired and used for scientific purposes and decision making. This paper provides practical guidance about the opportunities and limitations of small UAS-based remote sensing by highlighting a small sample of scientific and commercial case studies. Case studies span four themes: (i) mapping, which includes case studies to measure aggregate stockpile volumes and map river habitat; (ii) feature detection, which includes case studies on sandhill image classification and detection of agricultural crop infection; (iii) wildlife and animal enumeration, with case studies describing the detection of fish concentrations during a major salmon spawning event, and cattle enumeration at a concentrated animal feeding operation; (iv) landscape dynamics, with a case study of arctic glacier change. Collectively, these case studies only
represent a fraction of possible remote sensing applications using small UASs, but they provide insight into potential challenges and outcomes, and help clarify the opportunities and limitations which UAS technology offers for remote sensing of the environment.

Key words: UAS, remote sensing of the environment, case studies, unmanned aerial vehicles, remotely piloted aircraft, remote sensing

1. Introduction

Remote sensing from satellites and from manned aircraft is a valuable tool that can provide summary measurements of land cover, surface conditions, and related changes at a variety of spatial and temporal scales. Remote sensing is continuously and rapidly evolving with the advent of new technology. In the past, most remote sensing relied upon medium-resolution imagery from sensors such as Landsat ETM and SPOT (ground resolutions ≈ 5-30 m). The latest generation of optical satellites (e.g., GeoEye, WorldView) have ground resolutions in the range of 0.5-1 m, which is starting to rival traditional aerial photography (resolutions typically 0.1-0.5 m). This “resolution creep” is also blurring the distinction between photogrammetry and remote sensing. Satellite imagery is now often used in traditional photogrammetric roles, such as the generation of digital elevation models (DEMs) and orthoimages.

Further evidence of the integration of photogrammetry and remote sensing can also be seen in technologies such as airborne LiDAR (e.g. Glennie et al. 2013) and Synthetic Aperture Radar (SAR) (e.g. Crosetto and Aragues 2000). These are active systems, which allow the production of DEMs through completely different workflows than those used in traditional photogrammetry. Frequently spectral information for analysis is being extracted from aerial photography (e.g. Hunt et al. 2010; Knoth et al. 2013). Similarly, the development and refinement of Structure from Motion (SfM) packages such as Bundler (e.g. Fonstad et al. 2013) and Photoscan (e.g. Turner et al. 2012) now make it possible to produce accurate Digital Surface Models (DSMs), Digital Terrain Models (DTMs) and orthoimage mosaics quickly and affordably.
The resolutions and capabilities of different sensors have seen major improvements over the last few years. However until recently, remote sensing surveys were largely carried out from satellites or manned aircraft. This is changing with the proliferation of small (< 25 kg) Unmanned Aerial Systems (UASs). Such systems typically consist of a lightweight Unmanned Aerial Vehicle (UAV), imaging payload, controller, navigational computer, and ground-based pilot (and spotters, if required). Distinction of the “small” class of UASs came about through the U.S. Federal Aviation Administration’s Modernisation and Reform Act of 2012 (cf. Hugenholtz et al. 2012). The use of UASs smaller than 5 kg is expected to expand rapidly for civil, commercial and scientific uses, because they are less expensive and more versatile than larger UASs. They are also capable of acquiring high-resolution imagery safely from much lower altitudes than those associated with manned aircraft and larger UASs.

There has been a great deal of interest and speculation about the potential applications of small UASs in the scientific community (cf. Hugenholtz et al. 2012). However much of the literature published to date only addresses potential applications, rather than analysing completed case studies and presently-viable uses. Other published studies relate to experimental applications of new sensors such as UAS-mounted LiDAR, (e.g. Lin et al. 2011), which are of interest for the future but are insufficiently mature at present to allow routine operation. To address this, we present seven case studies derived from our collective experience. These studies represent applications for which the current generation of small UASs are well suited, and which can be carried out on a routine basis without the need for customisation. These applications can therefore be considered as being representative of the current range of applications for which small UASs are being used. Although the examples presented here are all from Canada, similar applications are possible anywhere in the world (subject to local regulations). The case studies focus on four broad themes:

1) Mapping: Case studies include the determination of aggregate stockpile volumes and mapping of river habitat.
2) Feature detection: This section includes case studies on image classification of pocket gopher mounds and the detection of agricultural crop infection.

3) Wildlife: Examples include a survey of a major salmon spawning event and the use of thermal infrared imagery for cattle enumeration.

4) Landscape dynamics: This section features a case study in which imagery from a small UAS was used to study glacier dynamics.

While these case studies illustrate only a small number of the remote sensing applications that are possible using small UASs, they serve to illustrate both the advantages and the challenges of working with this type of data. Successful integration of data gathered by small UASs will ultimately depend on whether the advantages of such data (e.g. high spatial resolution, affordability, flexibility of acquisition) outweigh the disadvantages (e.g. variable illumination, inconsistent geometry, low quality imagery).

This review is the second part of a two part paper. Part 1 (Whitehead and Hugenholtz, in review) addresses the technology and present issues associated with spectral and topographic data collected from UASs. For more basic primers on the use of UASs and complementary perspectives, we refer readers to reviews by Hardin and Jensen (2011) or Watts et al. (2012).

2. Regulations governing the use of small UASs in Canada

As described in the companion paper (Part 1), regulations are in place in many countries which govern non-military uses of small UASs. These regulations influence the remote sensing data collected by UASs. Since this review features case studies performed in Canada, in this section we outline the regulatory framework and some of the rules that distinguish remote sensing data acquired by small UASs to provide necessary context.

In Canada, the operation of UASs falls under the Canadian Aviation Regulations, which are administered by Transport Canada – the federal agency overseeing Canada’s transportation systems. In order to carry out non-recreational remote sensing surveys with small UASs, an individual must hold
insurance and a Special Fight Operations Certificate (SFOC) (Transport Canada 2008). This permits the operation of a UAS, subject to several conditions, some of which are described below. Although Transport Canada may issue blanket SFOCs for organisations to operate in certain parts of the country, new applications are always dealt with on an individual basis.

The paperwork and time involved in completing SFOC applications can slow entry for many researchers and professionals wishing to become involved in UAS operations. To meet the demand from such users, Transport Canada makes provision for a simplified application process (Transport Canada 2008). This process streamlines the application and is designed to meet the needs of the majority of such users. However users who require greater operational flexibility, such as police and search and rescue, may need to apply through the standard SFOC process, as the conditions imposed by the streamlined application process may be too restrictive to meet their needs. The following discussion refers to SFOCs issued under the simplified application process, unless otherwise stated.

One important restriction that impacts remote sensing with small UASs is the regulatory requirement that they are operated within visual range at all times, even though the telemetry between the UAS and ground control system may reach well beyond this limit. In practice, this means that UASs must remain relatively close to the takeoff point, limiting the area that can be surveyed in a single flight. The maximum distance will vary according to the size, shape and colour of the UAS, as well as the weather conditions and lighting. Although Transport Canada may specify otherwise, for many UASs the maximum visual range is < 1 km, which yields a maximum surveyable area of \( \approx 3 \text{ km}^2 \) from one location.

A secondary restriction affecting remote sensing surveys is that the flying height of UASs is typically limited by Transport Canada to a ceiling of 400 feet (122 m) above ground level (Transport Canada 2008). This allows for very high ground resolutions in the imagery, but makes it necessary to collect many more images than would otherwise be necessary, which can in turn introduce problems at the processing stage. At low flying heights, the effects of relief displacement and tree lean are often greatly exaggerated, making it extremely difficult to produce good orthoimages for some areas. In areas
of high relief, the 400 feet limitation may not be practical, and may thus rule out the use of a UAS. Under such circumstances, Transport Canada may allow a higher flying height; however the additional time involved in obtaining the certification may impact the viability of a project.

The simplified SFOC application process currently limits UAS operation in Canada to daylight use only. For photogrammetric and most remote sensing applications this is not a problem. However the daytime-only requirement can be a limitation for thermal surveying. This particularly affects applications such as search and rescue operations, and heat loss and energy efficiency audits (e.g. Martinez-De Dios and Ollero 2006) as night enhances thermal contrasts. With the development of reliable sense and avoid systems, night flights may become more commonplace in the future. However at present night time operation is only permitted when a full SFOC application has been lodged.

Transport Canada also imposes restrictions on the size of UAS platforms that can be flown. In general, only aircraft with a take-off weight of less than 35 kg are permitted (Transport Canada 2008). While aircraft below this weight have the advantages of portability and safety, this restriction effectively limits the duration of flights, as well as impacting aircraft stability. However, the most serious impact is on the size of remote sensing payloads that can be carried. Payload limitations restrict most UASs to carrying only lightweight compact cameras. Larger sensors used on piloted aircraft, such as metric cameras, hyperspectral scanners, Synthetic Aperture Radar (SAR) and light detection and ranging (LiDAR) systems, are generally too heavy at present to be carried on most UAS platforms meeting this weight restriction, and although some proof-of-concept research has mounted some of these sensors to lightweight UASs (e.g. Turner et al. 2012; Wallace et al. 2012), the flying time is generally too short for practical applications. The development of miniaturised “Micro-Electro-Mechanical (MEMS) systems” may usher in a new generation of smaller, lighter sensors in the next few years, but at the present the takeoff weight restriction imposes practical limitations on the type of remote sensing data that can be acquired from small UASs.

Due to safety considerations, there are also restrictions on where small UAS surveys can be carried out. Currently in Canada, no UAS overflights are allowed in urban areas, or within 100 feet of
people or inhabited structures unless consented (Transport Canada 2008). The high spatial resolution that can be obtained from small UAS surveys would be very useful in many urban settings; however, for public safety and perhaps privacy concerns, this restriction is likely to remain in place for research and commercial applications. Further restrictions on location apply in restricted airspace, and close to airports.

A recent report by the Canadian UAV Systems Program Design Working Group proposes major changes for regulation of lightweight UASs under 25 kg in weight (Transport Canada 2012). In particular, this report proposes that UASs classified as “low energy” should be exempted from SFOC regulations. The proposed definition of low energy is that the kinetic energy imparted by the platform to a stationary person or object in the event of a crash is less than 12 J/cm², which is not considered to be a dangerous impact. The implications of this change are that many small UASs could potentially be operated without restriction, particularly those optimised for surveillance. This recommendation has been criticised for ignoring privacy concerns, and has prompted calls for a wider public debate on the implications of regulatory change (Gersher 2014).

3. Case studies

In this section we outline seven case studies. While not exhaustive, these applications represent a cross section of the types of applications for which small UASs are well suited. Many proposed applications of small UASs are experimental, or require expensive customisation of the UAS platform. However the case studies described here were all carried out using commercially-available systems, equipped with standard “off the shelf” components and cameras. As such, they can be considered to be representative of the current state of the industry. In all cases, photography or video is the primary data source. While there are a number of more advanced sensors that have been developed for use with small UASs, these are still largely experimental. The primary use of small UASs to date has been for the production of digital elevation models (DEM)s and orthoimage mosaics. This represents an extension of the traditional photogrammetric mapping process. It is expected that this emphasis will change as the industry matures.
and new sensors and analysis techniques become available. However the case studies presented reflect our intention to portray the current state of the industry.

For each survey we used one of four battery-operated UASs (Figure 1), which included one rotary-wing platform (Aeryon Scout Pro quadcopter) and three fixed-wing UASs (RQ-84Z Aereohawk, Outlander UAS, Ebee). The rotary-wing platform has a maximum flying time of \( \approx 20 \) minutes or less, depending on wind, while the fixed wing UASs range from 40 (Ebee) to 90 minutes (Aereohawk). The cameras used to acquire the imagery included consumer-grade RGB, near-infrared filters, and a FLIR thermal. The purchase price for these UASs ranges from $7,000 CAD for the Outlander UAS to $107,500 CAD for the Aeryon Scout Pro.

3.1. Mapping

3.1.1 Case study 1: Aggregate (sand and gravel) volumetrics

One of the leading commercial applications of UAS-based remote sensing is measuring aggregate stockpile volumes (e.g. Eisenbeiss 2009; Haala et al. 2011; Sauerbier et al. 2011). In Canada, aggregate companies have been early adopters of UAS surveys for several reasons. Aggregate quarries are usually self-contained, and encompass areas that are within or close to the LOS limit. The area involved can easily be covered by a small UAS, although larger quarries may require two or three flights for complete coverage. Quarries are also usually free of vegetation, making the production of accurate DEMs comparatively straightforward.

For this case study, two UAS surveys were carried out of a small stockpile in June and again in November 2012, using the Aeryon Scout Pro quadcopter. This UAS uses a proprietary RGB camera (Photo3S), which has a focal length of 7.5 mm and a field of view of 37° by 29°. For both surveys, 62 images were collected, spread over 6 flight lines, at a flying height of 100 m. In both cases, the aircraft flew at a speed of 5 m s\(^{-1}\) and the survey was completed in approximately 20 minutes. The same flight plan was used for both surveys in order to ensure that the imaging geometry remained as consistent as possible. For each survey, 10 ground control points (GCPs) were surveyed around the stockpile using a
real time kinematic Global Navigation Satellite System (GNSS). On each occasion the stockpile was also surveyed using the GNSS, in order to assess the vertical accuracy of the UAS-derived DEMs relative to the conventional field-based survey approach.

Processing for both jobs was carried out using EnsoMOSAIC software. Initial estimates of image centres and camera orientations were obtained from the aircraft log file. After aerial triangulation (AT) was completed, a 3.5 cm resolution DEM was constructed for each survey. Both DEMs were edited to remove the effects of vegetation and were then used to produce final orthoimage mosaics. The DEMs and orthoimage mosaics generated are shown in Figure 2. Volumetric estimates were produced in each case using ArcGIS.

For the June survey, the RMSE of vertical difference between the UAS-derived DEM and 126 GNSS points surveyed on the stockpile was 0.106 m, with the UAS-derived volume estimate being 2.6% lower than that estimated from the GNSS survey of the stockpile. For the November survey the RMSE of the difference between the UAS-derived DEM and 107 surveyed GNSS points was 0.097 m, with the UAS and GNSS-derived volumes differing by 3.9%. The volume removed from the stockpile between the two surveys was estimated at 1521 m$^3$, which was 2.5% greater than that estimated from the haul weight. Conversion of haul weight to volume necessitates the application of a conversion factor, so haul weight derived estimates are unlikely to agree exactly with the UAS data. Overall, this case study demonstrates that photogrammetric surveying using a small UAS can yield measurements that are comparable to conventional methods of measuring stockpile volume and volume changes.

### 3.1.2. Case study 2: River habitat mapping

One of the key advantages of remote sensing with small UASs is that the data can bridge an important gap between ground-based surveys and remote sensing data from satellites or piloted aircraft. For example, ground-based techniques are very effective for developing high-resolution maps over small areas, but impractical for large areas due to the time and physical effort required. Conversely, remote sensing data from satellites and piloted aircraft can be used to map large areas, but they either don’t have
adequate spatial resolution or are too expensive to map fine-scale features within small to intermediate areas on a routine basis. Small UASs are particularly well-suited to mapping at an intermediate spatial scale (i.e., 1-10 km$^2$).

The case study for this application was carried out along a 1 km segment of the Elbow River, approximately 21 km west of Calgary, Alberta. The UAS survey was conducted during low-flow conditions ($5.9$ m$^3$s$^{-1}$) in late September 2012. The purpose of the UAS survey was to evaluate the ability of the imagery to measure key metrics of reach-scale river morphology. At the field site (50.988°N, 114.509°W), the river flows through a ~200 m wide active channel belt with extensive gravel bars. In a number of places the river splits into separate channels. The channel belt consists of mixed sediment (silt-boulders) and was covered in places by Large Wood (LW), which included individual logs, trees, rootwads and large jams. LW has an important influence on the morphological and biological quality of aquatic ecosystems and as such, is a key component of fish habitat.

The Aeryon Scout Pro quadcopter was used for the survey with its proprietary Photo3S RGB camera. A total of 45 highly visible GCPs were distributed throughout the study area in order to assist with the photogrammetric processing. In total, the survey yielded 192 images, which were used to develop a DEM and orthoimage. One of the unique aspects of this survey was that the water in the active channels was relatively clear, which allowed extraction of the bathymetry. We then applied a two-dimensional hydrodynamic model (River2D) to estimate spatial variability in the flow (see details in Tamminga et al. 2014). We mapped the median grain size of surface sediment ($D_{50}$) using an empirical relation between image texture and field measurements of $D_{50}$ ($R^2 = 0.82$).

Results from the UAS survey are shown in Figure 3. The 5 cm spatial resolution orthoimage mosaic (Figure 3a) and DEM (Figure 3b) allowed for the detailed characterisation of channel morphology and aquatic habitat features (Figure 3c). Based on 297 check points, the vertical RMSE of the DEM was calculated to be 0.088 m in dry, exposed areas, and 0.119 m in submerged areas, following a correction procedure for the refractive effects of the water-air interface (Westaway et al. 2000). This topographic information was sufficient to apply the River2D model, which allowed for determination of depths and
velocities throughout the study reach (Figure 3d, 3e). When superimposed on the base orthoimage, these depth and velocity distributions provide an intuitive method with which to assess reach-scale flow patterns and their relationship to geomorphic context.

To evaluate the utility of the UAS survey data for aquatic habitat assessment, we then combined the modeled hydraulic data with features that provide visual overhead cover for fish species, including LW, overhanging vegetation, undercut banks, water surface turbulence, and pools. Such features are strong determinants of fish habitat availability and were digitised directly from the orthoimage. Using preference curves developed for the nearby, ecologically-similar Kananaskis River that describe the theoretical suitability of depths, velocities, and cover accessibility for adult brown trout, we were able to map out spatial patterns of habitat suitability (Figure 3f) in terms of a composite suitability index that ranges from 0 (least suitable) to 1 (most suitable). Although not validated directly, this method highlights distributions of potentially desirable habitat hotspots and can be used to estimate the total habitat availability for the reach. It also demonstrates how the perspective offered by UAS data can show the spatial complementarity of habitat features: deep, low velocity pools with abundant overhead cover sources were identified as highly suitable areas and easily mapped throughout the reach. Overall, the combination of the high-resolution orthoimage and detailed topographic data provided by small UAS-based remote sensing provides an ideal method for intermediate scale analyses of river morphology and aquatic habitat.

3.2. Feature Detection

3.2.1. Case study 3: Precision agriculture

Precision agriculture is a sophisticated method of actively managing within-field variability in crops, which often makes use of remotely-sensed imagery in order to provide data on spatio-temporal variability in crops (Mulla 2013). Remote sensing is especially useful for identifying areas needing additional treatment with water, chemicals, pesticides and herbicides. However, widespread adoption of remote
sensing in precision agriculture is contingent on affordability, accessibility, and the resolution (spatial, temporal, spectral and radiometric) of the imagery. For small-scale operations, the cost of data from conventional remote sensing platforms may be too high. Small UASs potentially offer a low-cost alternative to conventional remote sensing platforms, and research to date shows promise (e.g. Berni et al. 2009; Baluja et al. 2012; Zhang and Kovacs 2012; Bellvert et al. 2013; Calderon et al. 2013; Corcoles et al. 2013; Garcia-Ruiz et al. 2013; Gonzalez-Dugo et al. 2013; Huang et al. 2013; Urbahs and Jonaite 2013; Zarco-Tejada et al. 2013; Duan et al. 2014).

The case study for this application involved using imagery from a UAS survey in order to identify and track infections due to late blight (a pathogenic organism which occurs in high value potato crops). We used visible (VIS) and Near-InfraRed (NIR) imagery to identify areas of late blight. The primary characteristic of late blight is chlorosis, which occurs when leaves produce insufficient chlorophyll. To detect late blight we used the Normalised Difference Vegetation Index (NDVI), defined by:

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NDVI = \frac{(NIR - VIS)}{(NIR + VIS)}
\]  

We used the Ebee fixed-wing UAS equipped with a Canon IXUS/ELPH 125HS compact camera (16.1 MP resolution). In order to calculate and map NDVI, the UAS was flown twice over the ≈ 1 km² field located in southern Alberta: once with the camera setting for visible (RGB) light, and once with a NIR filter. A total of 12 flight lines were used to cover the field, resulting in 162 images. The altitude of the UAS was 120 m, yielding a ground resolution of 4.5 cm, which was resampled to 25 cm during the processing. To expedite the image processing and provide the farmer with quicker results, direct georeferencing, using GNSS positions from the UAS log file, was used instead of the more rigorous approach with GCPs. Typical levels of accuracy obtainable from direct georeferencing without differential correction are in the range of 2-5 m (Turner et al. 2013).
The first survey was flown in mid July, with a follow up survey two weeks later. The image mosaics of the visible and NIR imagery from both surveys are shown along with the computed NDVI maps in Figure 4. Imagery from the first flight in mid July showed that late blight was present in a small patch located in the southeast corner of the field. Identification of late blight is fairly straightforward because it typically begins in small patches, whereas water stress is not as isolated. The presence of late blight was later confirmed by the farmer, who then applied fungicide in an attempt to manage the infection and limit its spread. A second UAS survey was then performed in late July in order to determine if the fungicide had been successful. This survey was identical to the first and used the flight parameters and configuration from the first survey, two weeks earlier. In this case the imagery revealed that late blight had spread to other patches, thus requiring more intensive fungicide applications to limit further spread.

3.2.2 Case study 4: Pocket gopher mound feature detection and image classification

One of the unique characteristics of remote sensing imagery from small UAS is that it is able to resolve small-scale features that are otherwise difficult or impossible to resolve with imagery from satellites and manned aircraft. For example, after processing it is not uncommon to obtain ground resolutions of 5 cm or less with RGB imagery acquired from a UAS equipped with an off-the-shelf digital camera. This is about an order of magnitude smaller than the ground resolution of the highest-resolution satellite imagery that is available commercially (e.g., GeoEye-1: 0.5 m). However, the high ground resolution also brings a whole host of challenges in terms of adapting image classification techniques developed for low-resolution imagery (Laliberte et al. 2010; Laliberte and Rango 2011).

This case study illustrates feature detection of pocket gopher mounds in a grassland region of southwestern Saskatchewan. In June 2012 we acquired RGB imagery from the RQ-84Z Aerohawk UAS over an area of roughly 2 km². The camera used was an Olympus PEN Mini E-PM1 with a 14 mm lens. This camera had been pre-calibrated prior to the survey. A total of 280 images were gathered along 14
flight lines, with the overlap and sidelap between strips both set to 65% to ensure full stereo coverage. The flight was completed in 50 minutes under ideal conditions: clear skies and light winds.

Ground control for the survey consisted of 28 yellow plastic targets distributed throughout the site. Processing was carried out using the Match-AT module of Trimble’s Inpho software. Following Aerial Triangulation (AT), 1 m resolution DEMs and DSMs were created for the survey area. The process used by Inpho to create DEMs involves interpolation between points within a sparse point cloud (Hugenholtz et al. 2013). Consequently it is less sensitive to the effects of vegetation than a surface model produced using a dense point cloud, and will often provide a better representation of the terrain in vegetated areas. In contrast a DSM better represents bare areas and areas which have low contrast variations. The DSM covering the bare areas, and the DEM covering the vegetated areas, were combined to form a composite terrain model, which was used to generate a set of 0.1 m resolution orthoimages. The final step was to combine these to form a seamless orthoimage mosaic (Figure 5).

While the primary goal was to test the vertical accuracy of a DEM derived from the UAS imagery relative to airborne LiDAR data (Hugenholtz et al. 2013), the final mosaiced orthoimage revealed the pervasiveness of a distinct feature that was otherwise unremarkable from the ground. Littered extensively across the survey area were small mounds of sand, usually 1 m in diameter or less, caused by the digging activities of fossorial mammals like the northern pocket gopher (Thomomys talpoides) and thirteen-lined ground squirrel (Ictidomys tridecemlineatus). These are highly active burrowing mammals that leave numerous, but relatively small, mounds of excavated sand above their burrow networks.

While there has been a significant amount of research on the impact fossorial mammal disturbance has on ecosystems at a localised scale, there is little in the literature to suggest how widespread such ‘bioturbation features’ actually are. For the most part, their intensity of disturbance in any one landscape has largely relied on proxies such as population censuses or rough estimates of mound coverage, with 5-25% being commonly reported numbers (see for example Richens 1966; Turner et al. 1973; Foster and Stubbendieck 1980; Grant et al. 1980; Hobbs and Mooney 1985; Spencer et al. 1985; Huntly and Inouye 1988; Reichman et al. 1993). The majority of mounds are too small to distinguish
using traditional remote sensing imagery, limiting all research to what is logistically feasible to achieve at the scale of a research plot (i.e., < 1 acre). With 10 cm or better resolutions over relatively large areas, imagery from small UASs presents an opportunity to directly measure the footprint of fossorial mammal disturbance at the scale of a landscape for the first time.

An automated workflow was developed using object-based image classification to avoid manually digitizing the mounds (estimated to take > 3 months). Using the feature extraction module in ENVI 5, groups of similar pixels in the image were segmented in order to create image objects at a scale fine enough to recognise the mounds. Spatial, spectral, and textural attributes for each image object were then calculated based on both the RGB bands in the original mosaic, and several custom bands generated in a pre-processing step that enhanced different aspects of mound characteristics (edges, brightness, etc.). Classification rule sets to isolate the mound objects from the background grassland matrix were then constructed based on the object attributes. Due to variability in focus and issues with bidirectional reflectance, no single rule-set could accurately separate mounds across the entire mosaic. As a result, the image was broken up into five locally similar sub-zones, with separate classification rule-sets built for each.

The final classification produced a binary vector map of mounds at study site (Figure 5). This allowed total area of disturbance to be assessed at a landscape scale, showing that while mounds can be locally extremely abundant, in aggregate they only cover ~ 1% of the landscape, one fifth of the area than has previously been estimated using ground based methods.

3.3. Animal and wildlife monitoring

3.3.1. Case study 5: Monitoring a salmon spawning event

Due to logistical challenges, cost, and the requirement for high resolution imagery, small UASs can fill an important niche for wildlife researchers. The imagery or video collected by the UAS can be used for wildlife enumeration or detecting the presence or absence of wildlife. This case study describes efforts to map the annual salmon run in October 2010 along the Adam’s River in southern British Columbia,
Canada. The goal was to provide an overview of salmon locations; salmon have important ecological and socio-economic implications in the region.

The October 2010 sockeye salmon run along the Adam’s River was believed to have been the largest in the last 100 years, with an estimated four million salmon returning to the river (Adams River Salmon Society 2013). During the peak of this run, a UAS survey was carried out along a 1 km segment of the river near Shuswap Lake. The survey involved the Outlander UAV, which is a lightweight fixed-wing UAV with a 2.5 m wingspan. The aircraft carried a Panasonic Lumix-LX3 camera, which is lightweight, compact, and has a retractable lens assembly. The camera was used at its widest angle setting, giving it an effective focal length of 5.1 mm.

The main purpose of the survey was to produce an image mosaic that would allow the major concentrations of salmon, and individual salmon on the spawning grounds to be clearly identified. The river survey was flown in four strips at a height of 150 m above ground level, which gave a spatial resolution of better than 5 cm. The aircraft was launched from a sandy beach adjacent to the river, and it was recovered after the survey by flying it into a net.

Five GCPs were placed at accessible locations along the river. For this application, high spatial accuracy was not required, and horizontal errors of up to 2 m were considered acceptable. Processing was carried out using Trimble’s Inpho software, with all GCPs being given the same nominal elevation. Rather than using a DEM to orthorectify the images, a simple flat surface was used to rectify the imagery. This process is sufficient to remove scale and perspective distortions, but residual relief distortions within the imagery are not corrected for. The final mosaic was assembled from the rectified images and is shown in Figure 6.

The imagery acquired provides a unique perspective of the distribution of salmon within the river, and clearly shows individual salmon occupying the spawning beds. Conventional aerial photography would not be able to provide the level of resolution, nor the flexibility in the timing of image acquisition that was achieved using the small UAS. When combined with external information from sources such as fish tagging, UAS imagery could potentially be used to arrive at an estimate of salmon numbers at the
time of the survey. In this case there was no such external information available, but it is estimated that the salmon shown in Figure 6 number in the hundreds of thousands.

### 3.3.2 Case study 6: Cattle enumeration

For larger mammals, imagery acquired from small UASs has been quite successful at detecting individuals, for example: elephants (Vermeulen et al. 2013), rhinoceros (Mulero-Pazmany et al. 2014), manatees (Jones et al. 2006), birds (Jones et al. 2006) (Chabot and Bird 2012) (Sarda-Palomera et al. 2012), and dugong (Hodgson et al. 2013). In most published examples the enumeration has been conducted with RGB imagery, but in order to improve detection against a complex background, Mulero-Pazmany et al. (2014) suggest it may be preferable to use thermal imagery.

Our animal enumeration case study was carried out with the Aeryon Scout Pro quadcopter and an integrated thermal FLIR camera. The application involved beef cattle enumeration at a concentrated animal feeding operation (CAFO) or feedlot. The CAFO consisted of separate holding pens where different groups of cattle were held. The flight was performed in late fall 2012, which provided reasonable temperature contrast between the ground and the cattle. The UAS was flown approximately 100 m above the ground along five flight lines. Individual frames from the thermal FLIR video were extracted and stitched together with Microsoft’s Image Composite Editor (ICE) in order to produce the final mosaic. Given the application, georeferencing was not required. Individual cows were then identified from manual interpretation of the imagery.

A portion of the CAFO is shown in Figure 7a, with individual animals denoted by points in Figure 7b. In most cases, the animals are clearly resolved from the background soil, which makes identification straightforward. There is some distortion in parts of the image caused by animals moving in between flight lines, which introduces some uncertainty to the counts. Capturing a single frame over each pen would likely reduce uncertainty, but this would also require an intervention by the operator in order to position the UAS manually, since the footprints of images acquired during autonomous operation are unlikely to be optimal for this purpose.
3.4. Landform dynamics

3.4.1. Case study 7: Repeat survey of an arctic glacier

Small UASs are ideal for multi-temporal remote sensing aimed at identifying and quantifying environmental changes. Under appropriate weather conditions, the baseline interval between UAS surveys can be specifically tailored to match the pace of the environmental changes under investigation, or can match the interval required for decision making. Furthermore, the ability to develop multi-temporal DSMs and DTMs enables researchers and professionals to track and quantify morphodynamic changes in three dimensions. Already, researchers have used multi-temporal imagery from small UASs to track landslides (Niethammer et al. 2012; Lucieer et al. 2013; Rothmund et al. 2013), monitor crop growth (Bendig et al. 2013), measure changes in stockpile volume (Hugenholtz et al. 2014), count birds (Sarda-Palomera et al. 2012), monitor crop water stress (Stagakis et al. 2012), and monitor changes in various vegetation indices (Zarco-Tejada et al. 2013).

For this case study, a UAS survey was carried out in the summer of 2010 over the terminus of an arctic glacier on Canada’s Bylot Island. A follow up survey was carried out a year later, using imagery captured from a piloted helicopter. Further details on this study are described by Whitehead et al. (2013). The resulting DEMs and orthoimage mosaics allowed detailed estimates to be made of surface thinning, marginal retreat, and flow rates at the glacier terminus, over the one year interval between the surveys.

The 2010 UAS survey was carried out using the Outlander fixed-wing UAS, which carried a Lumix LX3 compact camera with an effective focal length of 5.1 mm. The aircraft flew 16 north-south flight lines, and collected 148 photos from a nominal altitude of 300 m above the glacier surface. The survey covered the lower 1.5 km of the glacier adjacent to the terminus and took approximately 30 minutes to complete. Prior to the aerial survey, 16 targets were placed across the glacier surface, and in the adjacent moraine regions.

This job was processed using Trimble’s Inpho software, with the photos from every second strip being used, except for the steeply-sloping valley sides, where extra photos were added from the unused
strips in order to ensure full stereo coverage. Eight of the targets were used as horizontal and vertical GCPs, with the remaining targets being used as check points. The accuracy assessment showed RMS errors for the check points of 0.18 m, 0.21 m, and 0.42 m in X, Y, and Z, respectively. After the triangulation was completed, a 1 m resolution DEM was created. This was used to orthorectify each image, prior to the creation of an orthoimage mosaic, with a resolution of 10 cm.

For the 2011 survey, a Lumix GF-1 camera, equipped with a 14 mm lens was attached to the landing gear of a manned helicopter. The helicopter flew over the glacier in a series of north/south flight lines, with the camera being triggered manually every four seconds. In this case the helicopter had a nominal altitude of 400 m above the glacier surface and preliminary photo centre coordinates were estimated from the 2010 mosaic. The processing chain was similar to that for the previous year, although in this case natural features were used for GCPs and check points, because of time constraints. Horizontal RMS accuracies at the check points were lower than for the previous year at 0.63 m, 0.52 m, in X, and Y respectively, likely because target positions could not be as accurately identified. However the vertical RMS accuracy of 0.19 m was better than for the previous year. As with the previous year, a 1 m resolution DEM and a 10 cm resolution orthoimage mosaic were produced. The orthoimage mosaics produced from the 2010 and 2011 surveys are shown in Figure 8.

Using the DEMs generated from the two surveys, it was possible to quantify the thinning of the glacier from 2010 to 2011. The orthoimage mosaics also allowed changes to the terminus extents to be directly measured, making it possible to quantify glacial retreat over a one year period. The magnitude and direction of surface flow was also measured, by comparing the positions of approximately 400 points on the glacier surface. This study shows how comparative measurements can be made of rapidly-changing landscape features. It is likely that glaciology is one field which will benefit significantly from the availability of low-cost, on-demand imagery acquired from small UASs.

4. Discussion and conclusions
While the case studies described above are selective in their application, they are sufficiently diverse to illustrate many of the major benefits and challenges currently associated with the use of small UASs. They also provide a good snapshot of the present state of the industry. It can be seen that photogrammetric and mapping-type applications are well suited to the capabilities of the current generation of small UASs. The concomitant development of structure from motion software packages, such as Photoscan and Pix4D is also helping improve the application of small UASs for mapping.

The use of small UASs for photogrammetric surveying can meet a need for detailed, high-accuracy surveys of areas in the range of 1-10 km$^2$. This has traditionally marked the boundary between ground-based surveys and photogrammetric surveys from manned aircraft. For areas of this size, ground surveying is typically too time-consuming to be cost effective. The point density for ground surveys is generally much lower than that collected from a UAS, and while the accuracy of individual GNSS points can be very high, a survey with a small UAS will typically produce a DEM that contains much more detail and higher accuracy overall. Traditional photogrammetric surveying is typically inflexible in terms of scheduling. It is also very expensive, and only becomes economical for high value projects, or where large areas need to be covered. Because of the higher flying height, the ground resolution of photography acquired from manned aircraft is typically much lower than that gathered by small UASs. Surveying using small UASs is cost effective, flexible in terms of scheduling, and provides the highest resolution imagery available.

What these case studies also show is that currently the main use of the orthoimagery from small UASs is for qualitative analysis. There are many challenges, some of which are outlined in Whitehead and Hugenholtz (in review), that limit that ability to straightforwardly adapt automated mapping techniques developed for satellite and manned aircraft. Thus far, the imaging technology adapted for small UASs has not kept pace with the advances in UAS platforms and capabilities. Problems relating to image quality and illumination differences between images generally make imagery acquired from sUASs unsuitable for quantitative analysis. While the land classification study described above did involve some automated image classification, illumination differences meant that the job had to be separated into five
separate zones prior to classification, and unique classification rules developed for each zone. This example also serves to illustrate how object-based classification algorithms, which take account of shape, textural, and contextual attributes, are likely preferable to pixel-based classification for the analysis of imagery from small UASs.

With the continued expansion of small UAS for remote sensing and mapping, it is likely that new sensors will be developed that better match the needs of researchers and the market. For imaging sensors, key areas that need to be addressed include size and weight, image quality, sensor stability, signal to noise ratios, and the ability to record imagery across multiple wavebands simultaneously. The next generation of sensors, designed specifically for incorporation within small UASs, are likely to address many of these shortcomings. The capability for automated image analysis will greatly increase the utility of small UASs for many applications, and is likely to lead to greater uptake in many sectors.

In the case studies described here, we have attempted to show the types of applications for which small UASs are currently suitable. At present these are heavily biased towards photogrammetric applications. While small UASs do not provide a universal solution to all mapping requirements, they offer a cost-effective alternative to ground surveying and traditional photogrammetry for many jobs. With the continued evolution of platforms and sensors, it is likely that the range of applications for which small UASs are suitable will continue to expand.

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References


Four small UASs were used in the seven case studies presented herein: (a) RQ-84Z Aerohawk (Hawkeye UAV Ltd., New Zealand), (b) Outlander UAS (CropCam Inc., Canada), (c) Aeryon Scout Pro quadcopter (Aeryon Labs Inc., Canada), and (d) Ebee (senseFly Inc., Switzerland).
Figure 2: UAS orthomosaics and DEMs used for determining changes in stockpile volume following excavation (Case study 1). The images in (a) and (b) show the orthomosaic for the June survey and the corresponding DEM, respectively, while the images in (c) and (d) show the orthomosaic for the November survey and the corresponding DEM, respectively. The outline of the stockpile prior to excavation is denoted by the dashed line in each image.
Figure 3: River morphology and aquatic habitat analyses of the Elbow River, 2012 (Case study 2), showing (a) the orthoimage, (b) the DEM, (c) $D_{50}$ values and digitised cover features, (d) modeled depth, (e) modeled velocity, and (f) composite suitability index values for adult brown trout habitat.
Figure 4: The application of UAS-based remote sensing to identify late blight in a potato crop (Case study 3). The image sequences (a-c) and (d-f) are from two separate flights in mid and late July 2013, respectively. For the mid July flight the visible imagery is shown in (a), the NIR imagery is in (b), and the calculated NDVI is shown in (c). For the late July flight the visible imagery is shown in (d), the NIR imagery is in (e), and the calculated NDVI is shown in (f). Areas with confirmed or suspected late blight are circled. In the NDVI images the area outside the field was masked.
Figure 5: Object-based classification of gopher mounds in the Great Sand Hills, Saskatchewan (Case study 4).

Image (a) is the colour composite of the 1.92 km² study site. Image (b) is a detail close-up of a roughly 60x60m area with a linear stretch to highlight the bright yellow mounds while (c) shows the result of the binary object-based feature extraction (mounds are in black). (d) shows a cluster of 1-2 year old mounds as they appear on the ground.
Figure 6: Georeferenced image mosaic of the lower Adams River, British Columbia (Case study 5). Insets show large concentrations of salmon. Spawning salmon can be seen as individual dots adjacent to the main concentrations.
Figure 7: Cattle enumeration based on thermal imaging from the Aeryon Scout Pro UAS (Case study 6).

The image in (a) shows a portion of the CAFO, while (b) shows an oblique photo with individual cows identified. Two half-ton pickup trucks are circled in (a) for scale.
Figure 8: Fountain Glacier orthoimage mosaics from 2010 (a), and from 2011 (b) (Case study 7). Both images have 10 m contours superimposed.