Remote sensing of the environment with small unmanned aircraft systems (UASs), part 1: a review of progress and challenges

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Abstract: The recent development and proliferation of unmanned aircraft systems (UASs) has made it possible to examine environmental processes and changes occurring at spatial and temporal scales that would be difficult or impossible to detect using conventional remote sensing platforms. This review article highlights new developments in UAS-based remote sensing, focusing mainly on small UASs (<25 kg). Because this class is generally less expensive and more versatile than larger systems the use of small UASs for civil, commercial, and scientific applications is expected to expand considerably in the future. To highlight different environmental applications, we provide an overview of recent progress in remote sensing with small UASs, including photogrammetry, multispectral and hyperspectral imaging, thermal, and synthetic aperture radar and LiDAR. We also draw on the literature and our own research experience to identify some key research challenges, including limitations of the current generation of platforms and sensors, and the development of optimal methodologies for processing and analysis. While much of the potential of small UASs for remote sensing remains to be realised, it is likely that the next few years will see such systems being used to provide data for an ever-increasing range of environmental applications.

Key words: UAS, remote sensing, environment, review.

Résumé : Le développement récent et la prolifération des systèmes d’aéronef sans pilotes (UAS) ont permis d’examiner les processus et changements environnementaux qui se produisent aux niveaux spatial et temporel qui seraient difficiles, voire impossibles, à détecter depuis des plateformes de télédétection. Cet exposé résume les nouveaux développements en matière de télédétection à l’aide de UAS, en mettant surtout l’accent sur les petits UAS (<25 kg). Cette catégorie d’UAS étant ordinairement moins coûteuse et plus versatile que les systèmes plus gros, il faut s’attendre à ce que leur utilisation à des fins civiles, commerciales et scientifiques soit considérablement étendue à l’avenir. Afin de souligner les différentes applications environnementales, nous donnons un aperçu des progrès récents en matière de la télédétection à l’aide de petits UAS, y compris les domaines de la photogrammétrie, l’imagerie multispectrale et hyperspectrale, la thermophotométrie ainsi que les radars SAR et LIDAR. Nous avons également puisé dans la littérature et dans notre propre expérience de recherche afin de définir les enjeux de recherche importants, à savoir les limites de la génération actuelle de plateformes et de capteurs et le développement de méthodologies optimales pour le traitement et l’analyse. Bien qu’une grande partie du potentiel des petits
1. Introduction

Remote sensing data acquired from satellites and piloted aircraft are powerful tools for measuring the state and trends of environmental changes associated with natural processes and human-induced alterations of the environment. For many situations, data from these platforms provide the only way to measure features or processes on the Earth’s surface and in the atmosphere, and to evaluate how they are changing. To address the growing demand for data on the state of the environment, the science of remote sensing is continually evolving. A wide variety of sensors are now available (Jensen 2000), including hyperspectral imaging systems that characterise reflections from surface objects across a vast portion of the electromagnetic spectrum (e.g., Huesca et al. 2013), and LiDAR systems (light detection and ranging) that provide detailed three-dimensional representations of Earth surface features and topography (e.g., Glennie et al. 2013).

However, the conventional airborne and satellite remote sensing platforms upon which most sensors are mounted have not always met the demands of researchers and environmental professionals. For many environmental applications these platforms pose challenges or require tradeoffs, such as high cost, lack of operational flexibility, limited versatility, and (or) poor spatial and temporal resolution. The ability to identify, measure, and forecast environmental changes requires remote sensing data that match the resolution of the changes and the associated processes. Often data acquired from conventional remote sensing platforms do not have the resolution and operational flexibility to address this challenge effectively or affordably. Attempts have been made with different types of low-cost platforms to overcome this gap (e.g., telescoping masts, Schlitz 2004; balloons, Vierling et al. 2006; and kites, Wundram and Loffler 2007), but limited adoption suggests these platforms have not met the demands of the research and professional communities. We suspect this is because they involve customised designs, are operationally impractical for some environments, or rely on manual control.

One area of recent innovation in terms of remote sensing platforms is the development and application of small unmanned aircraft systems (UASs), also known as drones, unmanned aerial vehicles (UAVs), or remotely piloted aircraft. UASs are emerging as flexible platforms that, in many cases, have the potential to supplement and (or) complement remote sensing measurements acquired from satellites or manned aircraft. Spurred by growth in military applications, UAS technology is now mainstream and affordable, with UASs now being applied to a broad spectrum of environmental applications: from elephant enumeration in Africa (Vermeulen et al. 2013) to glacier measurements in Canada’s high arctic (Whitehead et al. 2013). Relative to conventional satellite and manned aircraft platforms, there are several characteristics that make UASs highly attractive to remote sensing researchers and professionals alike, including their: (i) low cost, particularly the “small” (<25 kg) category (Hugenholtz et al. 2012); (ii) ability to perform missions and acquire data autonomously so that human operation is minimised; (iii) manoeuvrability, which is ideal for low-altitude flying and navigating complex environments; (iv) ability to operate in adverse weather and dangerous environments; (v) reduced exposure risk to pilots; and (vi) a regulatory framework in many countries (like Canada) that enables research and commercial applications. For these reasons, as well as many others, tremendous growth in this sector is anticipated over the next decade (Hugenholtz et al. 2012; Watts et al. 2012; Nex and Remondino 2013).

Another indicator of the growth of UAS remote sensing research is the scientific literature. An analysis using the Web of Science and Scopus databases reveals that there has been an upward trend of papers published in scholarly journals since the early 2000s (Fig. 1). The data were compiled by searching for titles, abstracts, or keywords of journal articles and reviews in each database that contained “UAV” or “unmanned”, and “remote sensing” or “image”. The analysis is not exhaustive because it does not include conference papers and book chapters; nevertheless, it shows that the pace of scientific adoption of UAS-based remote sensing has increased in the last decade. We surmise that this increase reflects growing awareness of UAS technology and its remote sensing capabilities, their straightforward operation, as well as the growing commercial UAS manufacturing sector, which now offers a broad selection of small UASs that increasingly fall within the reach of research budgets.

In anticipation of the continued growth and expansion of small UASs for remote sensing of the environment (Hugenholtz et al. 2012), this paper presents an overview of recent developments in...
UAS-based remote sensing systems and methods. To expand on previous review articles (e.g., Hardin and Jensen 2011; Watts et al. 2012; Nex and Remondino 2013), this paper emphasises the remote sensing technology and highlights some of the major research challenges that lie ahead. After a brief overview of the technology, we outline the UAS-based remote sensing workflow and follow with recent developments in sensor technology and applications. Based on the literature and our own research experience using UASs and working with the remote sensing data they acquire, we then attempt to provide some guidance on future research by outlining some of the key challenges that currently exist in the context of environmental measurements and monitoring.

2. UAS basics

Several key papers and reviews have already outlined the main features of UASs (e.g., Hardin and Jensen 2011; Watts et al. 2012; Nex and Remondino 2013), so here we provide a very brief overview of the technology. First, it is important to clarify that a UAS consists of several components (Eisenbeiss 2009): the aircraft or UAV, a ground control system, a pilot or navigator who operates the UAS from the ground control system, and one or more spotters who monitor the UAS and other aircraft and hazards in the area.

For most remote sensing and mapping applications, UASs are autonomous and controlled via an on-board autopilot. Positional information is provided using a global navigation and satellite system (GNSS), which yields regularly sampled measurements of three-dimensional position. The majority of UAS platforms will also have an inertial measurement unit (IMU) that provides information on the aircraft attitude at any given time. The position and attitude of the aircraft is fed into the autopilot, which then makes the necessary course adjustments to keep the aircraft on course, either through varying the throttle, or adjusting flaps as appropriate. The autopilot may also be used to generate a signal that triggers a camera at predetermined positions. The operator at any time has the ability to override the autopilot via the ground control system.

UASs may be either fixed wing, or rotary wing, with fixed wing UASs typically having greater speed and longer range. Rotary-wing UASs include miniature helicopters and multirotor platforms. Typically, they have shorter flight durations, but offer greater manoeuvrability. Fixed-wing UASs are typically launched by hand or by catapult, and land with or without some form of arresting mechanism, such as a parachute or by flying into a net. Rotary-wing UASs typically require some manual operation for take-off, and may or may not require manual operation for landing.

UASs may also be divided into different classes, depending on weight and capabilities. In the United States, UASs are classified as micro (<0.9 kg), mini (0.9–13.6 kg), tactical (13.6–454.5 kg), medium altitude long endurance (454.5–13 636.4 kg), and high altitude long endurance (>13 636.4 kg). The U.S. Federal Aviation Administration Modernisation and Reform Act of 2012 also recognises a further class of small UASs (<25 kg; Hugenholtz et al. 2012). Within Canada, UASs with a maximum takeoff weight less than 35 kg are currently permitted, subject to regulatory approval (Transport Canada 2008). We estimate that the greatest uptake for commercial and remote sensing applications will occur at the lighter end of the scale, for platforms weighing less than 15 kg, because this is the region

![Fig. 1. Frequency of scholarly journal articles published before 31 January 2014. This list was compiled from key word searches in Scopus and Web of Science and does not include book chapters or conference papers.](image-url)
where the cost advantages of UASs are likely to be most significant and where risk associated with blunt force impact is reduced.

3. UAS regulations and remote sensing

There are several characteristics of remote sensing surveys with small UASs that stand out from those performed by satellites or manned aircraft. For the time being, many of the differences are driven by aviation regulations that are in place to address safety issues arising from civil uses of UASs. However, the regulations also place restrictions on how UASs are operated, which in turn has a major impact on the types of data that can be acquired from these platforms. In this section, we outline some of the key regulatory criteria that distinguish remote sensing data acquired by UASs.

At the time of writing, many countries and organisations are in the process of establishing or revamping regulatory frameworks for integrating UASs into civil airspace (e.g., United States; Hugenholtz et al. 2012), which makes it difficult to define a consistent set of regulations affecting UAS-based remote sensing. Nevertheless, according to existing rules in countries like Canada, the United States, and the United Kingdom, there are three criteria that, in our estimation, are likely to persist into the future: limited flying altitude, flying within visual range, and proximity to built-up areas.

In Canada and the United Kingdom, operators of small UASs are required to fly below 400 feet (122 m) above ground level unless otherwise specified. In the United States, similar height restrictions generally apply, although Rango and Laliberte (2010) were able to obtain permission to fly at up to 1,000 feet (305 m) above ground level. For remote sensing data, the low-flying height enables the acquisition of ultra high-resolution imagery (centimetre scale), which is a major benefit for some applications, but also introduces a trade-off in that a large number of images, perhaps several hundred, may be required to completely cover the area of interest. The trade-off emerges in the image processing, such that variations in viewing geometry, as well as the roll, pitch, and yaw of the aircraft, can yield radiometric and geometric distortions in the final image mosaic.

Requirements that the aircraft be in visual range at all times place an effective limit on the distance between the operator and the aircraft, which varies according to the shape and color of the aircraft, and the atmospheric conditions during flight. This requirement places a limit on the size of the survey area, thereby often necessitating extra flights to cover larger areas. Future advances in sense-and-avoid technology may permit UAS flights beyond visual range, thus enabling UAS-based remote sensing of larger areas.

The final regulatory criterion that is likely to persist into the future is the restriction of UAS flights near built-up areas. Without doubt, the high resolution of UAS surveys would be of benefit for many engineering and construction projects in urban environments. However, even with the development of reliable sense and avoid technology, public safety (and possibly privacy) considerations are likely to rule out UAS remote sensing in this context.

4. UAS remote sensing

4.1. Survey and flight planning

The remote sensing workflow for small UASs is essentially an adaptation of the same steps and processes used for piloted aircraft surveys, and in both cases, aviation regulations place certain restrictions on how the surveys are configured.

Though each UAS survey is unique in nature, the same generic workflow is normally followed. Typically, a UAS survey starts with flight planning (Hugenholtz et al. 2013). This stage relies on specialised flight-planning software and uses a background map or satellite image to define the survey area. Additional information is then added, such as the desired flying height, the focal length and orientation of the camera, the desired amount of overlap between images, and the desired flight direction. The flight-planning software will then calculate the optimal solution to obtain overlapping stereo imagery covering the area of interest. During this process, the various parameters can be adjusted until the operator is satisfied with the flight plan. An example of a flight plan with image footprints is shown in Fig. 2.

As part of the planning stage, the camera shutter speed may need to be set manually, but many consumer-grade cameras now use predefined automatic modes for different lighting conditions. When setting the manual shutter, experience tends to trump any given rule-of-thumb because the setting will depend on the ground surface cover and the ambient light levels. If the exposure time is too long, the imagery will be blurred, or will be too bright, but if it is too short, the imagery might be too dark to discriminate key features of interest.

Once a flight plan has been generated, it is uploaded to the UAS autopilot. The instructions contained in the flight plan are used by the autopilot to calculate the necessary climb rates and positional
adjustments that enable the aircraft to follow the planned course as closely as possible. Readings from the GNSS and IMU are typically logged by the autopilot several times per second throughout the flight. On completion of the flight, a log file is usually downloaded from the aircraft autopilot (Hugenholtz et al. 2013). This file contains details about the recorded aircraft position and attitude throughout the flight, as well as details about when the camera was triggered. This log file is typically used to provide initial estimates for image centre positions and camera orientations, which are then used as inputs to the photogrammetric process. These initial estimates will reflect the accuracy of on-board instrumentation. For example, a low-cost UAS using inexpensive mapping-grade navigational sensors will typically have positional accuracies in the 2–5 m range (Turner et al. 2014). Further errors will be introduced if there is uncertainty in the timing of the camera shutter release. Such errors can be significant, with a one second delay potentially resulting in an error of 30–50 m in the direction of flight for a fast-flying fixed-wing UAS.

4.2. Photogrammetry

Other than the collection of airborne video footage, the most common non-military application of UASs to date has been for large-scale photogrammetric mapping (e.g., Haala et al. 2011; d’Oleire-Oltmanns et al. 2012; Hugenholtz et al. 2013; Whitehead et al. 2013). Issues, such as platform stability and the use of nonmetric cameras, usually mean that the geometry of the imagery collected is of a lower quality than that obtained during traditional photogrammetric surveys carried out from manned aircraft (Hardin and Jensen 2011). UAS surveys also tend to collect images with large amounts of overlap. This is partly because the low flying height and comparatively low accuracy of onboard navigational sensors can lead to significant differences between the image footprints estimated during flight planning and the actual ground coverage of each image, especially in undulating terrain (Haala et al. 2011; Zhang et al. 2011). Image footprints can also drift from expectation because of changes in the roll, pitch, and yaw of the aircraft caused by wind and navigation corrections. In spite of these drawbacks, the low flying heights normally make it possible to gather imagery with subdecimetre spatial resolution. This level of detail combined with low costs, flexibility in the timing of image acquisition, and short turn-around times makes UAS-based photogrammetry an attractive option for many potential users across a broad spectrum of research and professional applications.

Within the field of aerial photography in general, the last twenty years has seen high-resolution digital imagery largely replace analog aerial photography, as well as the development of onboard navigational systems that provide accurate positional and attitude information. This has spurred the parallel development of automated photogrammetric processing packages, such as Inpho (e.g., Haala et al. 2011; Hugenholtz et al. 2013; Whitehead et al. 2013) and LPS (e.g., Laliberte and Rango 2011; d’Oleire-Oltmanns et al. 2012). These software packages provide a semi-automated workflow, allowing for the production of digital elevation models and orthophoto mosaics with limited operator intervention. The photogrammetric processing chain for a typical UAS survey is described in detail by Hugenholtz et al. (2013) and by Whitehead et al. (2013), who describe processing using Trimble’s Inpho software. The process is, however, the same for most photogrammetric software packages. The log file...
from the UAS autopilot is used to provide initial estimates for the position and orientation of each image. In addition, it is usual to include a number of accurately surveyed ground control points (GCPs) in the photogrammetric adjustment (see Fig. 3). These usually consist of specially placed targets that are surveyed with a GNSS at the time of the UAS survey (e.g., Hugenholtz et al. 2013).

Aerial triangulation refers to the process by which the true positions and orientations of the images from an aerial survey are re-established. This process includes project setup, measurement of GCPs and manual tie points, and bundle-block adjustment (Hugenholtz et al. 2013; Whitehead et al. 2013). During aerial triangulation, a large number of automated tie points are generated for conjugate points identified across multiple images. A bundle-block adjustment then uses these automated tie points, along with manually observed GCPs and tie points, to optimise the photo positions and orientations, with the goal being to recreate the positions and orientations associated with each image at the time of its capture (Hugenholtz et al. 2013). The bundle-block adjustment process generates a

Fig. 3. Orthomosaic of an aggregate quarry showing locations of GCPs. Instead of using targets, these GCPs were (inset image) marked with biodegradable spray paint.
high number of redundant observations, which are used to derive an optimal solution through a rigorous least-squares adjustment. It is also common practice to include a number of check points, which are not used during the aerial triangulation process and which can be used to later provide an independent check on the accuracy of the adjustment.

After aerial triangulation, the oriented images may be used to generate a digital surface model (DSM), which provides a detailed representation of the terrain surface, including the elevations of raised objects, such as trees and buildings. The DSM production process creates a dense point cloud by matching features across multiple image pairs (Whitehead et al. 2013). Another product that can be generated at this stage is a digital terrain model (DTM), which is often referred to as a bare-Earth model. For most purposes a DTM is a more useful product than a surface model, because the high-frequency noise associated with vegetation cover is removed. A DTM can be produced in a number of ways, including filtering of the dense point cloud used to produce a DSM, or interpolation of a sparse point cloud (Arefi et al. 2009). DTMs often require manual editing to remove the influence of larger buildings and heavily vegetated areas, which are generally not adequately filtered. Break lines and additional points are often added during this process, to augment the quality of the final DTM. While often used interchangeably, the term digital elevation model as used in this review is considered to be generic, and can thus refer to either a DSM or a DTM.

After a DTM has been created, it can then be used to orthorectify the original images. Orthorectification refers to the removal of distortions caused by relief, which result from the central-perspective geometry associated with photography. Once orthorectified, the images have an orthogonal geometry and can be used for direct measurement. After orthorectification, the individual images can be combined into a mosaic, to provide a seamless image of the survey area at the desired resolution. Orthorectification can also be carried out using a DSM, but the amount of noise associated with dense vegetation can often cause the resulting orthoimage to have a choppy and irregular appearance.

Photogrammetric processing of UAS imagery poses a number of challenges, because in many ways the characteristics of such imagery are more akin to those encountered in terrestrial photogrammetry than to conventional aerial photography (Turner et al. 2014). UAS imagery is subject to variable scales, high amounts of overlap, variable image orientations, and often high amounts of relief displacement arising from the low flying heights relative to the variation in topographic relief (Zhang et al. 2011). Under such circumstances traditional photogrammetric processing approaches developed for well-calibrated metric cameras and regularly spaced photography, may not be optimal (Hardin and Jensen 2011).

Over the last few years a number of structure from motion (SfM) software packages have been developed (e.g., Westoby et al. 2012; Fonstad et al. 2013; Turner et al. 2014). The SfM approach uses algorithms originally developed for computer vision, such as a scale-invariant feature transform, which identifies similar features in conjugate images. Unlike conventional photogrammetry, which is bound by rigid geometric constraints, SfM is able to accommodate large variations in scale and image acquisition geometry. The use of SfM packages, such as Bundler, along with its web implementation Photosynth (e.g., Fonstad et al. 2013; Turner et al. 2014) and Photoscan (Turner et al. 2014) allow for a high degree of automation, and makes it possible for non-specialists to produce accurate DSMs and orthophoto mosaics in less time that it would take using conventional photogrammetric software. Due to their comparatively low cost and ability to handle unconventional imagery, it is likely that SfM packages will increasingly become the software of choice for UAS photogrammetric surveys.

While most UAS photogrammetric surveys require GCPs to provide the required horizontal and vertical accuracies, there have been a number of examples of surveys that have obtained high accuracy results without the use of ground control (e.g., Bláha et al. 2011; Turner et al. 2014). These “direct georeferencing” systems use high-accuracy carrier-phase GPS measurements to obtain positional values for the aircraft that are in the 10–20 cm range, and these are complemented by extremely accurate measurements of the aircraft attitude. To obtain accurate results using this approach, the precise offsets between the camera and the GPS antenna must be known, and the camera calibration must be accurately determined. Turner et al. (2014) describe a system developed for an Oktokopter platform, which was able to obtain horizontal and vertical accuracies in the 10 cm range, with no GCPs. Direct georeferencing systems have also been described by Nagai et al. (2009) and Bláha et al. (2011).

Direct georeferencing is still comparatively rare. Because of the extreme sensitivity such systems have to timing errors, they tend to use slow-moving vertical take-off and landing platforms, rather than fixed-wing UASs (e.g., Bláha et al. 2011; Turner et al. 2014). Direct georeferencing systems also require the use of high-end survey-grade components, and to achieve good results they also need to carry heavier cameras. These factors mean that such systems are generally expensive, heavy, and...
have limited range (e.g., Nagai et al. 2009; Turner et al. 2014), but we surmise that UASs with these capabilities will become more common in the near future.

4.3. Multispectral and hyperspectral

A major thrust of remote sensing research and application is the analysis of the spectral content of the imagery, and how it relates to land cover and other biophysical properties. In traditional satellite and airborne remote sensing, it is usual to work with multiple image bands, covering different parts of the electromagnetic spectrum. Payload weight restrictions and the cost of high-end miniaturised imaging devices mean that small UASs are often restricted to carrying consumer-grade cameras that are typically designed only to record spectral reflectance between 400 and 700 nm, the visible region of the spectrum (Lebourgeois et al. 2008; Rump et al. 2011). The dynamic range of such cameras is also limited, and this can pose additional problems for spectral analysis (Hardin and Jensen 2011).

For applications that investigate vegetation health, near-infrared (NIR) reflectance is particularly important. Reflectance from healthy vegetation is at its highest in the region between 750 and 1250 nm, while this peak tends to be depressed in stressed vegetation. The sensor arrays of many cameras are sensitive to radiation in this region of the spectrum, but it is normally blocked out by the use of an internal “hot mirror” filter, which is designed to limit the camera response only to the visible part of the spectrum. Hunt et al. (2012) used a Fuji FinePix S3 Pro UVIR camera, which does not filter the NIR region, and instead used a customised red filter to produce composite images made up of the blue, green, and NIR portions of the spectrum. This camera was flown on a UAS and was used to monitor leaf area index for two fields of winter wheat. A similar approach was taken by Knoth et al. (2013), who used a specially converted compact camera to classify vegetation types in a peat bog. This approach provides a low-cost alternative to true multispectral sensors, but limitations in the quality of imagery that can be obtained generally mean that such cameras do not provide suitable imagery for quantitative analysis. In Fig. 4 we present an example of multispectral imagery from an abandoned oil well undergoing reclamation in southern Alberta. The area was flown twice: first to acquire visible or, RGB, imagery with a consumer-grade camera (Canon ELPH 115) and then a second time with a NIR filter. The resulting data were used to create a false-color infrared image and normalised difference vegetation index map of leafy vegetation.

In recent years, a number of lightweight multispectral sensors have been developed for UAS platforms. While these typically are bulkier, more expensive, and have lower resolutions than the converted cameras described earlier, they have higher dynamic ranges, and their spectral characteristics can often be customised. Many of these sensors also have multiple bands and have adjustable spectral ranges. The calibration of a six-band Tetracam MCA-6 camera for UAS-specific surveys is described by Kelcey and Lucieer (2012). The same camera was used to produce vegetation indices to monitor the health of a vineyard (Turner et al. 2011). Baluja et al. (2012) also investigated vineyard water status using a UAS-mounted Tetracam MCA-6 camera, along with a forward-looking infrared thermal camera. Another example is provided by Berni et al. (2009), who used a combination of six visible and NIR bands in combination with thermal imagery to investigate crop canopy metrics, including chlorophyll content, leaf water content, carotenoid concentration, dry mass, as well as structural parameters, such as leaf area index. The imagery was obtained from a rotary-wing UAS, over three test plots consisting of olive trees, peach trees, and cornfields.
Hyperspectral sensors sacrifice spatial resolution for spectral resolution and can provide a measure of spectral response across hundreds of narrowly defined spectral bands simultaneously. Recent advances in sensor miniaturisation, along with low flying heights, mean that hyperspectral surveys with ground resolutions of 0.2 m or better can now be carried out from UAS platforms (e.g., Zarco-Tejada et al. 2012; Uto et al. 2013). The widespread collection of airborne hyperspectral information with this level of spatial resolution has not hitherto been practical and this represents an example of a novel application for which UASs are uniquely suited. Such surveys are able to provide detailed information on vegetation health, and also can be used as a basis for mapping vegetation species. The testing and calibration of a miniaturised hyperspectral imaging system designed for UAS use was described by Duan et al. (2013). Uto et al. (2013) were able to use data collected by a lightweight hyperspectral sensor to monitor chlorophyll density in rice paddies, while Zarco-Tejada et al. (2013) were able to estimate water stress and vegetation health metrics in a citrus orchard, using a number of derived vegetation indices. Saari et al. (2011) describe the development of a lightweight hyperspectral system, suitable for use on a small UAS, and optimised for forestry and agricultural applications. Kaivosoja et al. (2013) investigated the use of UAS-acquired hyperspectral imagery, along with farm history records, for precision agriculture.

Despite the growing potential for multi- and hyperspectral remote sensing with UASs, there are also notable drawbacks and challenges in terms of the commensurability of these sensors relative to existing sensor systems developed for the field and piloted aircraft. In particular, a study conducted at the US Department of Energy’s Idaho National Laboratory by Hruska et al. (2012) showed that one type of hyperspectral imaging spectrometer designed for small UASs was of limited use for quantitative remote sensing of vegetation applications, including vegetation stress studies requiring red edge or specific bands for photochemical reflectance indices. They also found significant geometric errors that resulted in obvious image distortions (Fig. 5 in Hruska et al. 2012). Their research demonstrates that multi- or hyperspectral sensors designed for use on UASs must be tested to ensure that they adhere to the radiometric and geometric benchmarks necessary to be useful in a quantitative sense.

**4.4. Thermal**

Thermal imaging is one area that is particularly suited to the use of small low-flying aerial platforms. Traditionally, thermal imaging devices have required bulky and expensive cooling systems. However, the use of new materials in the design of thermal sensors has led to the development of a new generation of thermal imaging devices that operate at ambient temperatures. These tend to be considerably smaller and less expensive than the traditional cooled thermal imaging sensors, making it practical to include them as part of a UAS payload, alongside a regular camera; however, in spite of these technological advances, thermal imagers are still comparatively expensive, and this has served to limit their application to date.
Thermal imaging is commonly used in vegetation monitoring. Berni et al. (2009) describe a combined system that used UAS-acquired thermal imagery to monitor the temperature of a number of agricultural test plots at different times of day, providing an indication of water uptake by the different crops. Turner and Lucier (2011) used a UAS-mounted thermal camera to measure soil moisture as part of a study of vineyard health. Bellvert et al. (2013) also used UAS-acquired thermal imagery to assess vineyard health. Sullivan et al. (2007) used thermal imagery collected from a fixed-wing UAS to assess the response of cotton to irrigation and crop residue management. Gonzalez-Dugo et al. (2013) used UAS-acquired thermal imagery over a commercial orchard in Spain to investigate water uptake in five different species of fruit trees. The imagery acquired was of sufficient resolution to enable water stress to be measured at the individual tree level.

The potential of UAS thermal imaging for archaeology was demonstrated by Poirier et al. (2013), who were able to detect previously unknown roads and walls dating back to Roman times. UAS thermal surveys also show considerable potential for wildlife tracking and for anti-poaching operations. An example of wildlife detection is provided by Israel (2011), who describes a system to detect Roe deer fawns in grassland. By using a multirotor vertical take-off and landing UAS equipped with a thermal camera, researchers were able to detect fawns prior to grass cutting, allowing them to be moved out of harm’s way. Another application of thermal imagery is shown in Fig. 5, where temperature difference was used to delineate the waterline along a river channel.

Thermal imagery is also well suited for real-time applications. A prototype near-real-time fire monitoring system was described by Ambrosia et al. (2003). Using a variation of the military Predator drone, which was specially equipped with a combination of visible and thermal infrared detectors, the system was able to penetrate thick smoke and identify several thermal hot spots within a test burn. Using satellite telemetry, imagery was relayed to a control centre, where it was orthorectified and supplied to decision makers as a series of quick-look images within six minutes of being acquired. Another near-real-time application of thermal imagery acquired from a UAS for fire monitoring is described by Wu et al. (2007).

Potential applications for thermal imagery also exist within search and rescue, and for undertaking wildlife counts, although there have been few publications documenting such applications to date. Airborne remote sensing has been used to detect thermal plumes from power stations for many years (e.g., Scarpace and Green 1973) and this is also an application that offers considerable potential for UAS surveying. Another application of UASs that has potential is conducting thermal heat loss surveys from buildings. Martínez-de Dios and Ollero (2006), were able to detect areas of significant heat loss during a test overflight of an office building using a small helicopter UAS. This is an area with considerable potential for the future, although safety and privacy concerns may need to be addressed before such applications can become mainstream.

4.5. Synthetic aperture radar (SAR) and LiDAR

SAR is a mature technology for manned aircraft and satellite platforms. In 2004 NASA’s Jet Propulsion Laboratory began developing an L-band polarimetric SAR payload called UASSAR, specifically designed to collect repeat track SAR data for differential interferometric measurements (Madsen et al. 2005). Since 2009, UASSAR has been acquiring data for a broad range of science applications, including more than 160 flights across the globe. For the majority of applications the UASSAR payload or pod has been flown on a Gulfstream G-III aircraft, which is not a fully autonomous UAS; however, a recent campaign over the Canadian arctic involved the UASSAR pod attached to NASA’s high altitude, long endurance Global Hawk UAS.

SAR systems suitable for small UASs are generally still in the development phase, and we are unaware of any published case studies on specific applications. To be suitable for incorporation into a small UAS, SAR systems must be lightweight and have low power consumption. Two proof-of-concept technology examples of miniature SARs for UASs include the ka-band MISAR described by Edrich (2004) and the c-band, single VV-polarization SAR developed by Koo et al. (2012). This remains an area of active research with considerable potential for the future.

LiDAR measurements from small UASs are also still in a proof-of-concept phase, but are further along than SAR in terms of case studies and miniaturisation. One of the main challenges is that the accuracy of LiDAR data are highly dependent on positional information from the aircraft GNSS and IMU sensors. It follows that if the aircraft position and attitude are not known to a high level of accuracy, the corresponding accuracy of any measurements made by a LiDAR sensor will be affected. This is a limitation for most small UASs, which are typically equipped with navigation-grade GNSS and IMU sensors (Turner et al. 2014). Thus, to obtain high absolute accuracies, these platforms need to be equipped with high-end carrier-phase GPS units (e.g., Turner et al. 2014). Nevertheless, initial
proof-of-concept case studies demonstrate the potential for acquiring LiDAR measurements from small UASs.

Lin et al. (2011) developed a lightweight UAS-mounted LiDAR system and assessed its utility for ground height determination and tree height estimation. Because of flying heights that ranged between 10 and 40 m above the ground, an extremely high density of points was generated for the area of interest, allowing for a high percentage of ground returns through the forest canopy, as well as accurate estimation of tree heights and discrimination of utility poles. Similarly, Wallace et al. (2012) describe another UAS-LiDAR system and its use for the measurement of tree structure. Both studies used vertical take-off and landing UAS platforms, owing to their ability to incorporate and support the LiDAR payload. While results from both these studies were encouraging, both systems were restricted to low flying heights and could cover only small areas during the course of a single flight. With continued development of sensor technology, it is likely that more powerful UAS-mounted LiDAR systems will become available in the near future. Such systems will allow LiDAR surveys to be carried out from greater heights, making it possible to cover larger areas per flight. The accuracy achievable using such systems will, however, depend on the accuracy of the on-board navigation sensors.

An alternative application of UAS-mounted LiDAR was demonstrated by Chisholm et al. (2013). In this case, a LiDAR system was developed for below-canopy use on a quadcopter. This system was developed for areas where GPS signals are poor or completely absent, and obtains measurements only in the horizontal plane. Using this approach, it was found that 70% of trees with a diameter of greater than 20 cm could be detected for a patch of trees 20 m by 20 m in size. This system is still in the proof-of-concept phase, and the authors point out that some form of (non-GPS) location device will be necessary for this application to become practical.

5. Challenges and research needs

5.1. Camera shortcomings

While the applications of small UASs have seen tremendous growth in recent years (Fig. 1), there remain a number of outstanding issues that need to be addressed for their full potential to be realised for environmental measurements and monitoring. Chief among these are the radiometric and geometric limitations imposed by the current generation of lightweight, consumer-grade digital cameras (Hardin and Jensen 2011). These are designed for the general market and are not optimised for photogrammetric or remote sensing applications. Higher-end instruments tend to be too bulky to be used with current lightweight UASs, and for those that do exist, there is still a question of calibration commensurability with conventional sensors (Hruska et al. 2012).

Spectral limitations include the fact that spectral response curves from consumer-grade cameras are usually poorly calibrated (Hakala et al. 2010; Rump et al. 2011), making it difficult to convert brightness values to radiance (Lebourgeois et al. 2008), which is important for comparative studies. However, even sensors designed specifically for UASs may not meet the necessary scientific benchmarks (e.g., Hruska et al. 2012). With consumer cameras, the detectors may also become saturated when there are high contrasts (Fig. 6), such as when an image covers both a dark forest canopy and a snow covered field. Wavebands tend to be broad, with considerable overlap between all bands in the visible (300–700 nm) portion of the spectrum (Lebourgeois et al. 2008; Rump et al. 2011), making it difficult to obtain useful spectral signatures from different cover types. The lack of a NIR band is also a serious drawback for vegetation surveys, although some progress has been achieved with the six-band multispectral Tetracam mini-MCA-6 (e.g., Turner et al. 2011; Calderón et al. 2013; Garcia-Ruiz et al. 2013; Torres-Sánchez et al. 2013). The spectral characteristics of most cameras therefore tend to limit their applicability towards vegetation analysis, and the imagery they produce is seldom suitable for doing much more than distinguishing vegetated from nonvegetated areas.

Another drawback is that many consumer cameras are prone to vignetting (Fig. 6), where the edges of images appear darker than the centres (Lebourgeois et al. 2008; Hakala et al. 2010; Kelcey and Lucier 2012). This effect occurs because rays of light at the edges of the image have to pass through a greater optical thickness of the camera lens, and are thus more strongly attenuated than light rays in the centre of the image. Lebourgeois et al. (2008) noted that for modified cameras, vignetting tends to be more pronounced in the NIR band. Custom-built multispectral and hyperspectral imaging sensors are less likely to be significantly affected by this problem, although some degree of vignetting will always be present. Hakala et al. (2010) estimated vignetting accounted for a 25% variation in brightness between the centre and corners of images acquired using a consumer camera. However, if the effects can be quantified, then they can be removed using a flat-field correction (Hakala et al. 2010). The low-cost lenses used by many consumer-grade cameras can also cause different wavelengths

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of light to be refracted differently (Fig. 6). Known as chromatic aberration, this effect can cause separation of colours at the edges of images, presenting further difficulties for spectral analysis (e.g., Eisenbeiss 2006; Van Achteren et al. 2007; Seidl et al. 2011).

While it is possible to compensate for many of these effects, and to create a mosaic that appears seamless, ad hoc colour balancing is likely to impact the performance of automated image classification algorithms. These limitations necessarily degrade the quality of the spectral information that can be recovered from a typical UAS survey. For multispectral and hyperspectral imagery, the lens characteristics of the sensor are normally well established, and this information can be used to compensate for the effects of vignetting. The use of vegetation indices, which are typically based on the ratios of different wavebands can also help to reduce this effect. Nonetheless, as a general rule, imagery acquired from consumer-grade cameras cannot be considered suitable for quantitative spectral analysis (Lebourgeois et al. 2008).

The geometry of consumer-grade cameras also presents challenges (Haala et al. 2011; Hardin and Jensen 2011). Even under ideal conditions it can be difficult to obtain reliable calibrations for such cameras. This is especially true for retractable lens cameras, where the focal length may be affected by extraneous factors, such as particles of dust in the mechanism. The small size of the image sensor and short focal length of such cameras mean that the effects of microscopic errors or misalignments are greatly magnified, compared to similar errors in conventional full-frame cameras. The low costs of such cameras also mean that traditional, high-end calibration using a precision test field is seldom carried out. Instead, calibration is typically done using an inexpensive and quick flat target algorithm, which in many cases can yield inconsistent results. Consumer cameras rarely remain stable for any length of time (Habib and Morgan 2005; Hardin and Jensen 2011), and therefore frequent recalibration

Fig. 6. Common image artifacts and distortion from UAV remote sensing: (a) saturated image; (b) vignetting; (c) chromatic aberration; (d) mosaic blurring in overlap area; (e) incorrect colour balancing; (f) hotspots on mosaic due to bidirectional reflectance effects; (g) relief displacement (tree lean) effects in final image mosaic; (h) image distortion due to DSM errors; (i) mosaic gaps caused by incorrect orthorectification or missing images.
may be required. While such cameras can give acceptable results for many applications, users need to be aware of these constraints on the potential accuracy requirements of a project. However it is worth noting that in many cases these limitations are more than compensated for by the low flying height from which UAS surveys are typically conducted.

While the issues relating to camera geometry and image quality can never be entirely eliminated, there are a number of steps that can be taken to improve the quality of the final product. Consumer-grade cameras are often used for UAS surveying because of their light weight. A good alternative is to use a micro-four-thirds format camera instead (e.g., Hugenholtz et al. 2013; Whitehead et al. 2013). This class of camera has similar characteristics to a full single lens reflex camera, but in a much smaller body. Instead of having a retractable lens, micro-four-thirds cameras can use fixed interchangeable lenses, allowing for much improved calibrations and image quality. Other ways to improve image quality include removing photos that are blurred, under- or overexposed, or are saturated. This is a simple step that can make a big difference in the processing stage. Future research into improving body. Instead of having a retractable lens, micro-four-thirds cameras can use fixed interchangeable lenses, allowing for much improved calibrations and image quality. Other ways to improve image quality include removing photos that are blurred, under- or overexposed, or are saturated. This is a simple step that can make a big difference in the processing stage. Future research into improving.

### 5.2. Image classification

UASs can be used to gather aerial images at a considerably higher spatial resolution than has hitherto been achieved, often to centimetre level (e.g., d’Oleire-Oltmanns et al. 2012; Harwin and Lucieer 2012; Turner et al. 2014). While this resolution offers a number of advantages, the amount of detail presents new challenges from the point of view of image classification. The brightness of an individual pixel represents an aggregate of the reflected solar radiation from the different cover types making up that pixel. Traditionally in remote sensing, the low resolutions of satellite imagery and high-altitude aerial imagery have tended to result in comparatively homogenous clusters of pixels, which are well-suited to pixel-based analysis techniques. However at resolutions of only a few centimetres, the individual component parts of plants and trees often become apparent, with separate pixels often representing leaves, branches, and underlying ground cover. Because of the high contrast differences between these features, mixed pixels, comprising various combinations of these components, will also tend to show greater variation than would be apparent for lower resolution imagery. In such circumstances, pixel-based image classification algorithms are unlikely to give good results.

An alternative workflow is to use an object-based analysis strategy (e.g., Rango et al. 2009; Laliberte et al. 2010; Laliberte and Rango 2011). Such a strategy amalgamates groups of pixels into discrete objects, based on spectral, textural, and shape characteristics. These objects are then classified based on their inherent properties. If the objects thus defined represent meaningful units, such as individual trees, then such a strategy can potentially deliver much improved classification results. Variations in brightness across image mosaics can also present problems for a purely spectral analysis. By integrating structural and textural parameters into the analysis, object-based analysis is likely to considerably improve classification accuracies.

### 5.3. Illumination issues

One factor that has thus far received little attention in the published literature is the effect of variable illumination on the photogrammetric processing of UAS imagery (see Figs. 2 and 6). Differences between sunlit and shaded areas can be significant on a bright sunny day, especially where there are cumulus clouds overhead, which give sharp well-defined shadows. From our combined experience, such conditions can pose significant challenges for the automated image matching algorithms used in both triangulation and digital elevation model generation. Where clouds are moving rapidly, shaded areas can vary significantly between images obtained during the same flight, potentially causing the aerial triangulation process to fail for some images, and also resulting in errors in automatically generated digital elevation models. Moreover, patterns of light and shade across images can confuse automated colour balancing algorithms used in the creation of image mosaics. This can result in output mosaics of poor visual quality, which have obvious variations in contrast or colour (e.g., Fig. 6), and that may be excessively dark or light in places.

The best recommendation is to avoid flying under such conditions. However there may be no other available time to carry out the survey. SfM software is generally more robust when it comes to coping with image variations (Turner et al. 2012; Westoby et al. 2012), and it may be possible to carry out a successful triangulation using a SfM package, when conventional photogrammetric software fails. One possibility is to generate band ratio images from the original images and use these for triangulation. Rasioing will normally reduce shadowing considerably. However there is no published literature.
on the use of band ratio images in photogrammetry, suggesting that the potential of this method remains untested.

Another commonly seen illumination effect is the presence of image hotspots, where a bright spot appears in the image (Fig. 6). These are due to the effects of bidirectional reflectance, which is dependent on the relative position of the image sensor and the sun (Hakala et al. 2010; Grenzdörffer and Niemeyer 2011; Laliberte et al. 2011). Hotspots occur at the antisolar point, which is the point where the line defined by the sensor position and the sun intersects with the ground.

5.4. Relief displacement

Because of the low flying heights used, UAS imagery is particularly prone to the effects of relief displacement (Eisenbeiss 2009; Mozas-Calvache et al. 2012; Niethammer et al. 2012). For nonvegetated areas, such displacement is removed during the orthorectification process, assuming that the DSM or DTM used correctly represents the terrain. The situation is more complicated when dealing with trees and buildings (e.g., Mozas-Calvache et al. 2012). In such cases, local displacement is often considerable (Fig. 6), and there can often be hidden areas where no data has been captured. If a DSM is used to orthorectify such images, the result can often be a choppy looking, irregular image, due to the noise present in the surface (Fig. 6). Using a DTM will typically result in a smoother looking image; however, locally elevated features will often still be subject to the effects of relief displacement. As such it is often difficult to produce a true orthoimage, which accurately represents all features.

There are a number of work-arounds to this problem. These include obtaining high overlaps and only using the centres of each image, flying higher, and using a longer focal length. All of these options will help to reduce, but not eliminate, the effects of relief displacement. Problems with relief displacement will often surface at the mosaicking stage, where images with different amounts and directions of relief displacement are combined (Fig. 6). This can result in features being displaced in the final image, with linear features in rapidly changing areas, such as in the case of a road surrounded by high trees, showing sudden jumps in horizontal position. Certain mosaicking packages may also produce effects, such as blurring and ghosting (Fig. 6), where the same feature appears multiple times in the final mosaic in slightly different positions. Some of these issues can be avoided by manual selection of seam lines, but this can often add considerably to the time required for processing.

5.5. Mosaic artifacts

The production of mosaics can lead to additional problems. In addition to the problems that result from vignetting, relief displacement, misregistration, and ghosting, image artifacts are often created where the colour-balancing algorithms fail to work properly. These can occur where the contrasts of individual image bands fall outside the range of the image histograms used for image matching. Another common occurrence is striping on the final mosaic. This will often occur where there is insufficient overlap between flight lines to allow colour matching to be carried out successfully.

Geometric artifacts may also occur where poorly orthorectified adjacent images are used as inputs to the final mosaic. This can result in mismatching of features across the mosaic, as well as holes in the final mosaic (Fig. 6). In general such features are indicative of problems at the orthorectification stage.

6. Conclusions and outlook

In this review we have described the current state of remote sensing with UASs, specifically focusing on image-based environmental measurements and monitoring. In addition to updating the progress on various types of remote sensing systems for UASs, we have also highlighted some of the major research challenges. The use of UASs for environmental monitoring is still in its infancy. While the last few years have seen a tremendous leap forward in the availability and sophistication of aerial platforms, the imaging and sensor technology has not kept pace with this surge. The result is that most UASs still carry a basic compact camera as their primary payload. The rapid growth of the UAS industry has also created a heterogeneous patchwork of UAS regulations, with regulatory frameworks moving more slowly in some countries (e.g., United States) than others (e.g., Canada).

Technological improvements will undoubtedly play an important part in the development of commercial and civil applications. Improvements to platform stability, ease of operation, and operating range are likely to expand the scope of UAS surveys beyond the limited extents that can currently be covered in a single survey. The development of automated sense-and-avoid systems will also help to mitigate safety concerns, and will most likely result in a less restrictive regulatory environment, allowing UAS remote sensing surveys to be carried out over wider areas and at greater operating altitudes.
For widespread adoption of advanced sensor payloads, such as hyperspectral scanners, LiDAR, and SAR, improvements need to be made to UAS navigation sensors. This process is now starting to happen, although UAS systems using carrier phase GPS are still rare. Such sensors are also bulky at present, and inexpensive, miniaturised versions will need to be developed, which also have lower power requirements than currently available. If these issues can be successfully addressed, then the versatility of UASs as data collection platforms will be considerably enhanced.

Until many of these issues can be addressed, it is likely that the primary use of UAS surveys will continue to be for large-scale topographic surveys. The low cost and operational flexibility offered by UAS platforms, along with the recent development of SfM-based photogrammetric packages provide unique advantages compared with traditional aerial photo surveys. However, looking to the medium term it is likely that UASs will start to be used in ways that cannot yet be conceived of, as the technology of both the platforms and the sensors undergoes a process of continual development.

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References


