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REVIEW

Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges

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ABSTRACT

1. Regular monitoring of animal populations must be established to ensure wildlife protection, especially when pressure on animals is high. The recent development of drones or unmanned aircraft systems (UASs) opens new opportunities. UASs have several advantages, including providing data at high spatial and temporal resolution, providing systematic, permanent data, having low operational costs and being low-risk for the operators. However, UASs have some constraints, such as short flight endurance.

2. We reviewed studies in which wildlife populations were monitored by using drones, described accomplishments to date and evaluated the range of possibilities UASs offer to provide new perspectives in future research.

3. We focused on four main topics: 1) the available systems and sensors; 2) the types of survey plan and detection possibilities; 3) contributions towards anti-poaching surveillance; and 4) legislation and ethics.

4. We found that small fixed-wing UASs are most commonly used because these aircraft provide a viable compromise between price, logistics and flight endurance. The sensors are typically electro-optic or infrared cameras, but there is the potential to develop and test new sensors.

5. Despite various flight plan possibilities, mostly classical line transects have been employed, and it would be of great interest to test new methods to adapt to the limitations of UASs. Detection of many species is possible, but statistical approaches are unavailable if valid inventories of large mammals are the purpose.

6. Contributions of UASs to anti-poaching surveillance are not yet well documented in the scientific literature, but initial studies indicate that this approach could make important contributions to conservation in the next few years.

7. Finally, we conclude that one of the main factors impeding the use of UASs is legislation. Restrictions in the use of airspace prevent researchers from testing all possibilities, and adaptations to the relevant legislation will be necessary in future.

INTRODUCTION

Due to the rapid international development of illegal wildlife trade networks, and increasing poaching of flagship species, more and more species are at risk. Rapid habitat loss and environmental degradation exacerbate these circumstances, making regular wildlife monitoring essential in understanding processes in which the pace surpasses that of usual changes in wildlife communities.

Natural ecosystem conservation requires adaptive management that cannot be achieved without effective biodiversity monitoring, including regular wildlife abundance surveys (Jachmann 2001). In many cases, particularly in large areas, aerial surveys with light aircraft remain the best option for counting large mammals (Jachmann 1991). However, such surveys are logistically difficult to implement due to the lack of appropriate aircraft and fuel, particularly in developing countries. Implementation costs of these aerial survey operations are very high, and financial support from external donors is often necessary (Watts et al. 2010, Bouché et al. 2012a, Dunham 2012). Availability of external funds is often unpredictable, making long-term monitoring plans difficult (Dunham 2012). Moreover, aerial surveys are risky for operators (Jones 2003, Wilkinson 2007, Watts et al. 2010), and require trained pilots. Aircraft crashes have been found to be the greatest cause of death for field biologists (Sasse 2003). As a consequence of these limitations, the time between successive surveys can often reach a decade, and sometimes a quarter of a century in many protected areas of developing countries (Bouché et al. 2011). During this time, some species might become extinct in some areas without the implementation of appropriate management actions (Ferreira & Aarde 2009, Bouché et al. 2012b). Long delays between successive surveys may also mean that aircraft and flight plans change, and it is therefore difficult to compare data and assess their evolution accurately.

UltraLight Motorized aircraft (ULM) use has grown in response to the logistical problems posed by regular aircraft (Dejace 1995, e.g. the need for trained pilots and airfield requirements). ULMs are less costly and highly manageable, but not resistant to bad weather, and only fitted for two passengers. The aircraft can be used in surveillance missions and for environmental and wildlife monitoring, such as bird surveys, migration studies (Ellis et al. 2003), and freshwater and saltwater animal counts (e.g. for crocodiles Crocodylinae, hippopotami Hippopotamidae), but they are not appropriate for ungulate inventories (Jachmann 2001). Despite the advantages of ULM, the risks to operators remain high.

Because of these problems, there have been more and more attempts to replace onboard observers with remote sensing systems. Remotely sensed satellite imagery has been tested with certain levels of success in some species, such as large ungulates (cattle *Bos* spp., American bison *Bison bison*; Laliberte & Ripple 2003), and large marine and arctic mammals (seals, walruses Pinnipedia, whales Cetacea and polar bears *Ursus maritimus*; LaRue et al. 2011, Platonov et al. 2013). This methodology covers large areas and avoids any human risk. Despite constantly increasing resolution, it remains inadequate for the recognition of most species and is only effective in highly colour-contrasted environments. Furthermore, remotely sensed images are very expensive, are not flexible, cannot be reproduced at any time (due to fixed orbits and time-of-day characteristics) and are weather dependent, as cloud cover is a major constraint in high spatial resolution optical satellite systems (Loarie et al. 2007, Anonymous 2013b).

The recent development of drones or unmanned aircraft systems (UASs) for various civilian applications, such as law enforcement (Finn & Wright 2012), rapid response operations (Haarbrink & Koers 2006, Eisenbeiss 2009), precision agriculture (Sugiura et al. 2005, Lelong et al. 2008, Hunt et al. 2010), forestry (Wing et al. 2013), hydrology (Niethammer et al. 2012, Westoby et al. 2012), archaeology (Verhoeven et al. 2012) and environmental monitoring (Lejot et al. 2007, Hardin & Hardin 2010, Getzin et al. 2012) presents possibilities for a new direction in wildlife monitoring. Indeed, UASs possess numerous indisputable advantages. UASs exhibit high spatial and temporal resolution (Xiang & Tian 2011, Westoby et al. 2012), low operational costs, easier logistics and manipulation than manned aircraft, and they can fly below cloud cover (Jones et al. 2006, Xiang & Tian 2011). UASs are also safe for the operator (Jones et al. 2006, Watts et al. 2012). Finally, the images and videos they produce constitute systematic and permanent data, which can be reviewed later by other individuals (Hodgson et al. 2013).

The use of lightweight UASs in wildlife monitoring may therefore be a viable alternative to typical field methods (Watts et al. 2012). However, a long road must be traversed before this emergent technology becomes fully operational, and important primary issues must be resolved prior to wider UASs application. Among those issues are the mainly short flight endurance and sensor resolution (both impacting the area covered). Indeed, a compromise must be found between costs and logistics, and UAS capacity in terms of flight endurance and payloads. Finally, even when using remote sensing platforms, human observers remain essential for reviewing the images. Reviewing the huge amount of data collected with UASs is time consuming, and automatic processing is a major need.

In this article, we describe what has been accomplished so far in wildlife monitoring using new UAS technology, evaluate the range of available models used by scientists and the possibilities this work offers, and propose new perspectives for future research.

METHODS

We conducted a bibliographic survey on the data base Scopus and Google Scholar to achieve our objectives. The keywords 'aircraft', 'unmanned aerial system', 'UAS', 'UAV', 'drone', 'wildlife', 'survey', 'inventory' and 'monitoring' were applied in the search. Masters and PhD theses were included because developments in this research area are very recent, and little has been published on the subject in the scientific literature. For the same reasons, unpublished reports ('grey literature') were also briefly reviewed to assess the current trends and new progress. The documentation was reviewed in April 2014, and no date limit was set. Information on UASs was obtained from the literature, and characteristics were compiled from manufacturer or constructors' fact sheets when available.

Many studies used in this review were associated with one another, and results from one study were presented in several papers using different forms of analysis. It was difficult to assess a global number of reviewed surveys, so we chose to classify studies by the different use of UASs and the species detected.

AVAILABLE SYSTEMS

Platforms

The development of UASs is not new; the technology has been in use by the military for decades. Nevertheless, civilian applications have been increasing during the last decade. This new UAS focus has resulted in efforts to renew UAS classification and update legislation.

The classification used by Lee (2004) is based on aircraft size and weight, and ranks drones as micro, small, medium and large. Small UASs have a wingspan of a few meters and weigh less than 10 kg. Other more elaborate classifications are also used in civil aviation, and include other criteria, such as endurance, take-off and landing type, and range, among other things (Watts et al. 2012).

The UASs chosen for wildlife applications covered by this review are primarily small, fixed-wing UAS aircraft (Fig. 1a). In only three studies, helicopter UASs were used (Fig. 1b; Israël 2011, Kudo et al. 2012, Grenzdörffer 2013). This can be explained by the fact that fixed-wing UASs can fly at a higher speed than helicopters, use less energy for lift and then cover a larger area with the same flight endurance (Hardin & Jensen 2011, Niethammer et al. 2012). UAS endurance is generally very short compared with that of manned aircraft, and fixed wings can cover a greater area. However, multicopters can remain stationary in flight, take pictures at any orientation, and take off from and land on small flat areas within uneven terrain (Wallace et al. 2011, Niethammer et al. 2012). They have only been used for studies on small areas.

All UAS specifications reviewed for this paper are displayed in Table 1. The size of fixed-wing UASs ranges from one to a few meters wingspan, and most can be dismantled and carried in a suitcase. Fixed-wing aircraft are typically hand-launched and land on their belly, thus minimizing components required for launch and recovery. Only three UASs employ alternative systems: The X100 requires a catapult to launch, which means a second bag is necessary to carry it in the field. The Inside A-20 and the ScanEagle are the largest UASs we found used in wildlife studies. They are in fact military drones from the same family, chosen due to their high endurance and long range. All other UASs have autonomy reaching a ceiling at 2 hours; however, the Inside A-20 and the ScanEagle can fly for one full day without refuelling. This is superior to many manned aircraft. Moreover, these aircraft have wide ranges, up to 150 km, while the other UASs have a range rarely exceeding 10 km. Usually, range limitations are due to radio and real-time video transmitters, and are governed by laws on radio transmission (the range of frequencies is limited in civil areas). Enhanced antennas in the Inside A-20 and the ScanEagle are based on military concepts. However, in practice, the aircraft have some serious disadvantages. Because of their size and weight, they have to be launched with a pneumatic catapult and recovered in a net, the SkyHook, both of which require a lot of space. This makes the aircraft and associated equipment difficult to carry from one location to another and to use in remote areas.

Only four UASs are powered by liquid fuel. Fuel generally allows for increased endurance; however, it is definitely less practical than electric engines that are easier to handle for people without expertise. Fuel poses several additional disadvantages. It is difficult to procure and maintain fuel in remote areas, and fuel-powered engines produce more

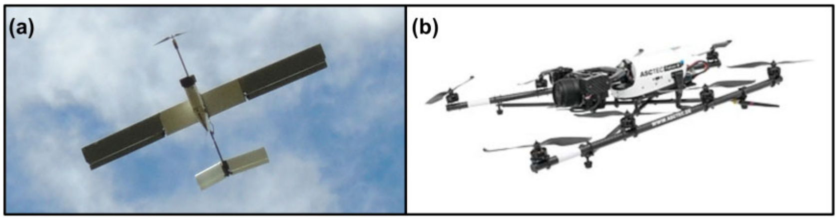

Fig. 1. Types of UASs in flight: (a) fixed-wing Falcon (photo: Julie Linchant) and (b) hexacopter Falcon-8 as used by Israël (2011) (photo: Ascending Technologies).

Table 1. Characteristics of unmanned aerial systems (UASs) determined from the studies reviewed

Study	UAS model	Type of UAS	Propulsion	Take-off	Landing	Wingspan (m)	Endurance (min)	Range (km)	Cruise speed (km.h⁻¹)
Abd-Elrahman et al. 2005	Vehicle from Autonomous Unmanned Air Vehicles	Fixed-wing	Electric	Hand launched	Belly	2.0		0.8	64
Jones 2003, Jones et al. 2006	FoldBat	Fixed-wing	Fuel	Hand launched	Belly	1.5	60	3	48
Buck et al. 2007, Koski et al. 2009	Inside A-20	Fixed-wing	Fuel	Catapult	SkyHook	3.1	20 hours	150	90
Hutt 2011, Owen 2011	RQ-11A Raven	Fixed-wing	Electric	Hand launched	Belly		60–90	10	48
Wilkinson 2007, Wilkinson et al. 2009, Martin et al. 2012	Nova 2, 2.1	Fixed-wing	Electric	Hand launched	Belly	2.4	60	10	90-108
Chabot 2009, Chabot & Bird 2012	CropCam	Fixed-wing	Electric	Hand launched	Belly	2.5	45–55	3	60
Sardà-Palomera et al. 2012	Multiplex Twin Star II model	Fixed-wing		Hand launched	Belly	1.4			30–40
Koh & Wich 2012	Conservation drone based on Hobbyking Bixler DIY drone	Fixed-wing	Electric	Hand launched	Belly		25		
Kudo et al. 2012	Voyager GSR260	Multicopter	Fuel			1.8	45	0.15	
Anonymous 2009, Hodgson et al. 2013	ScanEagle	Fixed-wing	Fuel	Catapult	SkyHook	3.1	24 hours	100	90
Anonymous 2013a	Puma UAS	Fixed-wing	Electric	Hand launched			120	150	
Israël 2011, Grenzdörffer 2013	Falcon 8	Multicopter	Electric				15		
Grenzdörffer 2013	MD4-1000	Multicopter	Electric				30		18
Vermeulen et al. 2013	X100	Fixed-wing	Electric	Catapult	Belly	1	30–45	15	60
Snitch 2013	Falcon	Fixed-wing	Electric	Hand launched	Belly/parachute	2.4	60–90	10	80
Mulero-Pázmány et al. 2014	Easy Fly St-330	Fixed-wing	Electric	Hand launched	Belly	2.0	50	10	15–50

Spaces indicate that information was not provided in the article reviewed.

vibration and waste than electric engines. There is also a risk of engine ignition, and they are noisier (Lee 2004).

There are several ways to command a UASs. The aircraft can be autonomous and follow a pre-programmed flight plan based on global positioning system (GPS) waypoints, manually controlled or a combination of both. Manual control can be performed by visual line-of-sight flying, or remotely by immersion first person view (based on what is seen with real-time video provided by the camera fixed to the aircraft). UASs almost all have the capacity to be fully autonomous, and flight plans can be prepared prior to take-off. However, most autopilot settings allow the flight path to be altered while flying, and manual control can be resumed, at least for landing which is the trickiest component of the flight, or to follow a specific element. Most UASs mentioned in this review function on autopilot with pre-programmable flight paths. Sardà-Palomera et al. (2012) used a fully manual, radio-commanded UASs. This UAS is an off-the-shelf drone designed first for amusement, and subsequently modified for research purposes. The helicopter used by Kudo et al. (2012) is also manually controlled and piloted with first person view provided by live video.

Sensors

UASs can carry various sensors, one or even several at a time, depending on payload capacity and connections with the control station. In wildlife surveys, two main types of payloads are used, digital still cameras and video cameras, in true colours, infrared and thermal infrared (Table 2). The spatial resolution provided by those sensors is one of the major constraints in UAS surveys. The better the physical properties of the sensor are, the higher and faster UASs can fly to provide the same resolution, and so the greater area they can cover. The sensor choice suffers the same compromise as the airframe between price, quality, and size and weight. Medium-format compact cameras are smaller and cheaper and therefore can be mounted on small UASs. Authors choose their sensors based on the compromise between the carrying possibilities of their UASs, the price and the quality of the images.

The digital still cameras used are mainly commercial off-the-shelf compact system cameras, with a sensor size ranging from 8 to 24 megapixels; these are easily adapted for use on the UASs. Video cameras are primarily for real-time retransmission of surrounding conditions, and are compact and lightweight cameras, such as GoPro. However, some authors have been using video retransmission to detect and survey some species, including, but not limited to, American alligators *Alligator mississipensis*, whales, and black and white rhinoceros *Diceros bicornis* and *Ceratotherium simum* (Jones 2003, Jones et al. 2006, Koski et al. 2009, Mulero-Pázmány et al. 2014). These are often high definition video cameras (full

Table 2. Characteristics of unmanned aerial systems (UASs) and flight characteristics determined from the studies reviewed, and the animal species or other items detected

Study	UAS model	Captor	Real-time video	Georeferenced	Flight altitude (m)	Ground resolution (cm)	Species or items detected
Abd-Elrahman et al. 2005	Vehicle from Autonomous Unmanned Air Vehicles	Progressive scan video camera Canon Elura 2	Yes: black-and-white CMOS analogue video chip camera	No			**Wading birds, decoy birds**
Jones 2003, Jones et al. 2006	FoldBat	Progressive scan video camera Eo-IR Canon Elura 2	Yes: black-and-white CMOS analogue video chip camera	No	100–150		**White ibis *Eudocimus albus*, egret *Egretta* sp., wood stork *Mycteria americana*, American alligator *Alligator mississippiensis*, West Indian manatee *Trichechus manatus*, cattle, decoy alligators**
Buck et al. 2007, Koski et al. 2009,	ScanEagle/Inside A-20	AltiCam 400/AltiCam 600 video camera	Yes		305	25–32	Pinnipeds and cetaceans, **painted kayaks simulating whales**, one minke whale *Balanoptera sp.*
Brush & Watts 2008	Nova 2	Evoltmodel 420 digital still camera		Yes			Red knot *Calidris canatus*, egrets *Ardea alba, Bubulcus ibis, Egretta* sp., pelicans *Pelecanus* sp., woodstorks *Mycteria* sp.
Anonymous 2009, Anonymous 2013a	ScanEagle		Yes				**Ice seals Phocidae**
Wilkinson et al. 2009	Nova 2	Evoltmodel 420 digital still camera		Yes	75–200	1–2.5	American alligator *Alligator mississippiensis*, Bison *Bison bison*
Chabot 2009	CropCam	Pentax Optio A-10 8MP and A-40 12MP	No	Yes	150–275		**Black bear *Ursus americanus*, woodland caribou *Rangifer tarandus*, white-tailed deer *Odocoileus virginianus*, grey wolf *Canis lupus***
Chabot 2009, Chabot & Bird 2012	CropCam	Pentax Optio A-10 8MP and A-40 12MP	No	Yes	180		**Snow goose *Chen caerulescens*, Canada goose *Branta canadensis*,** one bald eagle *Haliaeetus leucocephalus*, North American beaver *Castor canadensis* lodges
Hutt 2011, Owen 2011	RQ-11A Raven	Thermal video	Yes		60		**Sandhill crane *Grus canadensis***
Israël 2011	Falcon 8	Thermal infrared 10Mp	Yes	Yes	30–50		**Roe deer *Capreolus capreolus* fawns**
Martin et al. 2012	Nova 2.1	Olympus E-420 digital single lens reflex camera 10MP		Yes	200	5	West Indian manatee *Trichechus manatus*, alligator *Alligator mississippiensis*, **tennis balls used to model manatee distribution**
Sardà-Palomera et al. 2012	Multiplex Twin Star II model	Panasonic Lumix FT-1 12Mp		No, use of control points	30–40		**Black-headed gull *Chroicocephalus ridibundus***
Koh & Wich 2012	Conservation drone based on Hobbyking Bixler DIY drone	2 still cameras, Canon IXUS 220 HS 12MP and Pentax Optio WG-1 GPS 12MP	Yes: GoPro Hero	Yes	100–200	2.2–5.3	Asian elephant *Elephas maximus sumatranus*, orangutan *Pongo abelii*
Kudo et al. 2012	Voyager GSR260	Canon EOS Kiss X	Yes: Camera MacromaX MVC-10	No	30		**Wild Pacific chum salmon *Oncorhynchus keta***
Anonymous 2013a	Puma UAS		Yes				Roseate spoonbill *Platalea ajaja*, roosting frigatebirds *Fregata magnificens*, sea turtles, Key deer *Odocoileus virginianus clavium*
Hodgson et al. 2013	ScanEagle	Nikon D90 12Mp SLR cam	Yes		150–300	1.8–3	**Dugong *Dugong dugong***, dolphins, tortoises, sharks, rays, seasnakes, fish schools and birds
Grenzdörffer 2013	Falcon 8	Sony Nex5 12Mp		Yes	50	1.6	**Common gull *Larus canus***
Grenzdörffer 2013	MD4-1000	Olympus Pen E2 12Mp	Yes	Yes	50	1.6	**Common gull *Larus canus***
Vermeulen et al. 2013	X100	Ricoh GR3 still camera 10Mp	No	Yes	100	3	**African elephant *Loxodonta africana***
Snitch 2013	Falcon	EO/IR gimbal payload	Yes: GoPro Hero	Yes	100	2.5	**African elephant *Loxodonta africana*, humans**
Mulero-Pázmány et al. 2014	Easy Fly St-330	Still photo camera Panasonic Lumix LX-3 11MP, HD video camera GoPro Hero2, thermal video camera Thermoteknik Micro CAM (640 × 480)	Yes: GoPro Hero2	Yes	10–260	0.4–1.8	**Black rhinoceros *Diceros bicornis*, white rhinoceros *Ceratotherium simum***

Species in bold were the clearly intended subjects and were detected successfully; for others, anecdotal or limited information was given. Spaces indicate that information was not provided in the article reviewed.

HD) and can sometimes even be directed and zoomed in and out manually, as can the camera used by Koski et al. (2009). Video cameras can also record data and can provide image frames for further analyses (Jones 2003, Jones et al. 2006, Koski et al. 2009). Nevertheless, video cameras provide images of lower quality than still cameras, and their use remains limited (Mulero-Pázmány et al. 2014).

Thermal infrared cameras have been applied, based on the assumption that animals can be detected due to differences between an individual's body temperature and the environmental temperature. These cameras can be used in low light conditions and during the night to help detect nocturnal animals (Hutt 2011, Israël 2011, Owen 2011, Mulero-Pázmány et al. 2014). However, this methodology is less common, probably due to the higher price of efficient equipment and the coarser resolution of these sensors. Thermal infrared cameras can also be considered to be dual-use materials (with military and civil applications) and are subject to certain controls in most parts of the world when associated with specific materials such as drones. Those issues are less and less important as progress is constantly made, and thermal cameras are becoming commonly available.

Most UASs have a GPS device coupled with the sensor, and provide direct geotagged images. A few authors indicated use of non-coupled GPS; they had to synchronize images and positional data afterwards for geo-referencing (Sardà-Palomera et al. 2012). Jones et al. (2006) reported difficulties when conducting synchronization of videos due to time lags and sporadic dropouts in transmission and positioning. Kudo et al. (2012) were the only authors whose UASs did not possess a GPS device and therefore direct geo-referencing was not possible in their study.

Imagery sensors are the most widely applied sensors in wildlife applications. Only Owen (2011) used a totally different sensor type, the Bio-Tracker device, in addition to a thermal infrared camera. The Bio-Tracker is a device capable of detecting data emitted by radio tracking systems carried by marked animals. It can locate the animal's position within a 100-m range and collect data from radio-collars. This can be advantageous when looking for a particular collared individual. The operator can avoid walking for hours in harsh environments with the receptor. This method is now broadly described as the 'follow-me' flight mode on specialized websites such as DIY Drones (diydrones.com), and could bring a very interesting perspective to following and surveying endangered collared animals such as rhinoceros and elephants.

Equipment costs

UAS price range is as important as the diversity of UAS configurations. Indeed, price depends on UASs and sensor characteristics (most often sold as a complete package, including one or several sensors, ground control station and spare pieces), and authors have to compromise on that basis. The difference between professionally manufactured complete UASs with payloads and do-it-yourself (DIY) systems is notable. Even in the same categories of UASs, prices can vary a lot depending on when the UASs was purchased, as cost has decreased substantially with rapid technology growth. In the studies we reviewed, prices started at around US$2000 for small DIY UASs assembled by the authors with separate components and payloads (Koh & Wich 2012, Sardà-Palomera et al. 2012) and reached over US$100000 for military concept drones such as the ScanEagle. Commercial small UAS complete packages now have median prices of around US$50000, but Lee (2004) reported prices of above US$100000 for two first-generation small UASs. Ten years later, Mulero-Pázmány et al. (2014) flew an aircraft costing €14000 (ca. US$17500). DIY is clearly a viable approach for the future, for authors who have the time and skills to develop and build the UASs, but commercial UAS prices are decreasing, and time lost in development and assembly will probably soon be compensated for by the money paid for a commercial UASs.

DEVELOPMENTS IN WILDLIFE SURVEYS AND CENSUS

Species detection

UAS applications in wildlife monitoring are recent; therefore, most studies have been focused on the possibilities of species detection, rather than on the realization of complete inventories (Jones 2003, Jones et al. 2006, Chabot 2009, Koh & Wich 2012, Mulero-Pázmány et al. 2014). UASs have been used to survey three groups of animals: large terrestrial mammals (e.g. deer Cervidae, woodland caribou *Rangifer tarandus*, Asian elephants *Elephas maximus*, African elephants *Loxodonta africana*, rhinoceros and orangutans *Pongo* spp.), aquatic animals (e.g. alligators, dugongs *Dugong dugon*, manatees *Trichechus* spp. and whales) and birds (e.g. geese Anserini, gulls Laridae and wading birds Charadriiformes; Table 2 and Fig. 2). The focus on large mammals and aquatic animals is not surprising, as these taxa are usually surveyed from manned aircraft (Jachmann 1991, Hodgson et al. 2013, Mulero-Pázmány et al. 2014). Therefore, replacement with another aerial method was primarily investigated with regard to the possible detection level and the factors influencing it. Indeed, with the exception of Vermeulen et al. (2013) surveying the African elephant and Hodgson et al. (2013) surveying dugongs, no researchers provided estimates of global population sizes for a large geographic area, and no comparisons were made with results of other methods of surveying free-ranging

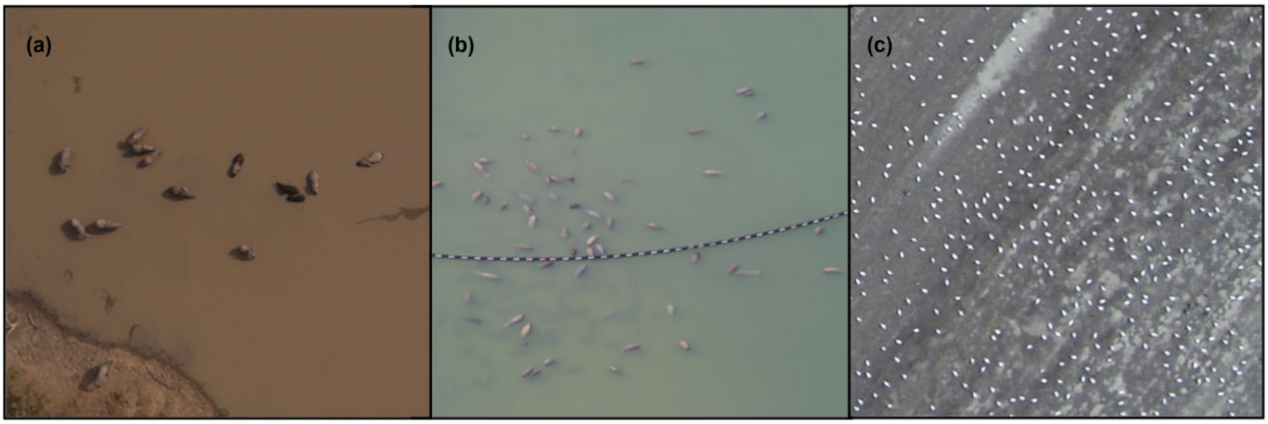

Fig. 2. Most of the various species that have been detected by unmanned aerial systems (UASs) fall into three major categories: (a) large terrestrial mammals (e.g. elephants *Loxodonta africana*; photo: Vermeulen et al. 2013); (b) aquatic mammals (e.g. Florida manatees *Trichechus manatus*; photo: Martin et al. 2012); and (c) birds (e.g. snow geese *Chen caerulescens*; photo: Chabot 2009). Details of the photo acquisition can be found in Table 2 for the relevant authors.

animals. Authors have mainly tested UASs on known populations to describe the flight and sensor parameters necessary to spot animals, and have even used fake animals to evaluate the possibilities, as Jones (2003) did with an American alligator decoy. Table 2 provides an overview of all species identified using UASs by different authors. Flight altitudes ranging from 10 to 300 meters have been used successfully, and have provided images with resolutions of a few centimetres. Flying at lower altitudes does not always result in more successful detection. Chabot (2009) showed that large mammals such as black bears *Ursus americanus* were easier to spot from higher altitudes, perhaps because the spatial resolution of the imagery is more appropriate, and creating images from higher altitudes reduces high-frequency variation in pixel values associated with higher spatial resolution sampling of the features of interest. Fewer details, in terms of colours and shapes, associated with larger image footprints and extended surroundings can help researchers isolate features of interest. This can also influence automatic detection, as coarser resolution and reduced frequency variation are suitable for detection algorithms.

The situation for birds is a bit different. Only colonial birds have been monitored with UASs, as these species aggregate for long periods of time and are therefore easier to count. The population census usually occurs during the nesting period, when nesting pairs can also be counted. Counts are often performed by observers on foot (ground counts) or from manned aircraft. These methods, however, disturb the birds and are difficult for scientists, as birds may fly away from or attack ground surveyors (Chabot & Bird 2012, Sardà-Palomera et al. 2012, Grenzdörffer 2013). UASs that fly low and silently provide images from which it is possible to detect medium-sized birds. Colonies of diverse wading birds (Abd-Elrahman et al. 2005), Canada geese *Branta canadensis*, snow geese *Chen caerulescens* (Chabot & Bird 2012), black-headed gulls *Chroicocephalus ridibundus* (Sardà-Palomera et al. 2012) and common gulls *Larus canus* (Grenzdörffer 2013) have been studied. In all cases, populations were over-flown by the UASs, and pictures were taken to cover the entire geographical area. Birds were counted on successive images, taking care not to double-count due to overlap or on mosaics resulting from the merged images. Sardà-Palomera et al. (2012) and Grenzdörffer (2013) discriminated nesting birds from non-nesting birds. During the test period, ground surveys were performed to compare results with UASs (detection and counting based on interpretation of UAS imagery), with the exception of common gull counts by Abd-Elrahman et al. (2005) and Grenzdörffer (2013). Results between ground and air counts were highly variable. Numbers of nesting black-headed gulls counted from UAS images differed by 0.8–6.1% from numbers counted from the ground. Results obtained by Chabot and Bird (2012) exhibited more notable positive and negative variation. White snow geese had an average detection rate of 60% higher with the UAS census, while dark Canada geese exhibited the opposite results: numbers were up to 30% lower from the UAS census; coefficients of variation ranged from 11% to 106% for UASs and from 1% to 6% for the ground census. Hutt (2011) and Owen (2011) conducted the same type of survey for sandhill cranes *Grus canadensis* by using a thermal infrared camera to census the birds. Sandhill cranes tend to aggregate at night and are dispersed during the day while searching for food. It is therefore easier to obtain an accurate bird colony count during the night. UAS census results showed a 4.6% underestimation compared with the ground count.

Only two other uses of thermal imagery have been reviewed. Israël (2011) conducted a study on a new roe deer *Capreolus capreolus* fawn detection system. Roe deer fawns tend to spend their first months of life in cultivated pastures hidden in tall grass. Unfortunately, when farmers mow their fields, fawns cannot escape, and the machines kill many of the animals. Fawns do not generate much heat, and it is almost impossible to detect them through thick grass when walking in the field with thermal devices. Therefore, Israël (2011) attempted to detect fawns from the air since the grass does not cover them. Results showed that insulation conditions are essential for detection. Under optimal conditions (a cold environment), few fawns were missed on video, and the rescue system was operational. A few other animals were also detected, such as adult deer, rabbit *Oryctolagus cuniculus* and fox *Vulpes vulpes*. The detection of such small specimens shows the potential of low flight altitude. Mulero-Pázmány et al. (2014) demonstrated the difficulties in obtaining clear species identification from thermal video. Black and white rhinoceros and people (representing poachers) were detected in a protected South African area, and the authors confirmed that the early colder hours of the day provided the finest images. Although the presence of targets was confirmed, they were not able to identify animals to species, and lower altitudes and zoom were required to identify humans by their body shape.

These results emphasize the importance of environmental conditions in animal detection using UAS imagery. Indeed, it is clear that not only animal characteristics and flight parameters have an impact on detection. It is important to consider animal behaviour and captor characteristics, as well as factors such as light, shadow and ground cover, which can influence detection, in order to apply the technology effectively. Chabot (2009) supported these recommendations by comparing aerial and ground counts of black bears, grey wolves *Canis lupus*, woodland caribou, and white-tailed deer *Odocoileus virgianus* confined to seminatural enclosures. During ground counts, the time and animal location, movement and the presence of shade and overhead cover were recorded, and these were compared with images of the animals from UASs. Data interpretation showed that besides a big and contrasting body, the attributes of animals favouring detection were low affinity for shade and concealed areas, and frequent local movements. Mulero-Pázmány et al. (2014) also examined environmental parameters. Results showed that rhinoceros were easily detected in grasslands and forested areas, and that image quality was best at midday when the sun was high and cast fewer shadows. In marine surveys, Koski et al. (2009) also tested parameters capable of influencing the detection of three whale species: bowhead whales *Balaena mysticetus*, grey whales *Eschrichtius robustus* and belugas *Delphinapterus leuca*. The researchers used kayaks to simulate whale backs in the sea, in order to survey the impact of specific parameters. They analysed the impacts of target colour, target inflation degree, sun brightness and glitter, turbidity, and Beaufort wind force. Inflation degree had the strongest influence on detection of the simulated whales. Koski et al. (2009) are not the only researchers to use simulated data instead of real animal data to compute detection statistics. Jones (2003) was the first to use this stratagem to simulate American alligator detection, and Abd-Elrahman et al. (2005) and Martin et al. (2012) compared the expected distribution and animal detection with those of decoy birds and tennis balls, respectively.

The process used to acquire images during an inventory is important. Although most flight plan assistants allow various configurations, researchers in papers we reviewed only used linear transects, probably because linear transects are commonly used by manned aircraft. Kudo et al. (2012) have been set apart by their work, which has little in common with other approaches. Linear transects were not established to collect data. Indeed, Kudo et al. (2012) used a remotely controlled first person view helicopter. The operator watched the transmitted video and triggered the camera from the ground. They collected images of wild Pacific chum salmon *Oncorhynchus keta*; this species is usually recorded from the riverbanks by capturing images when well positioned above the fish. The helicopter images were subsequently processed with software which detected fish automatically. Results were then compared with the number of fish seine-netted during the same period, and a strong positive correlation was revealed (Kudo et al. 2012).

In the studies we surveyed, no disturbance of animals by the UASs was reported, regardless of the altitude of the aircraft. Kudo et al. (2012) flew as low as 7 m without any notable response from the fish or from seabirds. However, in this single case, the salmon avoided the shadow of the UASs.

Statistical analyses for density estimations

In most studies, detection potential was the main purpose; when count comparisons occurred, there remained basic differences among results. However, some researchers examined the results further, and measured the quantitative impact of inventory parameters and environmental factors on their results. Chabot (2009) and Koski et al. (2009) clearly demonstrated the importance of such research.

Census data collected to date has primarily been used to examine global counts of all individuals representing one or more species in defined populations, in an area entirely surveyed with UASs and with one other method (e.g. a bird colony). Kudo et al. (2012) examined the possibility of comparing two different methods with absolute counts, and also of finding statistical correlations with other sampling methods that could be used to give an estimate of population size. The number of salmon caught in seine nets was higher than the number of salmon seen on images, but the correlation coefficient (93%) showed a strong positive significant correlation.

Martin et al. (2012) used objects to set a theoretical detection rate with UASs. Tennis balls were chosen to model manatee distribution in refuge areas, by hiding and uncovering a known proportion of balls to represent incomplete animal detection. When applied to the number of manatees detected in the model, this method was believed to generate an accurate estimate of the species population in the area.

Only Vermeulen et al. (2013) estimated numbers over a wide inventory area, by partially sampling the survey and the area inhabited by a population of African elephants. This first attempt applied the method typically used in aerial surveys with manned aircraft in African savannas. The estimation of animal density is based on the area covered, and is directly related to the flight altitude, which determines the image footprint. The area covered is a fundamental parameter when estimating populations. Currently, estimation of the area covered is a major technical challenge, as altimeter or on-board GPS difference with ground elevation models lack precision. Lisein et al. (2013) focused on another method to estimate the entire area covered by UASs: reconstructing three-dimensional models by merging all the pictures taken during a flight. The model determines the exact position of the photos and gives a very accurate surface result. It requires that photos are taken with a large degree of overlap (70–90%).

New statistical methods to estimate population sizes accurately need to be developed with the emergence of new survey approaches. One important advantage of UASs in terms of statistics is that they can be programmed to fly a specific flight plan that can be recovered and uploaded in another UAS later, so that it can fly the exact same profile. Statistical comparisons would be more accurate even if the two flights were conducted years apart, and this repeated design may have a major impact on the utility of aerial census.

Automatic counts

The development of automatic processes to review the data is another key for the successful use of UASs in wildlife monitoring. Substantial numbers of pictures are generated during every UAS flight; furthermore, an increased number is produced when overlap between pictures is important (70–90%). All pictures or the resulting mosaics must be examined, and specimens must be identified and counted by at least one operator. A single flight generates several hundred pictures; therefore, the work is exhausting and time consuming, decreasing the benefits of UASs.

Several authors have overcome this challenge with encouraging results. Abd-Elrahman et al. (2005) were the first to develop an algorithm that automatically detects birds on UAS images. They used a segmentation process to extract coloured areas, and shape and size parameters to limit detection to the expected bird elements. Wading and decoy birds were compared and verified with visual counts. For both sets of images, mean commission and omission errors were less than 20%, and the overall count error was less than 10%; the effects of the two error types tended to cancel each other out.

Grenzdörffer (2013) conducted two inventories on a common gull colony nesting in a small fenced reserve. He performed visual and automatic counts based on the same type of supervised classification methods, using colour and extraction by size. Results were 95.4% and 97.6% of numbers from visual counts. He then used standing birds' shadows to discriminate automatically between nesting and standing birds with a 74% success rate. The overall high success exhibited in this study can partially be explained by the fact that common gulls, which are white and light grey in colour, contrast well with the nesting environment (Grenzdörffer 2013). However, the sandy area of the mosaic was purposely removed because birds did not contrast with it well enough to perform automatic counts, and because nesting did not occur on this beach. If this approach can serve the aims of this particular study, it can also come across important complex automatic count problems in other studies. Chabot and Bird (2012) experienced a similar problem in counting snow geese and Canada geese. Snow geese are large white birds that contrast well with the environment; therefore, automatic counting was effective; however, Canada geese are dark grey birds and blend into the environment; therefore, the counts could not be performed well.

To date, automatic counts from UAS imagery have mainly been limited to bird inventories and have only been effective for white, contrasting birds, as the methods were based on image segmentation. Others try to apply similar methods to different animals such as big mammals (see, e.g. http://www.wipsea.com). However, the behaviour and environment of those species vary a lot and make it difficult to find them automatically on a colour and shape basis. Automatic wildlife counts became a major issue with the huge amount of data obtained from UAS flights, but have been tried for other aerial images. Oishi and Matsunaga (2010) developed an algorithm based on differences detected between two successive pictures, provided the images have sufficient overlap (60%). The algorithm identifies changes in pixel values due to animal movement. The tests have shown some success with the detection of three humans but have not detected other animals. Nevertheless, this opens possibilities for the development of more effective means to count moving animals automatically.

ANTI-POACHING AND ILLEGAL TRADE SURVEILLANCE

Anti-poaching and illegal activities surveillance are fundamental foundations of wildlife conservation, particularly in developing countries where pressures on wildlife are very high. In these countries, most of the agencies responsible for the management of protected areas experience financial, logistical and human difficulties, which decrease their ability to ensure biodiversity conservation. This subject is likely to be impacted by the breakthrough of civilian UASs. Numerous associations dedicated to the protection of endangered species regularly publish news online regarding their work with UASs to fight poaching. The World Wildlife Fund and African Parks (which manages several large protected areas; Snitch 2013), the International Anti-Poaching Foundation and many smaller organizations show substantial interest in this new technology to help save flagship species, such as elephants and rhinoceros.

Although the media and websites dedicated to wildlife conservation spread news on the subject, scientific articles about UASs used in anti-poaching surveillance are rare. Therefore, exploring more literature on UASs and the possibilities in terms of materials and methods is challenging. Articles addressing drones in law enforcement are available, but the content and context were too dissimilar to describe in this review. Indeed, anti-poaching surveillance requires enforcement in developing countries, in large remote areas where the environment and field conditions are harsh, and the methods must be adapted to these particular conditions. The ‘grey literature’ we reviewed showed that UASs used for anti-poaching surveillance are mostly small and use live thermal video to track poachers and signs of illegal activities.

Koh and Wich (2012) were the first to publish on the subject; while mapping an area in true colours, they showed that smoke from campfires, illegal tracks and large camps were visible. But data were trivial even if promising. More recently, the World Wildlife Fund published results regarding trials in South Africa and announced that it was possible to identify humans and elephants quite easily with the Falcon UAS, during day and night missions. Although this was encouraging, they emphasized that launching UASs is expensive and should not be done randomly. Further planning and mathematical modelling are required to develop a specific anti-poaching method (Snitch 2013). Mulero-Pázmány et al. (2014) used photos, HD video and thermal video to spot rhinoceros, people (representing poachers) and survey fences, and reached the same conclusions. Targets could be identified with variable accuracy on the photos, but the HD video exhibited poor results above 40 m due to deformations from the wide-angle lens. Thermal video showed the finest images in the early hours, but targets were not identified to species, and humans were confirmed only when flying low and zooming into images. These practical limitations support the need for well-planned actions in sensitive areas with a new method.

These studies were focused on detecting targets by visual observation of images, but other methods have been implemented for law enforcement purposes. Coulter et al. (2012) reported on another promising method for identifying people and vehicles moving in prohibited open land areas (during border surveillance in semi-desert between the USA and Mexico), using a true colour digital still camera. The method is similar to Oishi and Matsunaga’s (2010) approach to finding moving animals. UASs can span wide remote zones several times in a short period, so the idea was to detect changes associated with movement from a series of successive images (repeated transects with a time stamp of 10–30 min) using abnormality detection techniques. The results showed detection rates of 98% for people and 100% for vehicles, when the elements were almost invisible to the naked eye. Results are highly promising, and tests with thermal imagery are envisaged. This method is efficient and is worth targeting for further investigation in anti-poaching surveillance.

LEGISLATION AND ETHICS

Legislation is one of the major factors authors report as impeding the use of UASs. Indeed, drones used in civil applications are new and have been developing faster than the corresponding legislation. To date, universal legislation and certification do not exist for the material or applications. Consequently, most countries throughout the world attempt to develop and implement new rules as required, to address the rapid emergence and spread of the technology. UAS use is under the legislative authority of Civil Aviation, but the definition and characteristics of UASs vary substantially, and a normalized classification does not exist, making laws difficult to implement. Due to the absence of a definitive and active policy, legislation has progressed on a case-by-case basis in most countries. Countries in Europe and the USA have tended to have similar points of view and regulations, and have limited drone use to assure security. Until now, legislative gaps have allowed researchers and businesses that could support their reliability (show their expertise in the field, complete reports assessing the aims and risks of the surveys) to get exceptional permits (Watts et al. 2012). But gaps are closing, and most rules appear to be strengthening with the development of specific regulations. Indeed, in most cases, UASs are not permitted to fly out of sight of the operator, at night, or higher than the lowest limit for manned aircraft, preventing the development of projects with more requirements. In Belgium, for example, flights are restricted to test and scientific applications. Flying above roads, close to buildings and close to private properties is forbidden unless specific permission has been given. In such a densely populated country, it is almost impossible to get such permission in time to meet research deadlines. Restrictions have increased with the recent announcement that the European Commission will standardize control over UASs, as they can easily cross borders. The European Commission will examine the possibility of integrating UAS legislation in European airspace from 2016, and will give common directives that will then be implemented by National Aviation Agencies. Directives will focus on six main key topics: safety (complying with the European Aviation Safety Agency), security, privacy, data protection, insurance and liability. Operators and pilots will need a licence in order to fly drones. A licensing system is already operating in Australia, where it helped integrate UASs in civil airspace. Mulero-Pázmány et al. (2014) reported on a similar situation in South Africa. South Africa had no legislation in place for the use of remotely piloted aerial systems. Therefore, the Recreational Aviation Authority of South Africa first decided that UAS flights could be performed over protected areas for wildlife research, but not close to registered active airfields. Mulero-Pázmány et al. (2014) flew under that legislation involving aviation safety, and obtained a license for the radio frequencies used in the region. Unfortunately, the recent complete ban on the use of UASs in Kenya has spread to South Africa, and they are now forbidden even in private concessions. The ban may have a negative impact on conservation, as UASs were increasingly used in anti-poaching and wildlife monitoring in that part of the world.

There are many misconceptions about UASs: Individuals associate drones with war, or are concerned by the possibility of spying and ask for tougher regulations. However, the same rules apply to data acquired by drones and to data acquired by other means, such as from manned aircraft. Researchers have to comply with the existing national privacy and data protection rules.

Legislation is often accused of limiting commercial and research development of UASs. Fortunately, the recent creation of six test sites by the USA to start integrating UASs in civil airspace, as well as their accepted use by civil safety agencies, is likely to help legislation take a positive path. Most countries will probably follow suit.

CONCLUSIONS AND PERSPECTIVES

In this review, we provided evidence from the literature that a wide range of wildlife surveys can be successfully completed with UASs and that opportunities exist for future development. We addressed the developments required in UAS approaches and technology. Most surveys other than bird counts showed detection possibilities; few focused on the important question ‘can we really monitor wildlife populations using UASs, and is the method more effective than traditional well-defined and successful methods?’ Currently, the focus of wildlife aerial surveys is on distance sampling, and developing a reliable remote data capture system to replace human observers in the field will be very difficult unless it is proven to be very accurate and advantageous. The real costs of UAS-based surveys and their advantages over traditional methods are therefore of concern to natural resource managers. Researchers face a trade-off between the performance of the materials, the logistics and the investment, which explains why mainly small UASs and small captors are used. The main drawbacks remain low flight endurance and low captor quality, but these could be overcome in the near future if investment is made in better technology. The technology market is growing rapidly, and UASs will become more affordable as more DIY products become available: The DIY Drones website shows the growing interest. The broad community forum provides valuable advice and shares knowledge on how to create your own drone. The community also developed an open source autopilot (hardware and software) which can be adapted for almost all survey types. Data are rare, but Kudo et al. (2012) calculated that the cost of surveying one river using UASs was half the cost of conducting traditional inventories with manned aircraft. Mulero-Pázmány et al. (2014) evaluated the cost of classic surveillance in a protected area at approximately €11000/year/700–800 ha; the cost of the UASs was €14000, and it could be used for several years. The benefits of UASs in anti-poaching surveillance are hard to evaluate because substantial improvements are needed.

Before people invest more in UASs to monitor wildlife, new and efficient survey methods will have to be developed. UASs have technical limitations and cannot cover wide geographical areas; therefore, the creation and assessment of new protocols for sampling methods, inventories and statistical analyses are needed. Some authors have made attempts, but no surveys have been performed at large scales. The first step is to detect the target species in all conditions, including environmental, ground cover, contrast and meteorological conditions. For this purpose, a still camera remains best to date, but is still limited. The use of thermal video is promising and deserves more investigation. Thermal video might help detect cryptic animals and, combined with optic HD images, might increase discrimination of species. The next challenge in need of further development, particularly in big game surveys, is the sampling method and census flight plans. Almost all authors used traditional parallel transects, but a completely different protocol may be more efficient.

It is also easy to imagine other applications for UASs in biology, such as behavioural studies. There are many different UASs and sensors, some of which have not been tested, and their usefulness depends on the study subject, the geographic area covered, the type of survey and the purpose of the survey.

The development of automatic detection is important for most targets, as every flight results in hundreds of pictures that require time-consuming analyses. Automatic detection is probably one of the most important developments required for the future use of UASs to monitor wildlife, although human observers will always remain necessary.

Finally, we are optimistic that the development of new legal frameworks will facilitate the use of UASs and developments to provide new efficient means to monitor and protect wildlife. UASs have too much to bring in terms of development and economy to be held back for too long by legislation.

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