drones

Review

Unmanned Aerial Vehicles (UAVs) in Marine Mammal Research: A Review of Current Applications and Challenges

Miguel Álvarez-González [1], Paula Suarez-Bregua [1], Graham J. Pierce [2] and Camilo Saavedra [1,*]

[1] Centro Oceanográfico de Vigo, Instituto Español de Oceanografía (IEO-CSIC), Subida a Radio Faro 50, 36390 Vigo, Spain; miguel.alvarez@ieo.csic.es (M.Á.-G.); paula.suarez@ieo.csic.es (P.S.-B.)
[2] Institute of Marine Research, Spanish National Research Council (IIM-CSIC), Eduardo Cabello 6, 36208 Vigo, Spain; g.j.pierce@iim.csic.es
* Correspondence: camilo.saavedra@ieo.csic.es

Abstract: Research on the ecology and biology of marine mammal populations is necessary to understand ecosystem dynamics and to support conservation management. Emerging monitoring tools and instruments offer the opportunity to obtain such information in an affordable and effective way. In recent years, unmanned aerial vehicles (UAVs) have become an important tool in the study of marine mammals. Here, we reviewed 169 research articles using UAVs to study marine mammals, published up until December 2022. The goals of these studies included estimating the number of individuals in populations and groups via photo-identification, determining biometrics and body condition through photogrammetry, collecting blow samples, and studying behavioural patterns. UAVs can be a valuable, non-invasive, and useful tool for a wide range of applications in marine mammal research. However, it is important to consider some limitations of this technology, mainly associated with autonomy, resistance to the marine environment, and data processing time, which could probably be overcome in the near future.

Keywords: marine mammal; UAV; drone; monitoring; cetacean; pinniped; sirenian

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1. Introduction

Marine mammals are ecosystem engineers that influence ecosystem structure and function because of their role in middle and upper trophic levels, large body size, and high regional abundance, exerting an important top-down control effect on the food web. Studies focused on monitoring marine mammal populations and improving knowledge on their biology and ecology have significant relevance (e.g., for developing conservation management strategies). However, marine mammals can be challenging to monitor at sea as they are distributed over large areas, and when at sea they only come to the surface to breathe or rest for short periods and cannot be sighted when submerged. On land, pinniped haul-outs are often located in remote and inaccessible areas. Technological development provides the possibility of using new instruments to survey marine fauna, reaching milestones previously unattainable or in a more cost-effective way than before.

Unmanned aerial vehicles (UAVs), also known as "drones" or remote piloted aircrafts (RPAs), are an emerging tool for wildlife studies that could serve as a safer and non-invasive alternative or complement to traditional methodologies for marine mammal monitoring, with less impact on target populations. They are a component of unmanned aerial systems (UASs), which include the UAV itself, a launch and recovery system, a camera payload mounted on the UAV, and a ground control system. There are two main groups of UAVs: fixed-wing and rotary-wing aircraft. The advantages and disadvantages of each type depend on the nature of the study. Fixed-wing UAVs can cover significantly larger areas when operated beyond visual line of sight (BVLOS) due to their higher flight speed and autonomy. This kind of UAV usually needs a complex launch and recovery system, but can also work without these systems if it belongs to the VTOL (vertical take-off and landing) category. On the other hand, rotary-wing or "multirotor" UAVs, in addition to allowing vertical take-off and landing, provide flight stability and sometimes hovering capability, allowing them to be deployed from small vessels and manoeuvre or maintain their position over target species groups, but they often have less autonomy due to their high battery consumption, resulting in reduced operational time.

In this review, we explore the increasing number of applications of UAVs to study marine mammal populations. We focus on the main aims mentioned to date: (a) abundance and distribution monitoring; (b) photo-identification (photo-ID); (c) morphometry estimates through photogrammetry methods; (d) blow sample collection; (e) behavioural studies; and (f) others. We discuss the strengths and weaknesses of this new technology compared to more traditional methods, the opportunities that this technology offers, and its current limitations. Finally, we conclude with suggestions about future directions and the challenges that this technology will have to overcome.

2. Methodology

We conducted a search of the literature related to the use of UAVs in marine mammal studies from 2009 up to and including 2022 using SCOPUS and Web of Science (WoS). The literature search included the terms "marine mammal" or "cetacea" or "pinniped" or "whale" or "seal" or "dolphin" or "sirenia" or "porpoise" or "polar bear" or "manatee" or "dugong" or "sea otter" or "marine otter" or "sea lion" and "UAV" or "drone" or "unmanned aerial vehicle" or "UAS" or "RPA", or their plural forms, included in the title, the abstract, or the keywords. The search provided 614 (SCOPUS) and 502 (WoS) results, which were filtered to exclude reviews, news, opinions, perspectives, letters, posters and conference abstracts, and non peer-reviewed papers and reports. The remaining articles were revised manually to check whether the titles and abstracts were consistent with the search objective. In total, 169 publications were selected. The reviewed works are described and classified in the following sections, and information about the models and their use is summarized in Tables 1 and 2 according to the classification given in the following section and illustrated in Figure 1.

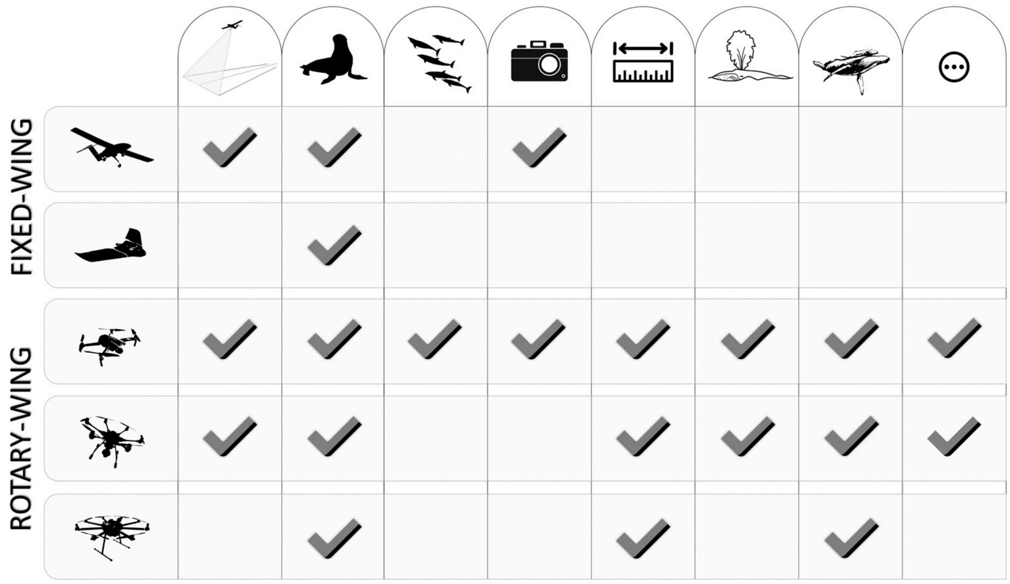

Figure 1. UAV classification (top to bottom: launch system and hand-launch fixed-wing UAVs, and quadcopter, hexacopter, and octocopter rotary-wing UAVs) and marine mammal research applications (left to right: line-transect surveys, pinniped aggregation census, group size estimation, photo-ID, photogrammetry, blow sample collection, behavioural studies, and other approaches) published for each group. The checkmarks in each cell indicate the usage of the UAV type in the row for the application mentioned in the corresponding column.

Table 1. Fixed-wing UAV models used in published studies on marine mammals, classified by their launch and recovery system. For each UAV model, one or more references are provided, indicating its primary application(s) and target species.

Type of UAV	UAV Model	Use	Target Species	References
Launch and recovery system, fixed-wing	General Atomics MQ-9 Predator B	Line-transect survey	*Megaptera novaeangliae, Pseudorca crassidens*	[1]
	Brican Systems TD100E	Photo-ID	*Balaena mysticetus, Eschrichtius robustus, Delphinapterus leucas*	[2]
	PW-ZOOM	Pinniped aggregation census	*Mirounga leonina, Arctocephalus gazella, Leptonychotes weddelli*	[3,4]
	Boeing Insitu ScanEagle	Line-transect survey	*Balaena mysticetus, Delphinapterus leucas, Eschrichtius robustus*	[5,6]
			Megaptera novaeangliae	[7]
			Dugong dugon	[8]
			Histriophoca fasciata, Phoca largha	[9]
	Boeing Insitu Insight A-20	Line-transect survey	*Balaena mysticetus, Eschrichtius robustus, Delphinapterus leucas*	[10]
	CryoWing Micro RPAS CryoWing Scout RPAS	Line-transect survey	*Megaptera novaeangliae, Orcinus orca, Phocoena phocoena*	[11]
	Trimble UX5	Line-transect survey	*Ursus maritimus*	[12]
Hand-launched, fixed-wing	Puma All-Environment	Pinniped aggregation census	*Neomonachus schauinslandi*	[1]
			Eumetopias jubatus	[13]
	SenseFly eBee	Pinniped aggregation census	*Halychoerus grypus*	[14–16]
	SenseFly eBee Plus	Pinniped aggregation census	*Phoca vitulina richardii, Callorhinus ursinus, Eumetopias jubatus*	[17]

Table 2. Rotary-wing UAV models used in published studies on marine mammals, classified by the number of rotors and recovery system. For each UAV model, one or more references are provided, indicating its primary application(s) and target species.

Type of UAV	UAV Model	Use	Target Species	References
Quadcopter rotary-wing	DJI Phantom 3	Line-transect survey	*Sotalia fluviatilis, Inia geoffrensis*	[18]
		Group size estimation	*Delphinapterus leucas*	[19]
		Photo-ID	*Delphinapterus leucas*	[20]
	DJI Phantom 3 Pro	Line transect survey	*Cetaceans*	[21]
		Photo-ID	*Trichechus manatus*	[22]
		Photogrammetry	*Balaenoptera musculus, Eschrichtius robustus*	[23]
			Megaptera novaeangliae, Balaenoptera musculus, B. physalus, B. edeni, B. bonaerensis, B. borealis	[24,25]
			Eschrichtius robustus	[26,27]
		Behavioural study	*Megaptera novaeangliae*	[28]
			Eubalaena australis	[29,30]
			Eschrichtius robustus	[31]
			Balaenoptera edeni	[32]
			Ursus maritimus	[33–35]

Table 2. *Cont.*

Type of UAV	UAV Model	Use	Target Species	References
Quadcopter rotary-wing	DJI Phantom 3 Advanced	Pinniped aggregation census	*Zalophus californianus*	[36,37]
			Eumetopias jubatus	[36]
	DJI Phantom 4	Line-transect survey	*Tursiops* spp.	[38,39]
		Pinniped aggregation census	*Arctocephalus pusillus*	[40]
			Eumetopias jubatus	[41]
		Photo-ID	*Balaena mysticetus*	[42]
			Delphinapterus leucas	[20]
			Trichechus manatus	[22]
		Photogrammetry	*Megaptera novaeangliae*	[43,44]
			Balaenoptera musculus, Eschrichtius robustus	[23]
			Eschrichtius robustus	[26,27]
		Behavioural study	*Megaptera novaeangliae*	[45,46]
			Balaenoptera physalus	[47]
			Grampus griseus	[48]
			Tursiops truncatus	[49]
			Lagenorhynchus obscurus	[50,51]
			Sousa chinensis	[52]
		Habitat study	*Phoca vitulina*	[53]
	DJI Phantom 4 Pro	Line-transect survey	*Dugong dugon*	[54]
		Pinniped aggregation census	*Phoca vitulina*	[55]
			Arctocephalus pusillus	[40,56,57]
		Group size estimation	*Sousa sahulensis*	[58]
		Scarring assessment	*Megaptera novaeangliae, Balaenoptera musculus, Balaenoptera physalus*	[59]
		Photogrammetry	*Megaptera novaeangliae*	[60]
			Megaptera novaeangliae, Balaenoptera musculus, B. physalus, B. edeni, B. bonaerensis, B. borealis	[24,25]
			Eschrichtius robustus	[26,27]
			Physeter macrocephalus	[61]
			Globicephala macrorhynchus	[62]
			Orcaella heinsohni, Sousa sahulensis	[63]
			Trichechus manatus	[64]
		Behavioural study	*Phocoena phocoena*	[65]
			Ursus maritimus	[33–35]
	DJI Phantom 4 Pro V2.0	Abundance study	*Trichechus manatus latirostris*	[66]
		Behavioural study	*Orcinus orca*	[67]
			Cephalorhynchus commersonii	[68]
			Phocoena phocoena	[69]
		Habitat study	*Dugong dugon*	[70]

Table 2. *Cont.*

Type of UAV	UAV Model	Use	Target Species	References
Quadcopter rotary-wing	DJI Phantom 4 Pro+	Pinniped aggregation census	*Phoca vitulina*	[71]
		Photogrammetry	*Megaptera novaeangliae*	[72]
		Behavioural study	*Tursiops aduncus*	[73]
	DJI Phantom 4 Advanced	Behavioural study	*Megaptera novaeangliae*	[74,75]
			Balaenoptera musculus	[76]
			Eschrichtius robustus	[31]
	DJI Phantom 4 Advanced+	Behavioural study	*Eschrichtius robustus*	[77]
	DJI Inspire 1	Line-transect survey	*Tursiops* spp.	[78]
		Blow sample collection	*Tursiops aduncus, Sousa sahulensis*	[79]
		Thermography	*Eubalaena glacialis*	[80]
	DJI Inspire 1 Pro/Raw	Pinniped aggregation census	*Eumetopias jubatus*	[41]
		Photogrammetry	*Megaptera novaeangliae*	[81,82]
			Eubalaena australis	[83–89]
			Eschrichtius robustus	[90]
			Physeter macrocephalus	[61,91]
			Globicephala macrorhynchus	[62]
			Phocoena phocoena	[92]
		Behavioural study	*Eubalaena glacialis, Megaptera novaeangliae*	[93]
	DJI Inspire 2	Pinniped aggregation census	*Mirounga leonina*	[94,95]
		Scarring assessment	*Megaptera novaeangliae, Balaenoptera musculus, Balaenoptera physalus*	[59]
		Photogrammetry	*Feresa attenuata*	[96]
			Neophoca cinerea	[97]
		Blow sample collection	*Megaptera novaeangliae, Balaenoptera musculus, Orcinus orca*	[98]
		Behavioural study	*Balaenoptera physalus*	[47]
	DJI Mavic Pro	Pinniped aggregation census	*Arctocephalus australis*	[99]
			Eumetopias jubatus	[41]
		Blow sample collection	*Megaptera novaeangliae, Balaenoptera musculus, Orcinus orca*	[98]
		Behavioural study	*Neophocaena asiaeorientalis*	[100]
	DJI Mavic Pro Platinum	Behavioural study	*Eubalaena australis*	[30]

Table 2. *Cont.*

Type of UAV	UAV Model	Use	Target Species	References
Quadcopter rotary-wing	DJI Mavic 2 Pro	Pinniped aggregation census	*Mirounga leonina*	[101]
		Photo-ID and behavioural study	*Kogia sima*	[102]
		Photogrammetry	*Megaptera novaeangliae*	[103]
			Trichechus manatus	[64]
		Searching faecal plumes	*Globicephala macrorhynchus*	[104]
	DJI Mavic 2 Zoom	Line-transect survey	*Steno bredanensis, Sotalia guianensis, Pontoporia blainvillei*	[105,106]
		Pinniped aggregation census	*Zalophus californianus, Eumetopias jubatus*	[36]
	DJI Matrice 100	Hydrophone attachment	*Phocoena phocoena*	[107]
	DJI Matrice 200	Pinniped aggregation census	*Phoca vituluna*	[55]
		Behavioural study	*Dugong dugon*	[108]
		Thermography	*Megaptera novaeangliae*	[109]
		Logger attachment	*Physeter macrocephalus*	[110]
	DJI Matrice 210 RTK	Abundance study	*Delphinapterus leucas*	[111]
	SwellPro SplashDrone	Photogrammetry	*Megaptera novaeangliae*	[112]
		Blow sample collection	*Tursiops truncatus*	[113]
			Tursiops aduncus, Sousa sahulensis	[79]
	SwellPro SplashDrone 3+	Hydrophone attachment	*Eschrichtius robustus*	[77]
	Draganflyer X4-P	Pinniped aggregation census	*Arctocephalus forsteri*	[114]
	Microdrones MD4-1000	Pinniped aggregation census	*Arctocephalus gazella, Hyrdurga leptonyx*	[115]
	APQ-18	Pinniped aggregation census	*Arctocephalus gazella, Hyrdurga leptonyx*	[115]
Hexacopter rotary-wing	APH-22	Pinniped aggregation census	*Arctocephalus gazella, Hyrdurga leptonyx*	[115]
			Halychoerus grypus	[14]
			Eumetopias jubatus	[13]
		Photogrammetry	*Balaenoptera musculus*	[116]
			Eubalaena glacialis	[86,117]
			Balaenoptera bonaerensis	[118]
			Orcinus orca	[119–122]
			Hydrurga leptonyx	[123]
		Blow sample collection	*Megaptera novaeangliae*	[124]
	APH-28	Pinniped aggregation census	*Arctocephalus gazella*	[125]

Table 2. *Cont.*

Type of UAV	UAV Model	Use	Target Species	References
Hexacopter rotary-wing	LemHex-44	Photogrammetry	*Megaptera novaeangliae*	[81]
			Megaptera novaeangliae, Balaenoptera musculus, B. physalus, B. edeni, B. bonaerensis, B. borealis	[24,25]
			Balaenoptera bonaerensis	[118]
			Tursiops truncatus	[126]
	Hex H2O TM	Behavioural study	*Megaptera noveangliae*	[45,127]
			Tursiops truncatus	[49]
	DJI Matrice 600	Line-transect survey	*Tursiops aduncus*	[128]
		Behavioural study	*Orcinus orca*	[67]
	FreeFly Alta 6	Photogrammetry	*Megaptera novaeangliae*	[81]
			Megaptera novaeangliae, Balaenoptera musculus, B. physalus, B. edeni, B. bonaerensis, B. borealis	[24,25]
			Balaenoptera bonaerensis	[118]
			Halychoerus grypus	[129]
	Ptarmigan	Habitat study	*Ursus maritimus*	[130]
Octocopter rotary-wing	APO-42	Photogrammetry	*Orcinus orca*	[122]
		Behavioural study	*Grampus griseus*	[131]
			Delphinus delphis	[132]
	Gryphon Dynamics X8-1400	Pinniped aggregation census	*Arctocephalus pusillus*	[40]

3. Main Uses of UAVs for the Study of Marine Mammals

Out of the 169 publications identified, 37.28% (n = 63) assessed abundance and distribution, 5.92% (n = 10) were focused on photo-ID, 28.4% (n = 48) used UAVs for morphometrics estimates via photogrammetry, 3.55% (n = 6) were focused on collecting cetacean blow samples, 20.71% (n = 36) assessed behaviour, and 7.1% (n = 12) used UAVs for other marine mammal research approaches. Studies that used UAVs for different types of research have been assigned to as many applications as shown for the publications.

3.1. Abundance and Distribution Monitoring

Monitoring abundance and distribution is one of the main marine-mammal-related applications for UAVs. For such studies, the flight parameters should be planned based on the aim. Flight altitude is a key factor since at low altitudes the area covered decreases but the image resolution increases, leading to more detections and more accurate identification of the animals. The image resolution and environmental conditions are the main factors affecting the detection and identification of marine mammals at sea from UAV images [133]. In UAV-based surveys, the resolution is usually measured as ground sample distance (GSD), which denotes the distance at ground level represented by a single pixel in the image (cm/pixel) resulting from the flight altitude, the focal length of the camera lens, and the sensor size of the camera [133]. The speed and camera inclination angle also affect detectability. A high flight speed allows the survey to cover the same area in less time but can affect the quality of the images by increasing blur. The angle at which the camera is oriented may vary according to the objectives pursued and may affect detectability in different ways. Fixing the camera at nadir increases the detectability of underwater animals [38], while pointing it to the horizon allows for coverage of larger observation areas and the detection of whale blows [105]. Detectability also depends on environmental variables such as light conditions (e.g., glare, which varies with the intensity, orientation, and elevation of the sun), wind and sea state [10,11], and turbidity [8,39]. Other biological factors affecting detection or identification probability are the size of the target species, its diving behaviour [7], colouration [10], and group size [11].

3.1.1. Line-Transect Surveys

The aerial perspective offers the possibility of detecting animals located in subsurface waters, increasing the time available for detection (i.e., reducing availability bias) compared to boat-based abundance studies. The methodological design for UAV-based line-transect surveys relies on systematically covering the study area through pre-programmed transects and collecting data either through videos or still images. The image capture rate for the latter should be scheduled. The collected footage is then analysed, recording sightings and gathering data on presence/absence, certainty of detection, species, number of individuals, and other relevant data such as the presence of calves. Additionally, the analysis usually considers recording data on environmental conditions that might affect the images, such as sea state, glare, and visibility.

Fixed-wing UAVs have primarily been used in flight trials to perform line-transect surveys for known marine mammal populations, assessing the detectability and applicability of this tool for estimating abundance in cetacean and sirenian species [5,7,8,11], as well as polar bears (*Ursus maritimus*) [12] (see Table 1). The flying altitudes in these studies ranged from 75 to 735 m.

Rotary-wing UAVs have mainly been used for monitoring small coastal and river dolphin populations [18,38,39,49,78,105,106] (see Table 1). These UAVs have also been used to survey megafauna (e.g., cetaceans, turtles, and sharks) in marine protected areas [21]. The flying altitudes in these studies ranged from 20 to 60 m.

3.1.2. Pinniped Aggregation Census

The population assessment of pinnipeds is usually based on ground counts at haul-out sites, which significantly reduces the required survey area. In these studies, UAVs are used to overfly the target aggregations, either through pre-programmed flight paths covering the area or via manual flights, as pinniped aggregations may expand, contract, or shift location. Although fixed-wing UAVs have been used for this kind of study, flying at altitudes of up to 550 m [3,4], most studies are based on rotary-wing UAVs [1,13–15,36,37,40,41,55–57,71,94,99,101,114,115,125] (see Table 2). Still images or video footage are processed and reviewed to count individuals and classify the animals by species and/or age classes (e.g., adults and pups). In most studies, images are previously processed to compile them into an orthomosaic of the study area [14,15,17,36,40,55,57,94,99,101]. In addition, UAV-based orthomosaic imagery allows for the study of terrain characteristics and social factors in haul-out sites, enabling spatial analysis of the distribution and site selection of pinniped haul-outs [17].

Pinnipeds are likely to move between adjacent flight paths during the survey, and therefore they may be captured in the image more than once, leading to an overestimation of abundance. In addition, they may enter the water or take refuge in caves or under rocks before being photographed, thus resulting in an underestimation of abundance [9,40]. However, the low level of disturbance caused by UAV surveys in comparison with ground-based studies, as suggested for some species [16,134], reduces this movement bias [9,40].

3.1.3. Group Size

The aerial perspective from UAVs is useful for increasing the accuracy of estimates of the group size of animals in the aquatic environment, which may be an important source of error in abundance studies. Brown et al. [58] suggested an underestimation of humpback dolphin (*Sousa sahulensis*) group size via visual estimation when compared with UAV-recorded videos. Several studies also used imagery collected during UAV surveys to estimate the number of individuals in groups of belugas (*Delphinapterus leucas*) [5,19], dolphins [38,49,63,68,105,135–137], and baleen whales [5,7,31,127].

3.2. Photo-ID

Some authors have used UAVs for individual identification as an alternative to (or to complement) traditional photoidentification. UAV-based photo-ID allows an observer to maintain visual contact, follow groups, and capture both sides of the animal, thus increasing the likelihood of obtaining good-quality photographs permitting the identification of individuals [20,102]. Aerial photographs have already been used to develop aerial photo-ID catalogues of southern right whale (*Eubalaena australis*) [83] and beluga [20] populations. Koski et al. [2] and Koski and Young [42] collected UAV imagery data suitable for mark and recapture studies in bowhead whales (*Balaena mysticetus*), and Hartman et al. [48] successfully identified individual Risso's dolphins (*Grampus griseus*). Pomeroy et al. [138] obtained images of grey seals (*Halichoerus grypus*) and harbour seals (*Phoca vitulina*) that were sufficiently detailed to allow for the identification of pelage patterns from altitudes around 50 m. Scarring patterns and unique marks of Antillean manatees (*Trichechus manatus manatus*) [22] and dugongs (*Dugong dugon*) [108] has also been identified using aerial imagery. Live recording from UAVs can also be a useful tool to assist boat-based photo-ID, enabling the photographer to anticipate when and where the animal will surface [139].

3.3. Photogrammetry

Aerial images from UAVs can be used to obtain morphometric measurements of marine mammals. These biometrics are calculated by measuring pixel dimensions and then scaling to real size using the focal length of the camera lens and the altitude, determined with a laser or pressure altimeter. Laser altimeters are more precise than barometric ones but can be more expensive [43]. During image processing, size distortions caused by the camera lens should be considered [23,43,84].

The most widely used biometric is total body length. Drone-based photogrammetric studies have assessed the body length of killer whales (*Orcinus orca*) [119], sperm whales (*Physeter macrocephalus*) [91], and several species from the family Balaenopteridae [24,25,84,116–118,140], as well as other parameters such as the dorsal surface area [26,44,81,112] or total body volume [72,82,85–88,90,96], which have been used to estimate the body condition. Photogrammetric studies assessing body volume and body condition have been widely applied for baleen whale species [23,26,27,44,60,72,81–83,85–88,90,112,141] and medium and large odontocetes [61,62,96,120–122]. However, they have also been shown to be feasible and reliable for smaller marine mammals such as dolphins [63,126], porpoises [92], and sirenians [64]. On land, drone-based photogrammetry studies have also been applied to determine the body length or body condition of pinnipeds [55,94,97,115,123,129,138,142]. In killer whales, head width [120,122] and eye patch ratio (i.e., the ratio comparing the distance between the inside edges of both white eye patches at the anterior end and at their 75% point) [121] have been used to assess body condition.

In addition to estimating body condition, morphometric measurements from UAVs can be useful for multiple purposes. Volumetric estimates obtained through photogrammetry provide valuable information to accurately estimate body mass in both cetaceans [61,89] and pinnipeds [97,129]. For the latter, body mass obtained through UAV-based photogrammetry has been used to determine the appropriate dosages of drugs necessary to anaesthetize animals for capture-based methodologies [115]. Cheney et al. [126] used UAV morphometric measurements to assign pregnancy status to individuals in a bottlenose dolphin (*Tursiops truncatus*) population.

Photogrammetry can also be applied to determine kinematics and feeding behaviours [143] or oscillatory swimming [24,25] in cetaceans. Accurate three-dimensional (3D) models of marine mammals can be developed for computational fluid dynamic models of locomotion or for educational purposes [89,92]. For example, Chenoweth et al. [103]

developed a 3D virtual necropsy of a humpback whale (*Megaptera novaeangliae*) using drone photogrammetry, providing valuable educational resources.

3.4. Blow Sample Collection

Health status studies have been carried out on cetaceans by sampling their exhaled breath or "blow" to analyse their microbial community [124,144], virome [145], or endocrine indicators of physiological state [98]. UAVs can be used to collect samples. In addition, cetacean blow sampling using a drone could also serve as an alternative or complementary method for obtaining genetic information, which traditionally requires invasive biopsy darting or faecal sample collection [79,98]. This method consists of attaching a sterile Petri dish to a waterproof VTOL UAV and bringing the vehicle over the animal when it surfaces to breathe. Some authors have developed a hinged opening and closing system that allows the Petri dish to be opened and closed remotely during flight, minimizing the risk of contamination and loss of the blow sample [79,144,145].

In small cetaceans, this approach has some limitations related to their swimming speed, unpredictable swimming pattern, respiratory rate, and social structure (i.e., groups can be densely concentrated and highly dynamic) [113], which make the sampling of single individuals difficult [79]. Small cetaceans have also a smaller volume of blow compared to large whales, so the collection of blow samples from small cetaceans requires a closer approach of the UAV [79] or the development of a sampling tool to get closer to the target individuals, increasing the potential for disturbance [113]. Despite these drawbacks, blow samples have been successfully collected using UAVs from delphinids such as bottlenose dolphins [113] or killer whales [98].

3.5. Behavioural Studies

The low impact of the presence of UAVs on the behaviour of marine mammals, in comparison with research boats, makes them a preferred tool for short-term ethological studies [49,74]. The recording of high-quality videos provides the possibility of a more detailed behavioural analysis and the opportunity to review the footage several times, increasing confidence in the detection and categorization of different behavioural states [49,74,127,135]. Moreover, the aerial perspective offers the possibility of observing subsurface behaviours, leading to more accurate interpretations of behavioural states and monitoring of animal movements, which reduces the likelihood of losing sight of target individuals [31,45,48–50,65,102,127,135]. This advantageous perspective also allows for research on poorly studied behaviours, such as the reproductive behaviours of dugongs [108] or epimeletic behaviour in cetaceans [52], as well as observations of previously undocumented behaviours, like synchronous lunge-feeding of humpback whale mother–calf pairs [46] or pilot whale placental expulsion [146]. However, the success of this approach depends on several factors such as the depth of dives, water clarity, and the angle of the sunlight [31,50,74,127].

UAVs have been used to carry out ethological studies related to social relationships [48,50,67,102], collaborative hunting [65] and foraging behaviours [33–35,47], kinematic studies and movement patterns [28,32,76,143], respiratory dynamics [93], energy expenditure and behavioural events involving mother—calf pairs [29,50,51], the effects of micropredators [30,75], the impact of swimmer approaches during in-water tourism activities [45], responses to boat traffic [100], responses to sound playback experiments [73], responses to the presence of naval sonar in military training areas [131,132], responses to pinger exposure [69], and comparisons with simultaneous underwater acoustic recordings [68,77].

3.6. Other Approaches

In addition to the above-mentioned applications, some authors have recorded acoustic data by attaching a hydrophone to a waterproof UAV landed at the surface [77] or hovering few metres above the water [107]. Murakami et al. [110] proposed a biologging method using a UAV to deploy a logger on sperm whales when they surfaced. UAVs can also be equipped with infrared thermography (IRT) sensors to conduct physiological studies [80]. IRT has already been used to measure vital signs such as respiration rate, heart rate, or body temperature as indicators of the health and physiological condition of humpback whales [109] and North Atlantic right whales (*Eubalaena glacialis*) [80]. Indirect applications such as habitat studies can make use of UAVs. For example, IRT imagery has been applied to identify occupied polar bear dens by detecting differences in snow surface temperature [130], and photogrammetric methods applied to aerial imagery have been used to calculate the height of icebergs and estimate their accessibility as haul-out sites for harbour seals [53]. Also, Yamato et al. [70] used UAV-based photogrammetry methods to detect dugong feeding traits in intertidal seagrass beds. Live recording using UAVs can also be a useful tool to assist in the search for strandings in certain places [147] or faecal plumes for sample collection [104].

UAVs can also be useful for assessing net entanglement. McIntosh et al. [114] was able to detect Australian fur seals (*Arctocephalus pusillus doriferus*) entangled in marine debris through UAV imagery. Ramp et al. [59] used aerial photo-ID images from UAVs to estimate entanglement scarring rates in fin whales (*Balaenoptera physalus*). They found that entanglement rates are currently underestimated using vessel-based photo-ID images because the body parts most prone to scarring from entanglements remain underwater and out of sight [59]. Other studies have also used UAVs to identify entanglement injuries in whales [117]. Similarly, these aerial images could be useful to characterize the epibiotic fauna of cetaceans [148].

4. Discussion

UAVs offers an enormous potential for multiple applications in marine mammal research. The most appropriate UAV model and flight characteristics depend on the purposes of the study. The relatively low cost and simple operation of rotary-wing UAVs makes them suitable for most wildlife applications including behavioural studies, photogrammetry, the collection of blow samples, and the monitoring of small and coastal populations. Fixed-wing UAVs fly faster and have greater autonomy and are therefore used to cover larger areas for monitoring a wide range of marine mammal populations. Flying at a high speed enables fixed-wing aircrafts to resist the effects of wind on stability [115] and may reduce other technical problems such as camera vibration [5,6]. However, whether they are fixed-wing or rotary-wing, UAVs also have some limitations in the study of marine mammals. First, professional UAVs can be relatively expensive, especially big fixed-wing models [5,149]. Second, flying UAVs at sea under some weather conditions such as rain or high winds implies significant risks in relation to the loss of or damage to the equipment [101], reduced image quality [115], and reduced detectability of the animals [65]. In addition, regulatory restrictions for operating UAVs in civil airspace may be a major limitation and will vary between study areas depending on international, national, and local authorities. The maximum altitude (120 m) and flying distance (within VLOS) established by legislative restrictions can limit the study range. The autonomy of the UAV may also be a limiting factor, as the flight duration is limited by the UAV returning to the take-off point to replace the battery. Accounting for survey flight limitations, some studies have used UAVs as stationary platforms at a constant height and location, covering small study areas such as canals [66] or estuaries [111], while Cleguer et al. [54] applied a grid-based aerial survey design using two UAVs to efficiently cover the study area despite these limitations. For carrying out operations beyond visual line of sight (BVLOS), which allows the user to expand the study range, it is necessary for the operator to have professional qualifications (which include theoretical and practical tests) as well as devices with a real-time kinematic positioning system (RTK), among other characteristics (see the Commission Implementing Regulation (EU) 2019/947 and the Commission Delegated Regulation (EU) 2019/945 for the EU legislation, and the FAA Reauthorization Act of 2018 for the USA as examples). In such cases, operational authorisation issued by the competent authority is usually mandatory. Exceeding the maximum flight height allowed will also require special authorisation. National regulations also include geographical zones (airspace portions defined for safety, security, privacy, or environmental reasons) where the flight is restricted. This does not always imply a strict prohibition, but it does require compliance with certain conditions, and prior request and authorisation, which can sometimes make it difficult to carry out studies in certain areas. Before conducting any operations involving marine mammals, in addition to possessing the necessary licenses, it is essential to consider the inherent risks of the intended operation, following published recommendations (e.g., Council of Managers of National Antarctic Programs (COMNAP), Antarctic Remotely Piloted Aircraft Systems (RPAS) Operator's Handbook).

Traditional methods to estimate the abundance and density of marine mammals usually use boats or manned aircraft with observers aboard. In comparison with boat-based surveys, the aerial perspective provided by drones and manned aircraft can reduce the bias that occurs when animals are lost from sight because they are underwater, since at shallow depths they can be observed if the seawater is sufficiently transparent. Drone-based marine mammal monitoring surveys are limited in relation to transect width, which depends on flight altitude [5,8–10,150]. High-altitude flights are recommended to increase the transect width and increase the coverage by reducing the flight time, but they require a good camera resolution. However, a higher altitude also increases the risk of encountering clouds [7]. UAV imagery also allows for capture–recapture population estimates [42,151]. Despite these limitations, drone-based monitoring programs have advantages over manned surveys, such as reduced human risk, reduced noise disturbance, and increased resolution of the geographical location of sightings [8,152], and they can provide a permanent record of sightings via photos and videos that can be reviewed by different experts, increasing the accuracy of species identification and reducing the bias associated with the skill, training, and experience of the observers [7,8,78]. Although some of these advantages could also be achieved by taking aerial photographs on manned aircraft surveys, the slower airspeed of UAVs results in less blur, thus increasing animal detectability [2]. In sea otters (*Enhydra lutris*), abundance studies based on aerial images have already been conducted, and these methods can be easily extended to data collected using UAVs [153]. An alternative to manned aircraft and UAV imagery is satellite telemetry, which allows for wide coverage [95,154]. However, satellite images have significantly lower spatial resolution and can only be captured on clear days without cloud cover [15,101,115]. Drone-based surveys may be used to remotely monitor hard-to-access or dangerous areas where other kind of operations could be difficult or risky, such as narrow fjords [11] or some haul-out sites of pinnipeds [3,4,101,125]. Compared to ground-based traditional studies of pinniped aggregations, aerial imagery from UAVs seems to also be a more efficient method to obtain accurate results [40,55,57,71,94,101] and may cause less disturbance to the animals, as has been suggested for some species [16,134]. Adame et al. [37] also reported an underestimation of sea lion pup counts from boat-based studies compared to UAV-based aerial surveys. Moreover, body parameters calculated via photogrammetry can help determine the age and sex of individuals [94]. However, it should be considered that pinnipeds could be difficult to detect through the vertical perspective of UAVs in areas with visual impediments such as plant cover, rugged terrain, or caves [40,99,101,114]. Similarly, the lack of contrast between the fur of polar bears and their surroundings can complicate their detection in aerial images [12,154]. In addition, thermal imagery can be applied for counting pinnipeds, allowing for the identification of individuals that are not easily visible to the naked eye [15,17,114,155]. The use of thermal imagery for the detection of pinnipeds also has its limitations. The layer of water that remains on animals that have just exited the water can mask their thermal signature, thermally homogenous groups of pinnipeds can be challenging to differentiate, and rocks exposed to high temperatures can lead to false detections [114]. Conversely, the lack of temperature difference may complicate the application of thermal imagery to detect cetaceans and sirenians underwater. Instead, multispectral and hyperspectral sensors can identify appropriate wavelengths for providing contrast of fauna and their surroundings [128,154]. Another limitation of UAVs compared to traditional methods is the data processing time required for analysis of the footage [5,31], since a manual review of the images can be particularly time-consuming [8,9,40,54,150]. Some authors [36,57] proposed citizen science projects as a way to reduce the time required for the laborious task of counting animals and to obtain data with replicates while providing an opportunity for conservation education. However, Wood et al. [36] found a decrease in the accuracy of results as citizens tended to underestimate pinniped abundance. On the other hand, imagery data allow the development of models that could automate identification, photogrammetry, or group size estimations [15,155,156]. Convolutional neural networks (CNNs) have already been applied to automatically identify and estimate the length of cetacean species such as blue whales (*Balaenoptera musculus*), humpback whales, or Antarctic minke whales (*Balaenoptera bonaerensis*) [140], as well as to detect belugas [111], dolphins [157], and seals [55,56].

UAVs can collect samples through video recording or taking consecutive images. The choice between using still images and video recording depends on the study's purpose. Video recordings allow for distinguishing animals from shadows, waves, and other visual distortions [22]. On the other hand, a higher resolution is usually achieved with still images, for which the proportion of overlap should be planned. Higher image overlap demands collection of a greater number of images, which affect data processing time and the amount of data storage space needed onboard the aircraft [5]. Nevertheless, higher overlap also allows for better identification of sightings if individuals are initially captured at awkward body angles or positions in the water column, or are masked by sea state or light conditions such as sun glitter, thus reducing perception and availability bias [4,5,7,54,138].

Some studies comparing UAVs and boat-based monitoring methods found an underrepresentation of social behavioural patterns in data collected by observers onboard for humpback whales [127], grey whales (*Eschrichtius robustus*) [31], and bottlenose dolphins [49]. Additionally, boat-based approaches could bias data due to greater disturbance effects, as motorised vessels produce higher noise levels than drones even at greater distances [158,159]. However, UAVs are not completely exempt from causing disturbance, which should be considered when planning flight parameters. Noise levels vary with the model, speed, and altitude of aerial overflight [40,158–162]. Noise disturbance is also dependent on species' hearing sensitivity [161]. Aside from noise levels, UAVs can cause disturbance to marine mammals through visual stimuli (the UAV, its shadow, and/or onboard lights if present) [135,137,158], as has been shown in observations of beluga whales reacting to drones flying through their visual field [160]. Although there are no reports of behavioural responses to UAVs in humpback whales [127], blue whales [163], southern right whales [164], North Atlantic right whales [165], or grey whales [31], responses such as tail slap events, reorientation, or changes in speed and/or surfacing patterns (i.e., changes in interbreath intervals) have been observed in beluga whales [160], bottlenose dolphins [135–137], common dolphins (*Delphinus delphis*) [165], and Antillean manatees [137,166]. Pinnipeds and polar bears are also vulnerable to disturbance on land, where UAV noise is louder than that detected from within the water column at the same distance [160,167,168]. It should also be considered that intraspecific differences in behavioural responses may be observed due to a variety of factors such as geographic location, sea conditions, water clarity, wind, cloud cover, and habituation to anthropogenic disturbances of local populations (e.g., in whale-watching areas). In addition to the potential disturbance of marine mammal species, UAVs can also disturb other marine fauna such as birds [2,18,40], the reactions of which could in turn affect the stability of the UAVs [1,101].

Drone-based photogrammetry approaches also have limitations in relation to associated error rates [96,141]. These error rates are related with flight altitude [63,91,169]; the UAV model [169]; environmental conditions such as glare, wave refraction, and water clarity [64,169]; the body position of the animal (i.e., body arch, edge certainty, body roll, and depth relative to the water surface) [43,44,60,63,91,112]; the position of the animal in the image frame due to lens distortion [23,43]; and human error in the digitization process [43].

Measurement errors are usually estimated by previously measuring a known-sized object on land or at the water surface from different altitudes [25,26,43,63,64,85,118,169]. In some studies, different researchers measured the body morphometrics of the same whale to permit calculation of the coefficient of variation from these measurements [43,85]. Measurement errors related to altitude can be reduced by incorporating laser altimeters into the UAV instead of a barometer [43,64,140,169]. Moreover, associated error rates are higher for multidimensional measurements of body area and volume, implying higher uncertainty in body condition estimates [169]. It should also be considered that changes in lipid concentration are not always reflected in the body shape, limiting the ability of photogrammetry to estimate body condition [112].

The collection of blow samples requires a close and accurate approach of the UAV at the time of surfacing, which may be challenging, especially for small cetaceans [144], and can cause greater disturbance to the animals than other drone-based approaches. However, use of UAVs still considerably reduces the disturbance to cetaceans compared with the traditional use of a large pole with a collection plate above the blow hole, which requires close proximity of the vessel to the animal [124,144]. This reduction in disturbance could avoid biases in some stress studies [144], and improve blow sample collection in elusive species that are less approachable with a pole [79]. To minimize disturbance, some authors recommend an approach path from the tail to head, avoiding flying in front of or over the head [163].

5. Conclusions and Future Directions

UAVs provide an opportunity to improve the traditional monitoring of marine mammals. When flown at the recommended altitudes, UAVs can also minimize disturbance to animals, reducing biases in studies of behaviour, health status, and abundance [9,165]. Information about population health and demographics based on abundance and group size estimates, photo-ID, and body condition assessments (via photogrammetry), obtained using UAVs, can provide indicators for management [120,121]. By reducing costs (compared to traditional methods), use of UAVs facilitates more frequent and finer scale data collection, potentially increasing the power of monitoring to detect trends and hence also facilitating adaptive management. It is expected that the ongoing technological development of UAVs could reduce some of the current limitations associated with this technology, for example leading to greater autonomy and increased sampling range; improved waterproofing and durability; and purpose-built attachments to collect blow samples [79,144,145], water samples for environmental DNA (eDNA) capture [170], or even biopsies. However, current UAVs are already suitable for integration into routine monitoring. Their use alongside AI-assisted data processing could permit at least partial automation of the detection and identification, counting, measurement, and even abundance estimation of species, reducing data processing time. Future developments in UAVs could allow for a significant increase in the spatial and temporal coverage of the studies of marine mammals, especially for monitoring distribution and abundance, as required by various national and international regulations (e.g., MSFD and MMPA).

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