Unmanned Aerial Vehicles in Marine Mammal Research

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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. 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.

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

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.

2. 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.

2.1. 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 [1]. 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 [1]. 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 [2], while pointing it to the horizon allows for coverage of larger observation areas and the detection of whale blows [3]. 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 [4][5], and turbidity [6][7]. Other biological factors affecting detection or identification probability are the size of the target species, its diving behaviour [8], colouration [4], and group size [5].

2.1.1. 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][6][8][9], as well as polar bears (*Ursus maritimus*) [10] (see **Table 1**). The flying altitudes in these studies ranged from 75 to 735 m.

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***	[11]
	Brican Systems TD100E	**Photo-ID**	***Balaena mysticetus*, *Eschrichtius robustus*, *Delphinapterus leucas***	[12]
	PW-ZOOM	**Pinniped aggregation census**	***Mirounga leonina*, *Arctocephalus gazella*, *Leptonychotes weddelli***	[13][14]
	Boeing Insitu ScanEagle	**Line-transect survey**	***Balaena mysticetus*, *Delphinapterus leucas*, *Eschrichtius robustus***	[9][15]
			Megaptera novaeangliae	[8]
			Dugong dugon	[6]
			Histriophoca fasciata*, *Phoca largha	[16]
	Boeing Insitu Insight A-20	**Line-transect survey**	***Balaena mysticetus*, *Eschrichtius robustus*, *Delphinapterus leucas***	[4]
	CryoWing Micro RPAS **CryoWing Scout RPAS**	**Line-transect survey**	***Megaptera novaeangliae*, *Orcinus orca*, *Phocoena phocoena***	[5]
	Trimble UX5	**Line-transect survey**	***Ursus maritimus***	[10]

Type of UAV	UAV Model	Use	Target Species	References
Hand-launched, fixed-wing	Puma All-Environment	Pinniped aggregation census	*Neomonachus schauinslandi*	[11]
			Eumetopias jubatus	[17]
	SenseFly eBee	Pinniped aggregation census	*Halychoerus grypus*	[18][19][20]
	SenseFly eBee Plus	Pinniped aggregation census	*Phoca vitulina richardii*, *Callorhinus ursinus*, *Eumetopias jubatus*	[21]

Rotary-wing UAVs have mainly been used for monitoring small coastal and river dolphin populations [2][3][7][22][23][24][25] (see **Table 1**). These UAVs have also been used to survey megafauna (e.g., cetaceans, turtles, and sharks) in marine protected areas [26]. The flying altitudes in these studies ranged from 20 to 60 m.

2.1.2. 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 [13][14], most studies are based on rotary-wing UAVs [11][17][18][19][27][28][29][30][31][32][33][34][35][36][37][38][39][40] (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 [18][19][21][27][29][31][33][35][36][37]. 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 [21].

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*	[22]
		Group size estimation	*Delphinapterus leucas*	[41]
		Photo-ID	*Delphinapterus leucas*	[42]
	DJI Phantom 3 Pro	Line transect survey	*Cetaceans*	[26]
		Photo-ID	*Trichechus manatus*	[43]
		Photogrammetry	*Balaenoptera musculus*, *Eschrichtius robustus*	[44]
			Megaptera novaeangliae, *Balaenoptera musculus*, *B. physalus*, *B. edeni*, *B. bonaerensis*, *B. borealis*	[45][46]
			Eschrichtius robustus	[47][48]
		Behavioural study	*Megaptera novaeangliae*	[49]
			Eubalaena australis	[50][51]
			Eschrichtius robustus	[52]
			Balaenoptera edeni	[53]
			Ursus maritimus	[54][55][56]
	DJI Phantom 3 Advanced	Pinniped aggregation census	*Zalophus californianus*	[27][28]
			Eumetopias jubatus	[27]
	DJI Phantom 4	Line-transect survey	*Tursiops* spp.	[2][7]
		Pinniped aggregation census	*Arctocephalus pusillus*	[29]
			Eumetopias jubatus	[30]
		Photo-ID	*Balaena mysticetus*	[57]
			Delphinapterus leucas	[42]
			Trichechus manatus	[43]
		Photogrammetry	*Megaptera novaeangliae*	[58][59]
			Balaenoptera musculus, *Eschrichtius robustus*	[44]
			Eschrichtius robustus	[47][48]
		Behavioural study	*Megaptera novaeangliae*	[60][61]
			Balaenoptera physalus	[62]
			Grampus griseus	[63]
			Tursiops truncatus	[23]
			Lagenorhynchus obscurus	[64][65]
			Sousa chinensis	[66]
		Habitat study	*Phoca vitulina*	[67]

Type of UAV	UAV Model	Use	Target Species	References
	DJI Phantom 4 Pro	Line-transect survey	*Dugong dugon*	[68]
		Pinniped aggregation census	*Phoca vitulina*	[31]
			Arctocephalus pusillus	[29][32][33]
		Group size estimation	*Sousa sahulensis*	[69]
		Scarring assessment	*Megaptera novaeangliae*, *Balaenoptera musculus*, *Balaenoptera physalus*	[70]
		Photogrammetry	*Megaptera novaeangliae*	[71]
			Megaptera novaeangliae, *Balaenoptera musculus*, *B. physalus*, *B. edeni*, *B. bonaerensis*, *B. borealis*	[45][46]
			Eschrichtius robustus	[47][48]
			Physeter macrocephalus	[72]
			Globicephala macrorhynchus	[73]
			Orcaella heinsohni, *Sousa sahulensis*	[74]
			Trichechus manatus	[75]
		Behavioural study	*Phocoena phocoena*	[76]
			Ursus maritimus	[54][55][56]
	DJI Phantom 4 Pro V2.0	Abundance study	*Trichechus manatus latirostris*	[77]
		Behavioural study	*Orcinus orca*	[78]
			Cephalorhynchus commersonii	[79]
			Phocoena phocoena	[80]
		Habitat study	*Dugong dugon*	[81]
	DJI Phantom 4 Pro+	Pinniped aggregation census	*Phoca vitulina*	[34]
		Photogrammetry	*Megaptera novaeangliae*	[82]
		Behavioural study	*Tursiops aduncus*	[83]
	DJI Phantom 4 Advanced	Behavioural study	*Megaptera novaeangliae*	[84][85]
			Balaenoptera musculus	[86]
			Eschrichtius robustus	[52]
	DJI Phantom 4 Advanced+	Behavioural study	*Eschrichtius robustus*	[87]
	DJI Inspire 1	Line-transect survey	*Tursiops* spp.	[24]
		Blow sample collection	*Tursiops aduncus*, *Sousa sahulensis*	[88]
		Thermography	*Eubalaena glacialis*	[89]

Type of UAV	UAV Model	Use	Target Species	References
	DJI Inspire 1 Pro/Raw	Pinniped aggregation census	*Eumetopias jubatus*	[30]
		Photogrammetry	*Megaptera novaeangliae*	[90][91]
			Eubalaena australis	[92][93][94][95][96][97][98]
			Eschrichtius robustus	[99]
			Physeter macrocephalus	[72][100]
			Globicephala macrorhynchus	[73]
			Phocoena phocoena	[101]
		Behavioural study	*Eubalaena glacialis*, *Megaptera novaeangliae*	[102]
	DJI Inspire 2	Pinniped aggregation census	*Mirounga leonina*	[35][103]
		Scarring assessment	*Megaptera novaeangliae*, *Balaenoptera musculus*, *Balaenoptera physalus*	[70]
		Photogrammetry	*Feresa attenuata*	[104]
			Neophoca cinerea	[105]
		Blow sample collection	*Megaptera novaeangliae*, *Balaenoptera musculus*, *Orcinus orca*	[106]
		Behavioural study	*Balaenoptera physalus*	[62]
	DJI Mavic Pro	Pinniped aggregation census	*Arctocephalus australis*	[36]
			Eumetopias jubatus	[30]
		Blow sample collection	*Megaptera novaeangliae*, *Balaenoptera musculus*, *Orcinus orca*	[106]
		Behavioural study	*Neophocaena asiaeorientalis*	[107]
	DJI Mavic Pro Platinum	Behavioural study	*Eubalaena australis*	[51]
	DJI Mavic 2 Pro	Pinniped aggregation census	*Mirounga leonina*	[37]
		Photo-ID and behavioural study	*Kogia sima*	[108]
		Photogrammetry	*Megaptera novaeangliae*	[109]
			Trichechus manatus	[75]
		Searching faecal plumes	*Globicephala macrorhynchus*	[110]
	DJI Mavic 2 Zoom	Line-transect survey	*Steno bredanensis*, *Sotalia guianensis*, *Pontoporia blainvillei*	[3][25]
		Pinniped aggregation census	*Zalophus californianus*, *Eumetopias jubatus*	[27]
	DJI Matrice 100	Hydrophone attachment	*Phocoena phocoena*	[111]
	DJI Matrice 200	Pinniped aggregation census	*Phoca vituluna*	[31]
		Behavioural study	*Dugong dugon*	[112]
		Thermography	*Megaptera novaeangliae*	[113]
		Logger attachment	*Physeter macrocephalus*	[114]

Type of UAV	UAV Model	Use	Target Species	References
Hexacopter rotary-wing	DJI Matrice 210 RTK	Abundance study	*Delphinapterus leucas*	[115]
	SwellPro SplashDrone	Photogrammetry	*Megaptera novaeangliae*	[116]
		Blow sample collection	*Tursiops truncatus*	[117]
			Tursiops aduncus, *Sousa sahulensis*	[88]
	SwellPro SplashDrone 3+	Hydrophone attachment	*Eschrichtius robustus*	[87]
	Draganflyer X4-P	Pinniped aggregation census	*Arctocephalus forsteri*	[38]
	Microdrones MD4-1000	Pinniped aggregation census	*Arctocephalus gazella*, *Hyrdurga leptonyx*	[39]
	APQ-18	Pinniped aggregation census	*Arctocephalus gazella*, *Hyrdurga leptonyx*	[39]
	APH-22	Pinniped aggregation census	*Arctocephalus gazella*, *Hyrdurga leptonyx*	[39]
			Halychoerus grypus	[18]
			Eumetopias jubatus	[17]
		Photogrammetry	*Balaenoptera musculus*	[118]
			Eubalaena glacialis	[95][119]
			Balaenoptera bonaerensis	[120]
			Orcinus orca	[121][122][123][124]
			Hydrurga leptonyx	[125]
		Blow sample collection	*Megaptera novaeangliae*	[126]
	APH-28	Pinniped aggregation census	*Arctocephalus gazella*	[40]
	LemHex-44	Photogrammetry	*Megaptera novaeangliae*	[90]
			Megaptera novaeangliae, *Balaenoptera musculus*, *B. physalus*, *B. edeni*, *B. bonaerensis*, *B. borealis*	[45][46]
			Balaenoptera bonaerensis	[120]
			Tursiops truncatus	[127]
	Hex H2O TM	Behavioural study	*Megaptera noveangliae*	[60][128]
			Tursiops truncatus	[23]
	DJI Matrice 600	Line-transect survey	*Tursiops aduncus*	[129]
		Behavioural study	*Orcinus orca*	[78]
	FreeFly Alta 6	Photogrammetry	*Megaptera novaeangliae*	[90]
			Megaptera novaeangliae, *Balaenoptera musculus*, *B. physalus*, *B. edeni*, *B. bonaerensis*, *B. borealis*	[45][46]
			Balaenoptera bonaerensis	[120]
			Halychoerus grypus	[130]
	Ptarmigan	Habitat study	*Ursus maritimus*	[131]

Type of UAV	UAV Model	Use	Target Species	References
Octocopter rotary-wing	APO-42	Photogrammetry	***Orcinus orca***	[124]
		Behavioural study	***Grampus griseus***	[132]
			Delphinus delphis	[133]
	Gryphon Dynamics X8-1400	Pinniped aggregation census	***Arctocephalus pusillus***	[29]

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 [16][29]. However, the low level of disturbance caused by UAV surveys in comparison with ground-based studies, as suggested for some species [20][134], reduces this movement bias [16][29].

2.1.3. 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. [69] 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*) [9][41], dolphins [2][3][23][74][79][135][136][137], and baleen whales [8][9][52][128].

2.2. 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 [42][108]. Aerial photographs have already been used to develop aerial photo-ID catalogues of southern right whale (*Eubalaena australis*) [92] and beluga [42] populations. Koski et al. [12] and Koski and Young [57] collected UAV imagery data suitable for mark and recapture studies in bowhead whales (*Balaena mysticetus*), and Hartman et al. [63] 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*) [43] and dugongs (*Dugong dugon*) [112] 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].

2.3. 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 [58]. During image processing, size distortions caused by the camera lens should be considered [44][58][93].

The most widely used biometric is total body length. Drone-based photogrammetric studies have assessed the body length of killer whales (*Orcinus orca*) [121], sperm whales (*Physeter macrocephalus*) [100], and several species from the family Balaenopteridae [45][46][93][118][119][120][140], as well as other parameters such as the dorsal surface area [47][59][90][116] or total body volume [82][91][94][95][96][97][99][104], 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 [44][47][48][59][71][82][90][91][92][94][95][96][97][99][116][141] and medium and large odontocetes [72][73][104][122][123][124]. However, they have also been shown to be feasible and reliable for smaller marine mammals such as dolphins [74][127], porpoises [101], and sirenians [75]. On land, drone-based photogrammetry studies have also been applied to determine the body length or body condition of pinnipeds [31][35][39][105][125][130][138][142]. In killer whales, head width [122][124] 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) [123] 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 [72][98] and pinnipeds [105][130]. 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 [39]. Cheney et al. [127] 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 [45][46] in cetaceans. Accurate three-dimensional (3D) models of marine mammals can be developed for computational fluid dynamic models of locomotion or for educational purposes [98][101]. For example, Chenoweth et al. [109] developed a 3D virtual necropsy of a humpback whale (*Megaptera novaeangliae*) using drone photogrammetry, providing valuable educational resources.

2.4. Blow Sample Collection

Health status studies have been carried out on cetaceans by sampling their exhaled breath or “blow” to analyse their microbial community [126][144], virome [145], or endocrine indicators of physiological state [106]. 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 [88][106]. 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 [88][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) [117], which make the sampling of single individuals difficult [88]. 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 [88] or the development of a sampling tool to get closer to the target individuals, increasing the potential for disturbance [117]. Despite these drawbacks, blow samples have been successfully collected using UAVs from delphinids such as bottlenose dolphins [117] or killer whales [106].

2.5. 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 [23][84]. 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 [23][84][128][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 [23][52][60][63][64][76][108][128][135]. This advantageous perspective also allows for research on poorly studied behaviours, such as the reproductive behaviours of dugongs [112] or epimeletic behaviour in cetaceans [66], as well as observations of previously undocumented behaviours, like synchronous lunge-feeding of humpback whale mother–calf pairs [61] 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 [52][64][84][128].

UAVs have been used to carry out ethological studies related to social relationships [63][64][78][108], collaborative hunting [76] and foraging behaviours [54][55][56][62], kinematic studies and movement patterns [49][53][86][143], respiratory dynamics [102], energy expenditure and behavioural events involving mother—calf pairs [50][64][65], the effects of micropredators [51][85], the impact of swimmer approaches during in-water tourism activities [60], responses to boat traffic [107], responses to sound playback experiments [83], responses to the presence of naval sonar in military training areas [132][133], responses to pinger exposure [80], and comparisons with simultaneous underwater acoustic recordings [79][87].

2.6. 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 [87] or hovering few metres above the water [111]. Murakami et al. [114] 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 [89]. 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 [113] and North Atlantic right whales (*Eubalaena glacialis*) [89]. 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 [131], 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 [67]. Also, Yamato et al. [81] 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 [110].

UAVs can also be useful for assessing net entanglement. McIntosh et al. [38] was able to detect Australian fur seals (*Arctocephalus pusillus doriferus*) entangled in marine debris through UAV imagery. Ramp et al. [70] 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 [70]. Other studies have also used UAVs to identify entanglement injuries in whales [119]. Similarly, these aerial images could be useful to characterize the epibiotic fauna of cetaceans [148].

References

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