Marine Pollution Bulletin 140 (2019) 17–29

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

A review of unmanned vehicles for the detection and monitoring of marine fauna

Ursula K. Verfuss[a,*], Ana Sofia Aniceto[b,1], Danielle V. Harris[c], Douglas Gillespie[d], Sophie Fielding[e], Guillermo Jiménez[f], Phil Johnston[f], Rachael R. Sinclair[a], Agnar Sivertsen[g], Stian A. Solbø[g], Rune Storvold[g], Martin Biuw[b,2], Roy Wyatt[f]

[a] SMRU Consulting, New Technology Centre, North Haugh, St Andrews, Fife KY16 9SR, UK
[b] Akvaplan-niva AS, Fram Centre, P.O. Box 6606, Langnes, 9296 Tromsø, Norway
[c] Centre for Research into Ecological and Environmental Modelling, The Observatory, University of St Andrews, St Andrews, Fife KY16 9LZ, UK
[d] Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, Fife KY16 8LB, UK
[e] British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[f] Seiche Ltd., Bradworthy Industrial Estate, Langdon Road, Bradworthy, Holsworthy, Devon EX22 7SF, UK
[g] Norut - Northern Research Institute, Postboks 6434 Forskningsparken, 9294 Tromsø, Norway

ARTICLE INFO

Keywords:
Unmanned vehicles
Marine animal monitoring
Underwater sound
Environmental impact assessment
Offshore industry

ABSTRACT

Recent technology developments have turned present-day unmanned systems into realistic alternatives to traditional marine animal survey methods. Benefits include longer survey durations, improved mission safety, mission repeatability, and reduced operational costs. We review the present status of unmanned vehicles suitable for marine animal monitoring conducted in relation to industrial offshore activities, highlighting which systems are suitable for three main monitoring types: population, mitigation, and focal animal monitoring. We describe the technical requirements for each of these monitoring types and discuss the operational aspects. The selection of a specific sensor/platform combination depends critically on the target species and its behaviour. The technical specifications of unmanned platforms and sensors also need to be selected based on the surrounding conditions of a particular offshore project, such as the area of interest, the survey requirements and operational constraints.

1. Introduction

In recent decades, there has been increased awareness concerning the potential impacts of underwater sound on marine animals, such as auditory injury and/or behavioural changes (e.g., Gordon et al., 2003; Ketten, 2014; Lucke et al., 2009; Pirotta et al., 2014). When conducting industrial activities involving sound, such as pile driving or the use of seismic sources, regulators often prescribe monitoring before, during and/or after operations to assess and/or mitigate anthropogenic impacts on marine species. Three types of monitoring are typically used in relation to industrial activities: (1) 'population monitoring' to assess animal abundance, density and/or distribution and changes therein; (2) 'mitigation monitoring' to trigger mitigation actions upon animal presence near or within a potential impact area; and (3) 'focal animal monitoring' to investigate fine-scale animal responses to anthropogenic sound.

Unmanned vehicles have the potential to greatly augment marine animal monitoring surveys. Some of the benefits of this technology compared to manned systems are improved mission safety, repeatability, and reduced operational costs. They also enable long-range operations beyond detection ranges of human observers. Unmanned vehicles can be deployed in air (Unmanned Aerial Systems – UAS), at the sea surface (Autonomous Surface Vehicles – ASV) or in the water column (Autonomous Underwater Vehicles – AUV).

Unmanned vehicles have quickly evolved over the past decade and are used in various studies, e.g., for gathering oceanographic and meteorological data (e.g. Eriksen et al., 2001; Funaki and Hirasawa, 2008; Leong et al., 2012; Meyer, 2016; Williams et al., 2010; Wynn et al.,

---

* Corresponding author.
E-mail address: ukv@smruconsulting.com (U.K. Verfuss).

[1] ARCEx (Research Centre of Arctic Petroleum Exploration) UiT The Arctic University, Department of Geology, Dramsveien 201, Postboks 6050 Langnes, N-9037 Tromsø, Norway.

[2] Institute of Marine Research, Tromsø Department, UK Sykehusveien 23, P. O. Box 6404, 9294 Tromsø, Norway.

https://doi.org/10.1016/j.marpolbul.2019.01.009
Received 10 February 2018; Received in revised form 14 December 2018; Accepted 5 January 2019

2014), and for monitoring sea ice (e.g., Inoue et al., 2008) and wildlife (e.g., Forney et al., 2012; Hodgson et al., 2010; Koski et al., 2009b; Lyons et al., 2006). Industry applications, such as for the Oil and Gas (O&G) industry, include subsea equipment inspections and leak detection (Budiyono, 2009) and marine mammal monitoring around petroleum operations (e.g., Koski et al., 2009a; Lyons et al., 2006).

We synthesize the findings of a review conducted by Verfuss et al. (2015), highlighting which type of unmanned vehicle would be suitable for population, mitigation, and/or focal animal monitoring. Section 2 describes the monitoring types and their demands on unmanned vehicles. Section 3 summarises the currently available unmanned platforms suitable for surveying marine mammals, sea turtles and fish. Sections 4 and 5 present the data relay systems and sensor types, respectively, which can be integrated with the platforms (forming an unmanned system). In Section 6 we evaluate which systems are currently most suitable for each of the monitoring types and conclude in Section 7 with a set of recommendations on future work.

2. Monitoring types

2.1. Population monitoring

Population monitoring is used to estimate absolute population abundance or density, assess spatial and temporal patterns in the distribution of populations and investigate changes in density and distribution as a result of anthropogenic activities.

Wildlife surveys for population monitoring typically take place along planned survey transect lines or from static monitoring point transects, which are systematically placed across the study area. Therefore, unmanned vehicles that follow transects with a minimum of operator oversight, by adhering to transect lines, or remaining stationary (or at least performing turns to stay in the same location) to create a monitoring point, are particularly suited to collecting data for transect surveys. When selecting a platform, it is important to consider the range of operating altitudes/depths, whether a system can follow a pre-designed track (e.g. using pre-programmed coordinates, and/or manual piloting) with sufficient power to ensure the surveys are completed on time, and what environmental limitations may affect a system's ability to remain on a survey path.

Real time data transfer or processing is generally not a requirement for population surveys, so data can be archived on board the vehicle for later analysis. Recording temporal and spatial survey effort is essential, as well as collecting either visual or acoustic data for species identification. While it is not necessary to detect all animals during a point or line transect survey, it is important to estimate the probability of detecting the target species, which is used to estimate abundance and/or density. There are several methods available to estimate detection probability from visual or acoustic data, such as distance sampling, mark-recapture (e.g., Borchers, 2012; Borchers et al., 2015; Buckland et al., 2001; Marques et al., 2013b), and spatial capture recapture (SCR). SCR is an extension to mark-recapture that, in contrast to mark-recapture, includes an estimation of the survey area size to enable density, as well as abundance, estimation (Borchers, 2012). Detection probabilities can also be estimated using alternative methods (Marques et al., 2013a) but should not be considered in preference to distance sampling or SCR.

The various methods require different information to be recorded about detected animals, which will determine what specific sensors are required for a given platform. Identification of animals to species or species group level is essential for all methods. Distance sampling requires the determination of the horizontal range from the transect line or point to each detection. SCR, when used with visual data (Section 5.1) or acoustic data where animals can be identified (Section 5.4), requires that individuals are re-identified, i.e. "re-captured" across surveying occasions and that the coordinates of each detected animal are recorded; this may require a high level of operator involvement to focus on detected individuals (e.g. to collect high resolution photographs). In passive acoustic surveys where individuals cannot be identified acoustically (Section 5.2), SCR data are collected by associating the same acoustic detection across multiple hydrophones, where the hydrophone locations are known (Stevenson et al., 2015). Determination of the received sound levels and time-of-arrival of the acoustic detections can improve the precision of SCR results (Stevenson et al., 2015).

When combining multiple systems or sensors into instrument arrays, clock synchronisation will be essential to enable range estimation for distance sampling, and may also facilitate identifying the same acoustic detection on multiple hydrophones for SCR. In addition to detection probability, other factors are likely to be required for abundance or density estimation, e.g. group size, call production rate for acoustically detected animals and surfacing rate for visually detected animals (Borchers et al., 2013; Marques et al., 2013a; Warren et al., 2017); such factors may require additional data collection from auxiliary fine scale focal follows (Section 2.3).

2.2. Mitigation monitoring

Mitigation monitoring is conducted to implement mitigation measures upon the presence of certain marine animals within a pre-defined area around an anthropogenic sound source (mitigation zone) in order to minimize the impact of sound on the animal.

The size of the area that needs to be monitored (the monitoring zone) and which species are to be monitored for are generally specified by the responsible authority. The typical radius of a monitoring zone ranges from 500 m (e.g., JNCC, 2017) to over 3000 m (e.g., DEWHA, 2008) (see Verfuss et al., 2016 for further details). Detection probability of the target species should be high across the entire monitoring zone. Accurate animal location or range determination are also desirable in order to avoid costly mitigation actions triggered by animals outside the mitigation zone. It is also essential that data processing can take place in near-real time, which either requires the transmission of raw data to a competent human operator, or real time on-board processing (which may include the use of detectors and/or classifiers) and the transmission of summary detection data, or a combination thereof (see Section 4). It is generally necessary for a trained human operator to check detections before implementing mitigation actions, as the detector performance may be poor, especially in the presence of noise (industrial, biological, weather generated, etc.) (Verfuss et al., 2018). The level of species identification for mitigation monitoring may be less stringent than for population monitoring since most regulations are likely to require a general classification such as "cetacean", "large whale", "dolphin" etc.

2.3. Focal animal monitoring

Focal animal studies focus on the behaviour and responses of individual animals to anthropogenic sound, and therefore technology requirements may vary from those for population and mitigation monitoring. Target animals need to be detected and tracked to assess their reactions to specific sounds (e.g., in playback experiments) or other stimuli (e.g., Antunes et al., 2014; Miller et al., 2014). Throughout focal studies, detection probability should remain sufficient so that enough data about the animal's behaviour are obtained to reveal potential responses of the animal to the sound, or other stimuli.

Unmanned vehicles need to be either mobile to follow a focal animal or remain static with a field of view such that an animal can be monitored over time. Mobile systems should be able to adapt their speed to the speed of the animal, including station keeping (remaining in one place) e.g., if an animal displays milling behaviour. These systems need to have a geo-referencing system to determine the target animal's location. Current systems need to be manually piloted since no system currently exists which can automatically detect and follow an animal.

Table 1
Unmanned vehicle platforms included in this review, their type (powered and unpowered ASV, propeller and glider AUV, lighter-than-air aircrafts (l-t-a) UAS, kites and powered fixed wing UAS), system name, manufacturer and/or designer/originating university as well as their technology readiness level.

Unmanned vehicle type		System name	Manufacturer, designer, originating university	Technology readiness level
Autonomous Surface Vehicles	Powered	ASV-6300	ASV, UK	Prototype system
		C-Cat 2, C-Worker 4, C-Worker 7, C-Worker Hydro		First of a kind commercial system
		C-Enduro, C-Stat, C-Target 3, C-Worker 6		Full commercial application
		Delfim	Institute for Systems and Robotics, Portugal	Applied Research
		Mariner	NTNU and Maritime Robotics. Norway	Full commercial application
		Measuring Dolphin (MESSIN)	University of Rostock, Germany	First of a kind commercial system
		ROAZ I, ROAZ II	Laboratório de Sistemas Autónomos, Portugal	Prototype system
		RTSYS USV	RTSYS, France	Demonstration system
	Unpowered	AutoNaut 2, AutoNaut 3, AutoNaut 5, AutoNaut 7	MOST (Autonomous Vessels) Ltd., UK	Demonstration system
		Saildrone	Saildrone Inc., USA	First of a kind commercial system
		Submaran	OCEANAERO, USA	n. p.
		Waveglider SV2, Waveglider SV3	Liquid Robotics, USA	Full commercial application
Autonomous Underwater Vehicles	Glider	ALBAC	Tokai University, Japan	Small scale prototype
		Coastal glider	Exocetus, Alaska Native Technologies, USA	Full commercial application
		Deepglider	University of Washington, USA	Demonstration system
		eFòlaga III	Graal-Tech, IMEDEA Institute, Italy	First of a kind commercial system
		Liberdade Xwing/Zray	SCRIPPS, USA	Prototype system
		Petrel	Tianjin University, China	n. p.
		SeaBird	Kyushu Institute of Technology, Japan	Prototype system
		SeaExplorer	ACSA, France	Full commercial application
		Seaglider (ogive)	Kongsberg, University of Washington, USA	Full commercial application
		Slocum G2 hybrid, Slocum G2 glider	Teledyne Webb, Webb/WHOI, USA	Full commercial application
		Slocum G2 thermal		Demonstration system
		Spray	SCRIPPS, USA	Full commercial application
		Sterne glider	Ecole Nationale Superiore D'Ingenieurs Brest, France	n. p.
		TONAI; Twilight Ocean-Zonal Natural Resources and Animal Investigator	Osaka Prefecture University, Japan Taiji Whale Museum, Japan Cetus, Japan	Basic research
	Powered	A18-D, A9-M	ECA Group, France	Full commercial application
		Bluefin-12D, Bluefin-12S, Bluefin-21, Bluefin-9, Bluefin-9M	Bluefin Robotics, USA	Full commercial application
		HUGIN 1000 (1000 m version), HUGIN 1000 (3000 m version), HUGIN 3000, HUGIN 4500	Kongsberg Maritime, Norway	Full commercial application
		MUNIN		n. p.
		REMUS 100, REMUS 3000, REMUS 600, REMUS 6000	Hydroid (Kongsberg Maritime, Norway) + OSL (WHOI, USA)	Full commercial application
		RTSYS AUV	RTSYS, France	Demonstration system
Unmanned Aerial Systems	Kite	Swan X1	Flying Robots SA, Switzerland	Demonstration system
	Lighter-than-air	Desert Star 10	Allsopp Helikites Ltd., UK	Full commercial application
		Ocean Eye	Maritime Robotics AS. Norway	Full commercial application
	Fixed winged	Bramor C4EYE, Bramor gEO, Bramor rTK	C-Astral, Slovenia	Full commercial application
		Fulmar	Thales, Spain	Full commercial application
		Jump 20	Arcturus UAV, USA (Note: this UAS has VTOL capabilities)	Full commercial application
		Penguin B	UAV factory, USA	Full commercial application
		ScanEagle	Insitu, USA	Full commercial application
		UX5	Trimble Navigation Limited, Belgium	Full commercial application

3. Platform types

Three main types of platform are discussed, Unmanned Aerial Systems (UAS), Autonomous Underwater Vehicles (AUV) and Autonomous Surface Vehicles (ASV). While “low cost, off the shelf” systems are slowly emerging (more rapidly in UAS and AUV than ASV), many will require tailoring to meet a particular set of monitoring requirements. This section provides a general overview of some of the unmanned systems available. A list of platforms suitable for marine animal monitoring considered in this study can be found in Table 1. Detailed information on the listed platforms can be found in Verfuss et al. (2015).

3.1. Aerial systems

Powered aircraft, kites and lighter-than-air aircraft are UAS-types suitable for marine animal monitoring. They are available in a variety of sizes, ranging from 18 g (PD-100 by Proxdynamics) to 14,000 kg (Global Hawk by Northrop Grumman), with a maximum operational time of 40 h. Based on the recommendations of Koski et al. (2009a), we defined a series of UAS features that are relevant for animal monitoring offshore. We included platforms that have a minimum horizontal operational range of 0.5 km from vessels or 200 km from land, and sensors (Section 5.1) capable of detecting objects as small as 1 m in length (e.g., sharks, turtles, fish shoals, and small marine mammals). Due to the large number of available systems, we restrict our review to UAS that can be quickly deployed and that can be operated by no more than three to four persons.

3.1.1. Powered aircraft

Powered aircraft systems include fixed-wing and Vertical Take-Off and Landing (VTOL) systems. Fixed-wing unmanned aircraft are launched using, for example, catapult systems and recovered by using a hook and net system (e.g., in ship deployments), or by landing on a flat surface. VTOL aircraft types include Multi-copters/Multi-rotors, Quadcopters, Hexacopters, and Octocopters. These systems have gained popularity due to their functional flexibility, i.e. they require no specific deployment or recovery facilities. During autonomous flights, these vehicles are capable of being manually piloted or follow a track based on a flight plan (with waypoints). In the case of the latter, pilots are often only needed for take-off and landing manoeuvers because the field operation is uploaded prior to the flight. In most cases, the operational range of VTOL is not sufficient for offshore marine animal monitoring. Most fixed-wing and VTOL aircraft are capable of using gimbal sensors (Section 5.1) to lock the camera onto the target animal during surveys. The two fully electric powered aircraft included in this review are the Trimble UX5 and the Bramor C4EYE (Table 1). These systems are lightweight, low cost, and easy to operate. We included four fuel-powered aircrafts, where the Arcturus Jump-20 (Table 1) is the only platform with VTOL capabilities, and the only VTOL included in this review. VTOL requires no extra infrastructure other than a flat surface when operating from ships or in areas without a suitable landing strip. The Insitu ScanEagle and Thales Fulmar (Table 1) have capabilities for wire or net landing on ship or land. The Penguin B (Table 1), on the other hand, is the only aircraft that requires a strip/runway to land. We identified a single aircraft that can land on the sea surface, the Thales Fulmar.

3.1.2. Kites

Kites comprise a steel frame with an engine, an on-board computer, and a parachute wing. Their advantages include easy transportation and the capacity to carry still cameras, video recording devices and/or multi-spectral and thermal sensors (Thamm, 2011) (see also Section 5.1). However, kites function poorly in strong wind conditions and are often not fully stabilised, resulting in difficulties in hovering over a point of interest. Kites generally operate in wind speeds < 12 knots, which may limit the locations in which they can operate (Thamm et al., 2013). Kite systems have a flight time that can go up to a few hours. These systems require slightly less training time for pilots and operators than powered aircraft (Thamm et al., 2013). Data can be stored in the same format and edited/processed as for the previous aircraft types. However, there has been a lack of survey testing in offshore regions, with only one platform (SWAN X1, Table 1) showing potential for marine surveillance.

3.1.3. Lighter-than-air aircraft

Lighter-than-air aircraft systems (blimps or balloons) consist of a buoyant gas-filled balloon (e.g. helium or hydrogen) that supports sensors with straight-down or tilted views. Balloons are tethered systems connected and towed by a vessel (Hodgson, 2007) while blimps lack a tethering system, which makes them less stable in harsh weather conditions but enables independent flight. Lighter-than-air aircraft may conduct transect-based surveys and can also maintain a hovering position. Balloons, however, are dependent on the presence of a support vessel, which may affect animal presence and/or increase the complexity of operational logistics. Additionally, heat and humidity may affect the lift of the balloon, which in rain, snow, and mist can become heavier from accumulated precipitation on top of the platform. The OceanEye (Table 1) is supplied with a triple sensor unit capable of real-time, night video and imagery. The Desert Star 10 (Table 1) platform is able to carry gyro-stabilised and standard pan-tilt-zoom (PTZ) and modular video cameras, which can be remotely operated to provide a wider view, or store information on-board. Desert Star 10 overcame the limitation of heat and humidity affecting the lift of the balloon by incorporating a tethered helium balloon with a kite wing. The combination of kites and lighter-than-air aircraft is called a kitoon (e.g., MacKellar et al., 2013; Verhoeven et al., 2009). Kitoons can endure stronger winds while maintaining a relatively stable position due to their balloon body and attached sail. Hence, they are a popular alternative for the acquisition of marine data. These UAS are less weather-dependent than kites, as they are typically tethered to a vessel.

3.2. Underwater and surface vehicles

There are a wide variety of AUV and ASV platforms available. ASV and AUV suitable for marine animal monitoring vary from relatively small vehicles, which can be lifted by one or two persons and deployed from a small inflatable boat, to large diesel powered surface vessels (Griffiths, 2002). The smaller vessels operate with a high level of autonomy and are capable of staying at sea for several months, while the larger surface vehicles tend to be more tightly controlled. All platforms, except drifters, described in this review (Table 1) are designed to follow a track line by waypoint setting. While navigating, surface vehicles have the advantage of being able to continuously receive GPS position data meaning that their location can be accurately recorded at all times. Subsurface vehicles cannot receive GPS data while under water and therefore must generally rely on depth measurements and dead reckoning using electronic compasses.

3.2.1. Propeller driven underwater craft

Propeller driven underwater craft are small automated vehicles that are manoeuvrable in the water column in three dimensions by an on-board computer. These systems are typically deployed from a support vessel, but they are not tethered to the vessel during data collection (Wynn et al., 2013). They follow a pre-programmed course operating for periods of a few hours to several days under most environmental conditions. Travelling speeds of propelled AUV are comparable to tidal currents, which can produce navigational drift and thereby affect data quality. This makes propelled AUV less suitable for shallow water operations (Wynn et al., 2013). Most propelled AUV operate at depths of over 200 m, with some models operating at depths up to 6000 m. Powered AUV can operate for a period of weeks. All powered craft face limitations in operational range, but most offer great flexibility depending on the specific mission.

3.2.2. Underwater buoyancy gliders

Underwater buoyancy gliders (hereafter UW gliders) are slow moving (~0.6 knots), typically small (< 2 m), low power platforms that house sensors capable of making multidisciplinary oceanographic observations with long-term deployments (months) and ability to cover large distances (hundreds to thousands of kilometres) (Davis et al., 2002). UW gliders move vertically through the water column by changing their volume and buoyancy. They typically undulate in the upper 1000 m of the water column, thereby making subsurface measurements. The vehicle is steered either by changes in the centre of gravity relative to the centre of buoyancy or by using a rudder. When at the surface, satellite navigation and communication enable the glider to be directed and controlled remotely and to transfer data. UW gliders are acoustically quiet platforms making them highly suitable for acoustic data collection. Mission durations for some glider models can last for many months, though mission durations will be reduced if the sensor payload draws significant power from the gliders batteries. There are, to our knowledge, currently four commercially available electric UW gliders: the Slocum electric (Webb et al., 2001), the Seaglider (Eriksen et al., 2001), the Coastal glider (Imlach and Mahr, 2012), and the Sea Explorer (ACSA, 2014) (Table 1). In addition there are others that are under development, including Spray (Sherman et al., 2001), Deep

Table 2
Data Relay systems that can be used for unmanned vehicles. Given are the data relay type, system name, manufacturer as well as their technology readiness level of satellite and WiFi systems.

	Data relay type	System name	Manufacturer	Technology readiness level
WiFi	900 MHz analog	Seiche bespoke solution	Seiche Ltd	Full commercial application
	1800 MHz analog			
	3.65 GHz	Nano station	Ubiquiti	
	WiFi 2.4 GHz	Bullet		
	WiFi 5 GHz			
Satellite	Inmarsat	FleetOne	Cobham Sailor 250	
	Iridium	MCG-101	Aurora	
	Iridium	Pilot	Iridium	
	Iridium L-band	L-band		

glider (Osse and Eriksen, 2007), Tsukuyomi (Asakawa et al., 2011) and the Liberdade Xray/Zray (D'Spain, 2009; D'Spain et al., 2011) (Table 1). These differ in their key optimisation of speed, mission duration and depth. The Coastal glider is designed for use in the littoral zone (it is self-ballasting from essentially fresh to full ocean water), with a faster maximum speed (2 knots) (Imlach and Mahr, 2012). The Deep glider, on the other hand, is designed to operate at depths of 6000 m (Osse and Eriksen, 2007). The Tsukuyomi is being designed for long duration as a virtual mooring (Asakawa et al., 2011) and the Liberdade Zray/Xray is designed for long distance, long duration and to carry large and high-data-rate payloads (D'Spain, 2009). In most commercially available systems, the manufacturer is able to provide a package that integrates a passive or active acoustic system into the UW glider.

3.2.3. *Powered surface craft*

Powered surface craft are categorised into three groups based solely on hull shape: boats, catamarans and semi-submersibles. Most vehicles are operated remotely from shore or by a support vessel and many resemble familiar craft, such as a rigid-hulled inflatable boat (RHIB) with an inboard or outboard motor. Due to the potential for navigational risk to other craft, these vessels are not fully automated and are required to have the capability for manned operation. One of the most popular ways to create automated or dual-mode (manned/unmanned) vessels is to integrate manual-to-automated control conversion kits into commercial vessels (Caccia, 2006; Caccia et al., 2009). This opens a new range of possibilities for using familiar vessels of greater size and complexity for unmanned observations. The disadvantage is that with increased complexity, there is a higher probability for mechanical issues to arise that may not be easily resolved during remote operations.

Powered ASV have the potential to stay at a single point, but this has implications for power/fuel requirements that result in widely varying station keeping capabilities. For example, the method of station-keeping, known as close circling, has more flexibility but by definition provides low positioning precision. Regarding mobility, powered ASV vary widely; a few large, high powered models are capable of high speeds (≥25 knots) (e.g., C-Target 3 and Mariner, Table 1) but the majority operate between 3 and 10 knots. Typically, powered ASV can run for up to several days.

3.2.4. *Self-powered surface vehicles*

Self-powered surface vehicles, such as wave and wind gliders, use renewable energy from wave, wind or solar energy for forward motion, idling, or station keeping. These vehicles mostly extract energy from wave motion and convert it directly into forward motion. The vehicles also use solar or wind power to maintain batteries used to power the navigation systems and the sensor payload. These vehicles are able to be deployed for time periods of up to several months. Self-powered USV are generally deployed further offshore, being launched from a vessel by hoist. Communication with shore via satellite is standard on all self-powered USV - though bandwidth may often be limited, if only by cost. Several self-powered surface vehicles that follow a track line have become available in recent years. Self-powered surface vehicles are extremely quiet, having no propeller noise, making them highly suitable for passive acoustic monitoring (see Section 5.2). The Waveglider SV3 and AutoNaut (Table 1) both have auxiliary propellers that can be switched on in calm conditions, when wave-power is unavailable. The Waveglider is now a well-established autonomous surface vehicle with proven missions of many months. Other wave and wind powered vehicles have also now completed significant sea time, including in storm conditions, and the AutoNaut, SailDrone (Mordy et al., 2017) and Submaran are now commercially available. The AutoNaut vehicles have a small draft and no sub-sea mechanism which allows easy deployment from a slipway and shallow coastal surveys.

3.2.5. *Drifting sensor packages*

Drifting sensor packages are unpowered AUV or ASV that are often used by oceanographers for long term ocean monitoring tasks (e.g., Barlow et al., 2018; Roemmich et al., 2009). These are low cost, allowing deployment of many sensors simultaneously in order to increase the amount of data collected during a project. Many drifters remain at the sea surface, relaying their positions via satellite link. More sophisticated devices also carry sensor packages and some sample at multiple depths by moving up and down in the water column before transmitting their data to shore. Like the self-powered surface vehicles, the drifting sensor packages are extremely quiet.

4. Data relay system types

Unmanned vehicles have the capability to carry several types of sensors that store or transmit data using different data relay systems (e.g., Table 2). For all vehicles, basic communication for piloting telemetry is undertaken with ease using satellite or radio frequency (RF) modem options since data volumes are relatively small. When data from unmanned platforms are required in real time, or near real-time, a number of options are available for sending data either to shore or to a nearby manned platform or vessel. Real time on-board processing and the use of detectors and classifiers help reduce data volumes that need to be stored or transmitted, but are generally accompanied with a certain false alarm rate and the need for a trained human operator to check detections identified by a system, especially for mitigation monitoring (Section 2.2).

Even if data are not required in real time, it can be advantageous to recover data at regular intervals in order to minimize the risk of data loss, reduce the need for on-board storage and to assess at regular intervals if there are any problems with the data collection. However, data relay to transfer information relevant for marine animal monitoring generally demands considerably more bandwidth and may be impractical due to the limitations of power requirement, transmitter size and cost.

Many different types of data relay system are available (Table 2), most using either a full internet access protocol or some form of short burst data service. As a general rule, sending larger amounts of data over longer distances will require more power, larger and heavier equipment and is likely to incur greater costs. In inshore waters, mobile phone technology can provide high data rates for modest cost and power requirements. In offshore waters, in line of sight of a manned platform or base station, wireless modems (Table 2) can be used to transfer data several kilometres. These systems are generally free to use, but local regulations may restrict the use of particular frequencies in some countries. Both acoustic and video data may also be transferred over short distances using analog transmitters, which may be free to use. In general analog systems are a dated technology, however they can have a role when precise time synchronisation is required between sensors mounted on different platforms.

For vehicles operating in remote locations far from a human operator or base station, satellite technologies are often the only practical solution. Satellite systems come in a variety of sizes (Table 2). Small systems, such as the Iridium L-band weigh < 0.5 kg and consume 2.5 watt (W) power when active, but have a very limited bandwidth of 2400 bits per second (bps). This is often adequate for vehicle control and to download low bandwidth data and is suitable for low power unmanned vehicles such as buoyancy gliders and self-powered ASV. The limited bandwidth of these devices could only be used for the transfer of very small quantities of acoustic or image data. Larger satellite systems such as the Inmarsat FleetOne (Table 2) weigh several kilograms and support data rates into the hundreds of kilobits per second (kbps). This would be sufficient for transmission of data summaries or low frequency raw data. These systems are also physically large (tens of centimetres in each dimension), high power (100–150 W) and cost thousands of dollars per month to operate. Such systems are therefore only suitable for use in large powered surface vessels.

5. Sensor types

Sensors suitable for marine animal monitoring can be integrated into unmanned vehicles as recording and/or real-time processing sensors. Recording-only devices may operate at lower power than real-time processing sensors. Conversely, real-time processing and transmission of data can reduce on-board data storage requirements and thus increase deployment durations. In addition to data reduction, detection and/or classification algorithms also decrease the workload of a human observer by pre-selecting potential detections within the huge amounts of data.

Generally, aerial systems use detection systems relying on electro-optical imaging sensors while underwater and surface vehicles rely mostly on acoustic methods. Table 3 lists sensor systems that may be integrated into the platforms discussed in Section 3. Detailed information on the listed sensors can be found in Verfuss et al. (2015).

5.1. Electro-optical imaging sensors

Electro-optical (EO) imaging sensors on UAS enable the detection of animals near or at the sea surface (Fig. 1). The application of EO imaging sensors on ASV and AUV was not considered in this review, as the detection range of these systems when used underwater or near the water surface is limited.

A single UAS may carry one or several EO sensors, depending on its payload capacity. Individual images can be georeferenced using flight logs or additional GPS information. The three main EO imaging technologies which can detect radiation in different parts of the spectrum (Red Green Blue (RGB), thermal Infra-Red (IR) or non-thermal IR sensors) are suitable for marine animal monitoring from UAS with video or still imagery. Sensors included in this review are listed in Table 3.

RGB cameras detect light in the visible range (VIS) of the electromagnetic spectrum. RGB commercial cameras come in a variety of different qualities with regard to resolution, dynamic range and light sensitivity. **Thermal IR cameras** register thermal radiation emitted from an object such as the breath of marine mammals (Churnside et al., 2009; Santhaseelan and Asari, 2015; Weissenberger et al., 2011; Zitterbart et al., 2013), limiting the detection to warm blooded animals at the sea surface. **Non-thermal IR cameras** operate at the low end of the IR spectrum and are often divided into two groups, differing in the wavelength spectrum: near-infrared (NIR) and short-wavelength infrared (SWIR) (Ibarra-Castanedo et al., 2015). SWIR cameras excel in

Table 3
Sensors that may be integrated into unmanned vehicles and included in this review, the sensor type (AAM, PAM, video), system name, manufacturer as well as their technology readiness level.

Sensor type	System name	Manufacturer	Technology readiness level
Active acoustic monitoring	Aquadopp	Nortek, Norway	Full commercial application
	ADP	Sontek, USA	Full commercial application
	AZFP	ASL, Canada	Basic research Full commercially application as moored system (for AUV)
	DT-X SUB	BioSonics, USA	Full commercial application
	ES853	Imagenex, Canada	Full commercial application
	Gemini 720i, Gemini 720is	Tritech, UK	Full commercial application
	Modular VR2C, VMT	Vemco, Canada	Full commercial application
	WBAT	Kongsberg/Simrad, Norway	Full commercial application
	WBT mini		Prototype system
Passive acoustic monitoring	A-Tag	Marine Micro Technology, Japan	Full commercial application
	AUSOMS-mini Black	Aquasound Inc., Japan	Full commercial application
	C-POD-F	Chelonia Ltd., UK	Small scale prototype
	C-POD		Demonstration system
	Cornell/AutoBuoys	Cornell (PAM)/EOS (buoy), USA	Ready
	Decimus	SA Instrumentation Ltd., UK	Full commercial application
	DMON	WHOI, USA	Available from WHOI n. p.
	SDA14	RTSYS, France	Demonstration system
	SDA416		Prototype system
	Seiche real time transmission system	Seiche Measurements Ltd., UK	n. p.
	SM2, SM3	Wildlife Acoustics, USA	Full commercial application
	SoundTrap 4 channel	Ocean Instruments, New Zealand	Prototype system
	SoundTrap HF		Full commercial application
	WISPR	Embedded Ocean System, USA	n. p.
Electro-optical system	CM100, CM202	UAV Vision, Australia	Full commercial application
	Dual Imager, EO900	Insitu, USA	Full commercial application
	OTUS U135 HIGH DEF, OTUS-L205 HIGH DEF	DST, Sweden	Full commercial application
	TASE 310, TASE 400HD	Cloudcap Technology, USA	Full commercial application

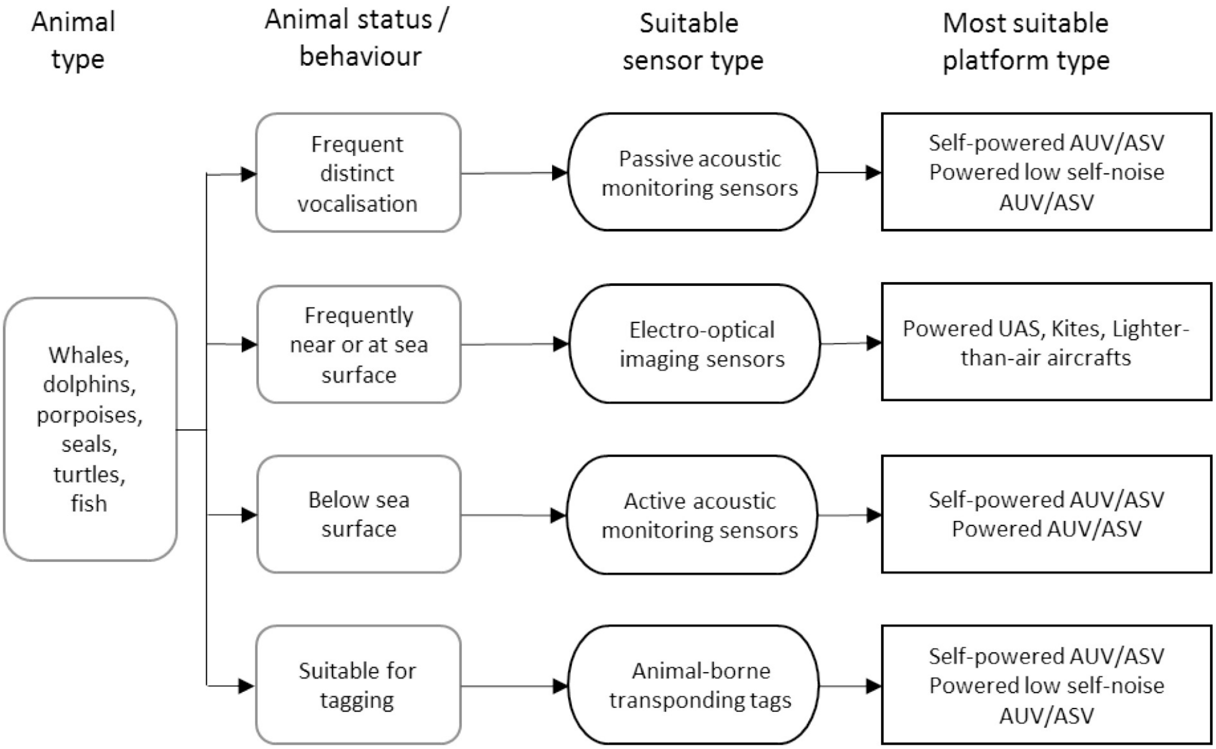

Fig. 1. Decision tree: sensor type suitable for animal type.

low light conditions though few studies have tested them in UAS deployments for the detection of marine animals (e.g. Contarino et al., 2010; Kemper et al., 2016; Podobna et al., 2012).

UAS sensors are typically positioned below the survey platform either at a straight or angled view. It is possible to exchange imaging sensors on a specific platform, depending on the compatibility of alternative sensors. Most platforms considered in this evaluation are available as a part of a set (e.g., ARCTURUS UAV and TRIMBLE).

We focus on stabilised camera systems (i.e. gimbal systems) capable of acquiring at minimum high-definition (HD) video quality, as this is key for the detection of marine animals. Most gimbal systems on the market come pre-assembled with sensors and manufacturers provide a selection of different sensors to suit customer applications and requirements. The biggest gimbals (e.g., Cloudcap TASE 400, Table 3) are used for non-standard camera configurations. The CM100 Gimbal (Table 3) is classified as a small, light-weight system making it compatible with most UAS. In addition, there are specialized gimbals from Insitu and C-ASTRAL that are compatible with both the ScanEagle and Bramor models, respectively.

Imaging sensors such as high resolution still or video cameras, operating in the visible spectrum or the non-thermal region of the infrared spectrum are the most relevant sensors for marine animal studies. A future system with high resolution gyro stabilised geocoded video or geocoded overlapping still images would be an effective tool for near-real-time animal detection and species identification from UAS data.

Some data processing capabilities, such as object tracking or motion detection, can be included in the sensor or gimbal. The communication system, used for transferring data from the sensor to the ground, is often an integral part of the UAS. Depending on the aim of the study, it is possible to create mosaics, analyse each photo or video individually, or use a real-time detection system such as the one developed by Ireland et al. (2015). Classification of animals with UAS-sensors is possible, but only with appropriately trained human observers monitoring the video stream.

5.2. *Passive acoustic monitoring systems*

Passive acoustic monitoring (PAM) relies on detecting sounds produced by animals and can therefore only be used for monitoring soniferous animals (Fig. 1). Vessel based or moored PAM systems have been used to study cetaceans for several decades (e.g., Gillespie, 1997; Sousa-Lima et al., 2013) and can also be used to detect the sounds of soniferous fish (Rountree et al., 2006). While an increasingly large number of PAM systems for fixed unmanned monitoring are available (many of which might be adapted for deployment on unmanned vehicles, Sousa-Lima et al. (2013)), we limit this review of PAM sensors to those which have been deployed on unmanned vehicles or that perform a high level of processing, making them suitable for real-time detection.

PAM systems consist of one or more hydrophones (underwater microphones) connected to a recording and/or processing device. Sounds from many species of marine mammal are easily distinguished using a combination of automated and human based methods. However, some sounds, such as clicks and whistles from some dolphin species are harder to accurately classify to the species level (e.g., Gillespie et al., 2013; Rankin et al., 2017).

A single hydrophone system cannot generally provide localisation data. Small clusters of hydrophones can measure bearings to detected sounds by using the time of arrival difference of the signal on different hydrophones. To measure range, hydrophones need to be far apart and in general, accurate range determination is not possible beyond about three times the array dimension. For some species, range can be determined using small (bearing only) arrays if multiple bearings to the same animal can be determined from different points along a track-line, a technique known as target motion analysis (Lewis et al., 2007).

Autonomous PAM systems to date have typically used only one or a small number of hydrophones close together. While the larger powered surface vehicles would be capable of towing larger hydrophone arrays, which might provide location data, this is impractical with small low powered vehicles, since the drag of a large array would overly impact vehicle performance. Determining animal location using target motion analysis is also impractical with slow moving vehicles since animal movement will introduce large errors into estimates of animal location. To overcome these limitations, Fucile et al. (2006) deployed three submarine gliders and used time of arrival differences on the different vehicles to determine animal location. Clearly though, deploying multiple vehicles in this way poses additional costs and logistical requirements in navigation and the need to accurately time-synchronise the different sensors.

The PAM systems most suitable for use on small low power unmanned vehicles such as UW gliders are the SoundTrap, the DMON and the WISPR board (Table 3). The SoundTrap and DMON have been deployed on both Slocum underwater gliders and Kongsberg seagliders (Baumgartner et al., 2013; Suberg et al., 2014). The WISPR board is available as a standard package with the Kongsberg seaglider. However, its relatively high power consumption significantly reduces the lifetime of glider deployments from months to weeks. The surface vehicles that have been reviewed could potentially work with any of the sensors listed in Table 3 since they have fewer space restrictions and generally have more power available than the UW gliders. We are unaware of any PAM systems being used on powered underwater vehicles.

In order to reduce both the quantities of data stored and transmitted, most of the PAM systems listed in Table 3 purport to offer real-time detection and several PAM systems offer serial and Ethernet based connectivity. The Decimus and the Seiche system (Table 3) can both be used with wireless modem systems to send enough data in real-time for mitigation monitoring of a wide range of species.

5.3. Active acoustic monitoring sensors

An active acoustic monitoring (AAM) sensor acts by broadcasting a sound wave and measuring the reflected signal from encountered targets. AAM can detect anything with a large enough target strength to reflect sufficient sound energy to the AAM sensor. Therefore any large "body", from zooplankton patches and fishes up to large whales can be detected (Fig. 1). Classification of the animal species or species group is complex with AAM and relies on knowledge of the animal's specific target strength at different frequencies and swimming behaviour. Specific algorithms for detecting and classifying marine animals such as seals, porpoise, dolphins and sharks are under development (e.g., Hastie, 2012; Sparling et al., 2016). These may however, only work in the context for which they were developed and therefore, may need to be tested for other situations or environments.

The performance of the AAM sonar system depends on the degree to which the beam of sound is focussed onto the target and hence the direction of the array generating the sound beam. It also depends on the level of background noise. As AAM is an active system emitting sound, it may have an influence on marine animals if the frequency of the emitted sound is audible to the receiving animal (e.g., Hastie, 2007; Ketten, 2004).

AAM have been used with UW gliders and ASV to detect zooplankton rather than fish and other larger animals (e.g., Guihen et al., 2014), although AAM is used in fisheries research to estimate fish biomass and distribution (e.g., herring, blue whiting, mackerel, sardines and anchovy: Doray, 2012; Huse et al., 2015). AAM systems typically operate from ~18 kHz through to ~500 kHz.

Currently there are a selection of AAM sensors integrated in AUVs (e.g., Bingham et al., 2012; Fernandes et al., 2003; Williams et al., 2010) or ASV (e.g., Greene et al., 2014). Potentially any of the echosounders listed in Table 3 could be mounted on AUV or ASV.

AAM systems generally store raw, unprocessed data. The Biosonics DT-X-Sub and the WBAT (Table 3) have on-board processors that in the former case produce data summaries viewable as simplified echograms with alerts triggered by acoustic events. Most of the AAM systems are able to observe fish and zooplankton, as well as provide a bearing and direct range estimate to an animal from a single device (albeit within a very small beam for some of them). Real-time data transmission of a limited amount of information is feasible for all systems listed in Table 3 except for the Vemco VMT (Table 1).

5.4. Animal borne-transponder tags

Animal borne-transponder tags in combination with a passive acoustic receiver help to monitor the movements of individual organisms, such as marine mammals, turtles and fish (e.g., Voegeli et al., 2001) (Fig. 1), but are mostly used with fish. A miniature electronic pinger is placed on an animal, of which the ping can be detected by hydrophones (e.g., Wroblewski et al., 1994; Wroblewski et al., 2000). Tags transmit at specific frequencies and use either encoded pulses or patterns of pulses to provide a unique marker for each individual. Detections are generally made with pre-assembled receivers from the tag manufacturer. Tag detection, range, and transmission duration are proportional to tag size. Acoustic receivers for the detection of acoustic tags have been integrated into AUV surveys (Eiler et al., 2013; Haulsee et al., 2015). Vemco tag locators have been integrated into a Slocum glider, REMUS AUV, Waveglider and AutoNaut (e.g., Eiler et al., 2013; Haulsee et al., 2015). PAM systems used for detecting marine mammals could also potentially be used to detect the signature of an acoustic tag (Sparling et al., 2016).

6. Suitability of unmanned vehicle system for the different monitoring types

Selecting the most appropriate vehicle and sensor package is very dependent on the specific details of a monitoring task and will be a function of the monitoring environment and available support infrastructure as well as the target species. For instance, mitigation monitoring around an industrial activity may require a highly mobile platform which can be rapidly deployed for relatively short periods of time, has real-time data relay and can move rapidly around a monitoring zone, whereas population monitoring for the same species may be better undertaken with a vehicle and sensor package suited to longer term deployments. Table 4 gives an overview of which systems included in this review may be suitable for the different monitoring types, and Fig. 2 illustrates which platform may be most suitable for which monitoring type under certain prevailing conditions, outlined in further detail in the following sections.

6.1. Population monitoring

Of the three classes of aerial platforms considered in this review (Section 3.1), powered UAS have many of the capabilities required for aerial surveys of marine animals (reviewed in Fiori et al., 2017 for marine mammals) and are therefore the best candidate for aerial surveys using autonomous vehicles (Fig. 2). Kites share similar attributes to powered aircraft and they are easier to transport and, in some cases, deploy than fixed wing aircraft. However, they are more susceptible to bad weather, particularly in offshore regions. Lighter-than-air UAS also have marine animal population surveying capabilities but, due to their requirement for a tether, would either have to be moored to static buoys or attached to a moving vessel. However, these scenarios are logistically complex compared to fixed wing platforms.

All classes of AUV/ASV reviewed (Section 3.2) are capable of conducting population monitoring (Fig. 2). Data required for detection probability estimation can be collected by both AAM and PAM sensors, though a careful survey design will be required, especially for PAM surveys that may need instrument arrays. The long mission durations of self-powered AUV/ASV is a major benefit for population monitoring, compared to the shorter deployment times (on the order of hours) of most powered AUV/ASV craft. Further, the ability of underwater gliders to vertically profile the water column, which may also aid detection of different marine animals occurring at varying depths, is another advantage of these self-powered vehicles. The low noise floor of the

Table 4
Recommended technology types that might be used in field trials for the different monitoring types. The monitoring types are furthermore divided into mitigation monitoring in areas either clear from or busy with other operational gear or traffic, short-term (hours, days) or long-term (weeks, months) monitoring and focal-follows conducted with static or mobile systems. L-t-a = lighter-than-air aircraft. While this table is based on what has been successfully trialled to date, the emergence of new sensors and platforms makes it highly likely that many more options will be available in the future.

			Monitoring type					
			Mitigation		Population		Focal-follow	
Sensor	Vehicle		Clear	Busy	Short-term	Long-term	Static	Mobile
Electro-optical	Powered aircraft		All	All	Bramor c4Eye, Bramor gEO, Bramor rTK Fulmar, Jump 20, Penguin B and ScanEagle	None	All – dependent on the sensor technology	
	Motorised gliders		None	None	NONE	None	None	None
	Kites		All	None	ALL	None	All	All
	L-t-a aircraft		All	None	ALL	All	All	All
PAM	Powered	AUV	None	None	NONE	None	Depends on speed of animals and volume for which tracking is required.	
		ASV	C-Worker, C-Enduro. Scoping ahead of source, specifically for LF detections.	None	C-Worker, C-Enduro.	None		
	Self-powered	AUV	None	None	Slocum and Seaglider	Slocum and Seaglider		
		ASV	None	None	Waveglider; Autonaut	Waveglider; Autonaut		
	Drifter		None	None		DASBR	None	
AAM	Powered	AUV	None	None	All – dependent on the specific species of interest, the geographic area, the water depth, local current strengths, shipping density, the expected animal encounter rate and the precision required of the study and possibly more, e.g. Bluefin 9/9M, A9M and REMUS 100 for shallow and medium waters and short duration surveys; Bluefin 12D and REMUS 600 for deep water and long duration surveys; Bluefin 21, A18D and REMUS 6000 for very deep waters and long duration surveys.			
		ASV	All[a]	None				
	Self-powered	AUV	None	None				
		ASV	None	None				
	Drifter		None	None	All		None	

[a] See population monitoring.

smaller, low powered autonomous vehicles is an additional advantage, because masking of animal sounds will be both low and stable across platforms, and animal reaction to smaller and low noise platforms is likely to be low.

A limitation of some AUV, and to a lesser extent to ASV is sensitivity to environmental conditions, particularly currents, and the subsequent

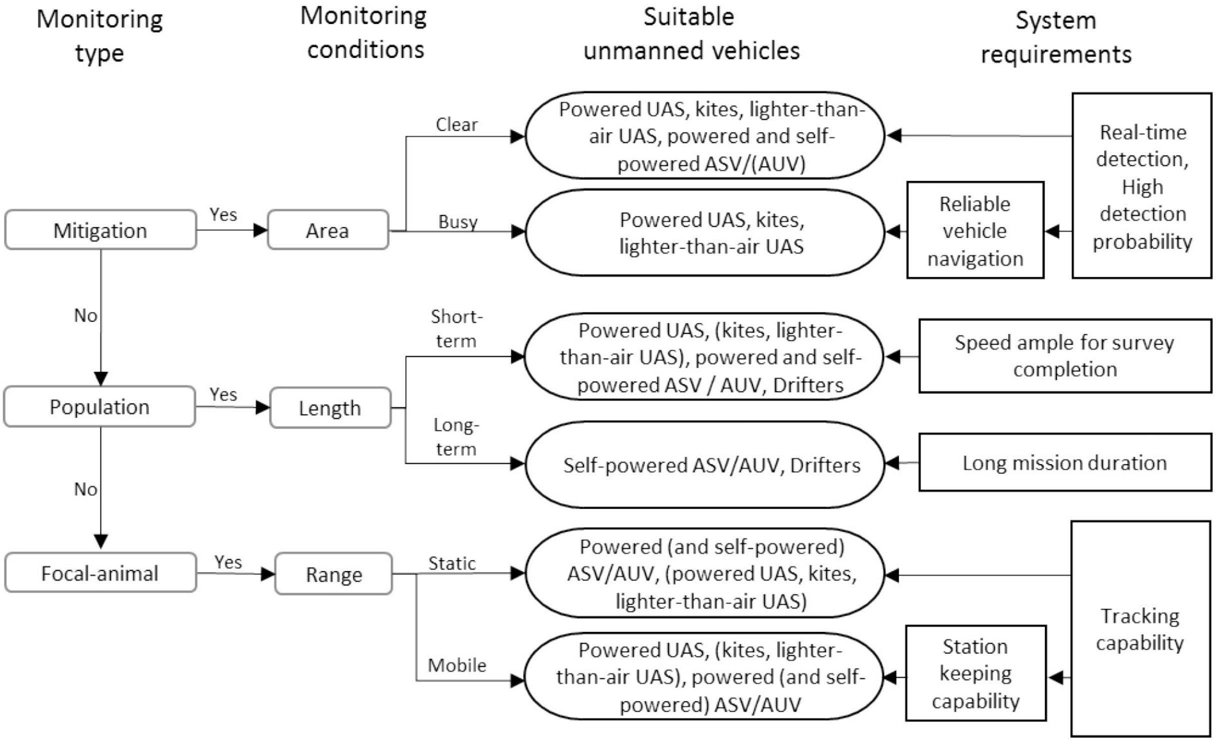

Fig. 2. Decision tree: unmanned platform suitable for monitoring type and condition. Unmanned vehicles in brackets are less suitable.

effect on survey design. Powered instruments are likely to have resistance to currents. Clearly, drifting buoys will be most affected by water movement, though their low price is a major advantage over other platforms. In the case of self-powered platforms, it may be that the extended survey duration is a suitable trade-off for some disruption to the planned survey. The slow movement of self-powered platforms does have consequences for density/abundance estimation; analytical approaches that explicitly deal with animal movement may be required (reviewed in Marques et al., 2013b). However, despite these additional considerations, autonomous vehicles' long deployment durations present a major advantage for marine animal surveys and their ability to move efficiently to other study areas make them a powerful asset.

6.2. Mitigation monitoring

For mitigation monitoring (Section 2.2), unmanned vehicles have, to our knowledge, not yet been used but they bring potential to this field. Some systems may be well placed for mitigation monitoring as they allow for (near) real-time detection. These systems would need to operate for long enough periods and cover wide enough ranges to meet the temporal and spatial requirements of the regulations set by the responsible authority, which are often in the order of hours. Where mitigation zones are larger than can be covered from a single platform, coordinated operation of a fleet of vehicles has the potential to cover larger areas. There is also the potential to use different unmanned systems concurrently with manned platforms to further increase the probability of animal detection, e.g., using UAS (Section 3.1) with thermal-IR cameras (Section 5.1) in addition to human observers.

For the continuous real-time surveillance that is required for mitigation monitoring, the platform must be able to report detections in near-real time. UAS and ASV (Sections 3.2.3 and 3.2.4) can readily achieve this using wireless modem technologies (Section 4). Communication with many AUVs while underwater is either not supported or has such restricted bandwidth that sufficient data for real-time mitigation cannot be relayed to the surface. Therefore AUVs would have to surface prior to transmitting data. This makes AUV less suitable for mitigation monitoring, as the time between the detection of a target animal by an AUV and triggering a mitigation action upon notice to the operator may not be sufficient to minimize the risk of impact. However, for some mitigation scenarios AUVs may still be of use, e.g. where species are known to move slowly, and mitigation monitoring is conducted prior to the activation of the potentially impacting sound source. In industrial areas, the deployment of ASV or AUV for marine animal monitoring during complex industrial operations may also be highly impractical unless suitable control and collision avoidance is implemented.

6.3. Focal animal monitoring

In focal animal monitoring (Section 2.3), lighter-than-air aircraft (Section 3.1.3) are a potential candidate platform (Fig. 2) (e.g., Ocean Eye), though their ability to follow animals will be restricted to the manoeuvrability of the support vessel to which they are tethered. Powered aircraft (Section 3.1.1) can be piloted to follow animals, with rotary wing vehicles performing well in existing studies (e.g., Durban et al., 2015). Fixed-wing aircraft cannot hover above stationary or slow-moving animals but can loiter around a target location. Though powered surface craft (Section 3.2.3) and propeller driven underwater craft (Section 3.2.1) have short survey duration times compared to self-powered vehicles (Sections 3.2.2 and 3.2.4), these powered platforms, particularly those with increased manoeuvrability, may be suitable for individual focal animal studies (Fig. 2).

The need for human piloting limits the range of unmanned vehicles used for focal follows, since the vehicles need to stay in communications range with the operator. The range may, however, be considerably greater than that of ship-based human observers. There has been some research into systems which can fully automatically detect and track animals. Aerial systems have been tested to detect and track ships (e.g., Helgesen et al., 2016) and whales (e.g., Selby et al., 2011). We are, however, unaware of any aerial system that has been developed to the point where it can autonomously track an animal at sea. AUV based systems have also been developed to automatically detect and follow specific underwater signals (e.g., Clark et al., 2013) with pinging transponders (Section 5.4) either attached to other vehicles or to fish. We are similarly unaware of any system that can track vocalising animals using passive acoustics.

7. Discussion and recommendations

Unmanned vehicles provide a safe and effective alternative to placing humans within a dangerous working area. Many unmanned vehicles are now commercially available, often with fully integrated sensor packages suitable for monitoring marine animals. The range of available vehicles and sensor capabilities is also expanding at a steady rate, making it likely that unmanned systems will play an increasing role in future marine animal monitoring.

Compromises and trade-offs in vehicle and sensor choices are inevitable. For example, while often desirable to use two or more cameras with a UAS, which are sensitive to different parts of the spectrum, the additional payload may shorten flight times, or require a much larger and more expensive vehicle. Or when using ASV or AUV with a PAM sensor to detect low-frequency baleen whales, only a low bandwidth acoustic system is required, with the ability to store many months of data with modest data storage requirements. To be able to detect high-frequency odontocete vocalisations, a higher bandwidth system is needed, with increased power and high data storage requirements, with storage probably lasting for days only, which restricts mission duration. Larger and more complex systems are generally more capable, but are likely to be more expensive and require greater supporting infrastructure.

Procedures for the deployment and recovery of a particular platform and associated sensors is also an important consideration. Specialist training may be required for deployment/retrieval and, more pertinently, for operation of the craft as well as personnel requirements for data analysis. For many industrial applications, the requirement of additional on-board personnel to operate unmanned vehicles may be a logistical constraint.

7.1. Comparison of different systems

The usefulness of unmanned systems should always be compared to more traditional methods, such as vessel, aircraft or even shore based surveys. Where multiple technologies have the potential to detect a particular species, we recommend direct comparisons be carried out for different unmanned solutions and, if feasible, alongside traditional monitoring methods. Both the detectability of animals and vehicle endurance are expected to vary with environmental conditions (e.g. summer/winter, temperate/tropical waters) so trials should be focussed on regions of high importance to industry and on species or regions which are currently poorly monitored with more traditional methods. Only a broad scale comparison of the results may be possible due to the differences in survey design caused by the operational differences of the various platforms.

We also recommend the development of a simulation tool which combines knowledge of animal movement, behaviour and cue production with models of sensor and vehicle performance and simulated monitoring scenarios. This could be used to more thoroughly assess the likely efficacy of using unmanned systems compared with traditional monitoring methods for a wider range of environmental conditions and for different monitoring tasks.

7.2. Behavioural studies

Continued behavioural studies of all species of interest is important for any survey method (unmanned as well as manned). Vocalising and surfacing behaviour are two key examples that are essential for estimating the availability of animals to be detected (Section 2.1). With regard to unmanned vehicles, it is especially important to understand if, under which circumstances, and how a target animal may react to a specific vehicle.

7.3. Improvement of detection and classification algorithm

Due to communication bandwidth limitations a key requirement is the improvement in automated summarisation of sensor data enabling real-time information to be sent back from unmanned platforms. Validation of, and estimates of uncertainty around those automated techniques will remain essential. Research into both the magnitude and the effects of mis-detection and mis-classification, and investment into systems that aid human observers in the decision processes is of high importance.

7.4. Health and safety developments

Any considered craft requires extensive testing to ensure sufficient safety and reliability during operations. Not all unmanned vehicles have a proven record of technical reliability (e.g., Brito et al., 2014). Further promotion of the Health Safety Environment (HSE) procedures might involve the development of a 'code of practice', as matured for USVs, for operation of unmanned vehicle use in industrial operations. Harmonised regulations and standards would create a smoother transition to, and acceptance of, unmanned vehicles. At present, both standards and regulations differ among countries. The lack of international harmonisation creates some resistance from current air or water space users as well as public apprehension. We recommend development of a framework of rules and regulations that are flexible and amendable to the specifics of an industrial project and to the rapid development of unmanned vehicles for a range of applications. Further research into 'detect-and-avoid' systems for unmanned vehicles would also lead to improvements in the operational safety of unmanned vehicles.

8. Summary

Recent technology developments have turned present-day unmanned vehicle systems into realistic alternatives to traditional marine animal survey methods. Benefits include longer deployments, improved mission safety, mission repeatability, and reduced operational costs. The technical and operational details of the unmanned vehicle need to be tailored to the specific needs of a monitoring task, such as, among others, the area of interest, survey length, target species and project budget. Population monitoring generally need systems with high endurance capabilities and the ability to follow track lines or to remain stationary. During mitigation monitoring, systems need to sufficiently cover a given monitoring zone and to be able to detect animals in real-time. Focal animal studies require systems with tracking ability. The target species mainly defines the kind of sensor most suitable for detecting an animal. Electro-optical imaging sensors deployed on Unmanned Aerial Systems (UAS), enable the detection of animals when near or at the sea surface. Acoustic monitoring sensors, deployed on Autonomous Underwater Vehicles (AUV) and Autonomous Surface Vehicles (ASV), detect animals under water. Passive Acoustic Monitoring (PAM) sensors can only be used for monitoring soniferous animals or animals tagged with transponders to monitor the movements of individual organisms. Active Acoustic Monitoring (AAM) sensors detect large "bodies", from patches of zooplankton and fish up to large whales.

Many unmanned vehicles are commercially available, often with integrated sensors suitable for animal monitoring. Powered UAS have many of the capabilities required for population monitoring, as do kites and lighter-than-air UAS. Powered and self-powered AUV and ASV are also suitable for population monitoring; the long deployment duration of self-powered AUV/ASV is particularly beneficial. For mitigation monitoring, where continuous real-time monitoring is required, generally only surface or aerial systems are suitable. In operationally busy areas, ASV are rather unsuitable, as they cannot safely operate. In focal animal monitoring, powered vehicles are suitable platforms. Lighter-than-air aircraft are also a potential candidate platform depending on the manoeuvrability of the support vessel to which they are tethered.

This review presents critical factors to be considered when planning marine surveys using unmanned vehicles as the main source of data collection. It gives the following recommendations to enhance the use of unmanned systems: Field comparisons of different unmanned solutions alongside traditional monitoring methods; studies on animal behaviour to better understand detection probability; improvement of detection and classification algorithms, and, with regard to the operational safety, 'detect-and-avoid' systems for unmanned vehicles; development of an international harmonised framework of rules and regulations, flexible and amendable to specific industrial projects and supporting rapid unmanned system development.

Acknowledgements

This work was supported by the Joint Industry Programme on E&P Sound and Marine Life - Phase III. We would also like to thank the Research Centre for Arctic Exploration (ARCEx), funded by the Research Council of Norway (project #228107). We thank all those companies and individuals who supported this review with technical details. We acknowledge Dr. JoLynn Carroll for synthesising and restructuring an earlier version of the manuscript. We would also like to acknowledge the anonymous reviewer for their valuable comments leading to a great improvement of the manuscript.

References

ACSA, 2014. The SeaExplorer underwater glider breaks world record. In: Underwater. The Association of Diving Contractors International, pp. 3.

Antunes, R., Kvadsheim, P.H., Lam, F.P.A., Tyack, P.L., Thomas, L., Wensveen, P.J., Miller, P.J.O., 2014. High thresholds for avoidance of sonar by free-ranging long-finned pilot whales (*Globicephala melas*). Mar. Pollut. Bull. 83, 165–180.

Asakawa, K., Nakamura, M., Kobayashi, T., Watanabe, Y., Hyakudome, T., Ito, Y., Kojima, J., 2011. Design concept of Tsukuyomi — Underwater glider prototype for virtual mooring. In: OCEANS 2011. IEEE, Spain, pp. 1–5.

Barlow, J., Griffiths, E.T., Klinck, H., Harris, D.V., 2018. Diving behavior of Cuvier's beaked whales inferred from three-dimensional acoustic localization and tracking using a nested array of drifting hydrophone recorders. J. Acoust. Soc. Am. 144, 2030–2041.

Baumgartner, M.F., Fratantoni, D.M., Hurst, T.P., Brown, M.W., Cole, T.V., Van Parijs, S.M., Johnson, M., 2013. Real-time reporting of baleen whale passive acoustic detections from ocean gliders. J. Acoust. Soc. Am. 134, 1814–1823.

Bingham, B., Kraus, N., Howe, B., Freitag, L., Ball, K., Koski, P., Gallimore, E., 2012. Passive and active acoustics using an autonomous wave glider. J. Field Robot. 29, 911–923.

Borchers, D., 2012. A non-technical overview of spatially explicit capture–recapture models. J. Ornithol. 152, 435–444.

Borchers, D.L., Zucchini, W., Heide-Jørgensen, M.P., Cañadas, A., Langrock, R., 2013. Using hidden Markov models to deal with availability bias on line transect surveys. Biometrics 69, 703–713.

Borchers, D., Stevenson, B., Kidney, D., Thomas, L., Marques, T., 2015. A unifying model for capture–recapture and distance sampling surveys of wildlife populations. J. Am. Stat. Assoc. 110, 195–204.

Brito, M., Smeed, D., Griffiths, G., 2014. Underwater glider reliability and implications for survey design. J. Atmos. Ocean. Technol. 31, 2858–2870.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L., Thomas, L., 2001. Introduction to Distance Sampling. Estimating Abundance of Biological Populations. Oxford University Press, Oxford.

Budiyono, A., 2009. Advances in Unmanned Underwater Vehicles Technologies: Modeling, Control and Guidance Perspectives.

Caccia, M., 2006. Autonomous surface craft: prototypes and basic research issues, control and automation, 2006. In: MED'06. 14th Mediterranean Conference on. IEEEpp. 1–6.

Caccia, M., Bibuli, M., Bono, R., Bruzzone, G., Bruzzone, G., Spirandelli, E., 2009.

Aluminum hull USV for coastal water and seafloor monitoring. In: OCEANS 2009-Europe. IEEE, pp. 1–5.

Churnside, J., Ostrovsky, L., Veenstra, T., 2009. Thermal footprints of whales. Oceanography 22, 206.

Clark, C.M., Forney, C., Manii, E., Shinzaki, D., Gage, C., Farris, M., Lowe, C.G., Moline, M., 2013. Tracking and following a tagged leopard shark with an autonomous underwater vehicle. J. Field Robot. 30, 309–322.

Contarino, V.M., Podobna, Y., Schoonmaker, J., Boucher, C., 2010. Techniques for determining marine mammal densities. In: OCEANS 2010. IEEE, pp. 1–5.

Davis, R.E., Eriksen, C.C., Jones, C.P., 2002. Autonomous Buoyancy-Driven Underwater Gliders. Taylor and Francis, London, pp. 37–58.

DEWHA, 2008. Australian Government EPBC Act Policy Statement 2.1 - Interaction Between Offshore Seismic Exploration and Whales. The Department of the Environment Water Heritage and the Arts.

Doray, M., 2012. Pelagic Fish Stock Assessment by Acoustic Methods at Ifremer.

D'Spain, G.L., 2009. Flying Wing Autonomous Underwater Glider for Basic Research in Ocean Acoustics, Signal/Array Processing, Underwater Autonomous Vehicle Technology, Oceanography, Geophysics, and Marine Biological Studies. (Scripps Institution of Oceanography La Jolla Ca Marine Physical Lab).

D'Spain, G., Hildebrand, J., Husband, W., Stevenson, M., 2011. Follow-on Tests of the ZRay Flying Wing Underwater Glider and Waveglider Autonomous Surface Vehicles, and Their Passive Acoustic Marine Mammal Monitoring Systems. Marine Physical Laboratory, Scripps Institution of Oceanography, University of California.

Durban, J., Fearnbach, H., Barrett-Lennard, L., Perryman, W., Leroi, D., 2015. Photogrammetry of killer whales using a small hexacopter launched at sea. J. Unmanned Veh. Syst. 3, 131–135.

Eiler, J.H., Grothues, T.M., Dobarro, J.A., Masuda, M.M., 2013. Comparing autonomous underwater vehicle (AUV) and vessel-based tracking performance for locating acoustically tagged fish. Mar. Fish. Rev. 75, 27–42.

Eriksen, C.C., Osse, T.J., Light, R.D., Wen, T., Lehman, T.W., Sabin, P.L., Ballard, J.W., Chiodi, A.M., 2001. Seaglider: a long-range autonomous underwater vehicle for oceanographic research. IEEE J. Ocean. Eng. 26, 424–436.

Fernandes, P.G., Stevenson, P., Brierley, A.S., Armstrong, F., Simmonds, E.J., 2003. Autonomous underwater vehicles: future platforms for fisheries acoustics. ICES J. Mar. Sci. 60, 684–691.

Fiori, L., Doshi, A., Martinez, E., Orams, M.B., Bollard-Breen, B., 2017. The use of unmanned aerial systems in marine mammal research. Remote Sens. 9, 543.

Forney, K.A., Ferguson, M.C., Becker, E.A., Fiedler, P.C., Redfern, J.V., Barlow, J., Vilchis, I.L., Ballance, L.T., 2012. Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. Endanger. Species Res. 16, 113–133.

Fucile, P.D., Singer, R.C., Baumgartner, M., Ball, K., 2006. A self-contained recorder for acoustic observations from AUV's. In: OCEANS 2006. IEEE, pp. 1–4.

Funaki, M., Hirasawa, N., 2008. Outline of a small unmanned aerial vehicle (ant-plane) designed for Antarctic research. Polar Sci. 2, 129–142.

Gillespie, D., 1997. An acoustic survey for sperm whales in the Southern Ocean sanctuary conducted from the RSV Aurora Australis. In: Reports of the International Whaling Commission. 47. pp. 897–907.

Gillespie, D., Caillat, M., Gordon, J., White, P., 2013. Automatic detection and classification of odontocete whistles. J. Acoust. Soc. Am. 134, 2427–2437.

Gordon, J., Gillespie, D., Potter, J., Frantzis, A., Simmonds, M.P., Swift, R., Thompson, D., 2003. A review of the effects of seismic surveys on marine mammals. Mar. Technol. Soc. J. 37, 16–34.

Greene, C.H., Meyer-Gutbrod, E.L., McGarry, L.P., Hufnagle Jr., L.C., Chu, D., McClatchie, S., Packer, A., Jung, J.-B., Acker, T., Dorn, H., 2014. A wave glider approach to fisheries acoustics: transforming how we monitor the nation's commercial fisheries in the 21st century. Oceanography 27, 168–174.

Griffiths, G., 2002. Technology and Applications of Autonomous Underwater Vehicles. CRC Press.

Guihen, D., Fielding, S., Murphy, E.J., Heywood, K.J., Griffiths, G., 2014. An assessment of the use of ocean gliders to undertake acoustic measurements of zooplankton: the distribution and density of Antarctic krill (*Euphausia superba*) in the Weddell Sea. Limnol. Oceanogr. Methods 12, 373–389.

Hastie, G.D., 2007. Using Active Sonar to Detect Marine Animals Around Marine Energy Devices: Behavioural Responses by Porpoises to Sonar Signals.

Hastie, G., 2012. Tracking Marine Mammals Around Marine Renewable Energy Devices Using Active Sonar.

Haulsee, D., Breece, M., Miller, D., Wetherbee, B.M., Fox, D., Oliver, M., 2015. Habitat Selection of a Coastal Shark Species Estimated From an Autonomous Underwater Vehicle.

Helgesen, H.H., Leira, F.S., Johansen, T.A., Fossen, T.I., 2016. Tracking of marine surface objects from unmanned aerial vehicles with a pan/tilt unit using a thermal camera and optical flow. In: 2016 International Conference on Unmanned Aircraft Systems (ICUAS), pp. 107–117.

Hodgson, A., 2007. "BLIMP-CAM": aerial video observations of marine animals. Mar. Technol. Soc. J. 41, 39–43.

Hodgson, A.J., Noad, M., Marsh, H., Lanyon, J., Kniest, E., 2010. Using unmanned aerial vehicles for surveys of marine mammals in Australia: test of concept. In: Final Report to the Australian Marine Mammal Centre, pp. 30.

Huse, G., MacKenzie, B.R., Trenkel, V., Doray, M., Nøttestad, L., Oskarsson, G., 2015. Spatially explicit estimates of stock sizes, structure and biomass of herring and blue whiting, and catch data of bluefin tuna. Earth Syst. Sci. Data 7, 35–46.

Ibarra-Castanedo, C., Sfarra, S., Genest, M., Maldague, X., 2015. Infrared vision: visual inspection beyond the visible spectrum. In: Liu, Z., Ukida, H., Ramuhalli, P., Niel, K. (Eds.), Integrated Imaging and Vision Techniques for Industrial Inspection: Advances and Applications. Springer London, London, pp. 41–58.

Imlach, J., Mahr, R., 2012. Modification of a military grade glider for coastal scientific applications. In: OCEANS 2012. IEEE, pp. 1–6.

Inoue, J., Curry, J.A., Maslanik, J.A., 2008. Application of Aerosondes to melt-pond observations over Arctic sea ice. J. Atmos. Ocean. Technol. 25, 327–334.

Ireland, D., Leonard, K., Schaefer, G., Sparks, C., Jannarone, R., Koski, B., Funk, D., Macrander, A., Broker, K., 2015. Automated detection of large cetaceans in aerial digital imagery. In: Abstract to the Conference of the Society of Marine Mammalogy, San Francisco, USA.

JNCC, 2017. JNCC Guidelines for Minimising the Risk of Injury to Marine Mammals From Geophysical Surveys.

Kemper, G., Weidauer, A., Coppack, T., 2016. Monitoring seabirds and marine mammals by georeferenced aerial photography. Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci. 41.

Ketten, D.R., 2004. Marine mammal auditory systems: a summary of audiometric and anatomical data and implications for underwater acoustic impacts. Polarforschung 72, 79–92.

Ketten, D.R., 2014. Sonars and strandings: are beaked whales the aquatic acoustic canary? Acoust. Today Summer 2014, 46–56.

Koski, W.R., Abgrall, P., Yazvenko, S.B., 2009a. A review and inventory of unmanned aerial systems for detection and monitoring of key biological resources and physical parameters affecting marine life during offshore exploration and production activities. In: IWC Paper SC/61 E 9.

Koski, W.R., Allen, T., Ireland, D., Buck, G., Smith, P.R., Macrander, A.M., Halick, M.A., Rushing, C., Sliwa, D.J., McDonald, T.L., 2009b. Evaluation of an unmanned airborne system for monitoring marine mammals. Aquat. Mamm. 35, 347.

Leong, S.C.Y., Tkalich, P., Patrikalakis, N.M., 2012. Monitoring harmful algal blooms in Singapore: developing a HABs observing system. In: OCEANS, 2012-Yeosu. IEEE, pp. 1–5.

Lewis, T., Gillespie, D., Lacey, C., Matthews, J., Danbolt, M., Leaper, R., McLanaghan, R., Moscrop, A., 2007. Sperm whale abundance estimates from acoustic surveys of the Ionian Sea and Straits of Sicily in 2003. J. Mar. Biol. Assoc. U. K. 87, 353–357.

Lucke, K., Siebert, U., Lepper, P.A., Blanchet, M., 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. J. Acoust. Soc. Am. 125, 4060–4070.

Lyons, C., Koski, W., Ireland, D., 2006. Unmanned aerial surveys. Chapter 8, 15pp In: Joint Monitoring Program in the Chukchi and Beaufort Seas, Open Water Seasons 2008.

MacKellar, M.C., McGowan, H.A., Phinn, S.R., 2013. An observational heat budget analysis of a coral reef, Heron Reef, Great Barrier Reef, Australia. J. Geophys. Res. Atmos. 118, 2547–2559.

Marques, T.A., Buckland, S.T., Bispo, R., Howland, B., 2013a. Accounting for animal density gradients using independent information in distance sampling surveys. Statistical Methods and Applications 22, 67–80.

Marques, T.A., Thomas, L., Martin, S.W., Mellinger, D.K., Ward, J.A., Moretti, D.J., Harris, D., Tyack, P.L., 2013b. Estimating animal population density using passive acoustics. Biol. Rev. 88, 287–309.

Meyer, D., 2016. Glider technology for ocean observations: a review. Ocean Sci. Discuss. 26.

Miller, P.J., Antunes, R.N., Wensveen, P.J., Samarra, F.I., Alves, A.C., Tyack, P.L., Kvadsheim, P.H., Kleivane, L., Lam, F.P., Ainslie, M.A., Thomas, L., 2014. Dose-response relationships for the onset of avoidance of sonar by free-ranging killer whales. J. Acoust. Soc. Am. 135, 975–993.

Mordy, C.W., Cokelet, E.D., De Robertis, A., Jenkins, R., Kuhn, C.E., Lawrence-Slavas, N., Berchok, C.L., Crance, J.L., Sterling, J.T., Cross, J.N., 2017. Advances in ecosystem research: saildrone surveys of oceanography, fish, and marine mammals in the Bering Sea. Oceanography 30, 113–115.

Osse, T.J., Eriksen, C.C., 2007. The Deepglider: a full ocean depth glider for oceanographic research. In: OCEANS 2007. IEEE, pp. 1–12.

Pirotta, E., Brookes, K.L., Graham, I.M., Thompson, P.M., 2014. Variation in harbour porpoise activity in response to seismic survey noise. Biol. Lett. 10, 20131090.

Podobna, Y., Schoonmaker, J., Boucher, C., Saggese, S., Oakley, D., Medeiros, D., 2012. Modular Multi-Channel Imaging System for Littoral Observation and Target Detection, Ocean Sensing and Monitoring. IV. International Society for Optics and Photonics, pp. 837202.

Rankin, S., Archer, F., Keating, J.L., Oswald, J.N., Oswald, M., Curtis, A., Barlow, J., 2017. Acoustic classification of dolphins in the California Current using whistles, echolocation clicks, and burst pulses. Mar. Mamm. Sci. 33, 520–540.

Roemmich, D., Johnson, G.C., Riser, S., Davis, R., Gilson, J., Owens, W.B., Garzoli, S.L., Schmid, C., Ignaszewski, M., 2009. The Argo Program: observing the global ocean with profiling floats. Oceanography 22, 34–43.

Rountree, R.A., Gilmore, R.G., Goudey, C.A., Hawkins, A.D., Luczkovich, J.J., Mann, D.A., 2006. Listening to fish: applications of passive acoustics to fisheries science. Fisheries 31, 433–446.

Santhaseelan, V., Asari, V.K., 2015. Automated whale blow detection in infrared video. In: Computer Vision and Pattern Recognition in Environmental Informatics, pp. 58–78.

Selby, W., Corke, P., Rus, D., 2011. Autonomous aerial navigation and tracking of marine animals. In: Proc. of the Australian Conference on Robotics and Automation (ACRA).

Sherman, J., Davis, R.E., Owens, W., Valdes, J., 2001. The autonomous underwater glider "Spray". IEEE J. Ocean. Eng. 26, 437–446.

Sousa-Lima, R.S., Norris, T.F., Oswald, J.N., Fernandes, D.P., 2013. A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. Aquat. Mamm. 39, 23–53.

Sparling, C., Gillespie, D., Hastie, G., Gordon, J., Macaulay, J., Malinka, C., Wu, M., McConnell, B., 2016. Scottish Government Demonstration Strategy: Trialling Methods for Tracking the Fine Scale Underwater Movements of Marine Mammals in Areas of Marine Renewable Energy Development. Scottish Marine and Freshwater

Science, The Scottish Government.

Stevenson, B.C., Borchers, D.L., Altwegg, R., Swift, R.J., Gillespie, D.M., Measey, G.J., 2015. A general framework for animal density estimation from acoustic detections across a fixed microphone array. Methods Ecol. Evol. 6, 38–48.

Suberg, L., Wynn, R.B., van der Kooij, J., Fernand, L., Fielding, S., Guihen, D., Gillespie, D., Johnson, M., Gkikopoulou, K.C., Allan, I.J., 2014. Assessing the potential of autonomous submarine gliders for ecosystem monitoring across multiple trophic levels (plankton to cetaceans) and pollutants in shallow shelf seas. Methods Oceanogr. 10, 70–89.

Thamm, H., 2011. SUSI62 a robust and safe parachute UAV with long flight time and good payload. Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci. 38, C22.

Thamm, H.-P., Ludwig, T., Reuter, C., 2013. Design of a Process Model for Unmanned Aerial Systems (UAS) in Emergencies. ISCRAM.

Verfuss, U.K., Aniceto, A.S., Biuw, M., Fielding, S., Gillespie, D., Harris, D., Jimenez, G., Johnston, P., Plunkett, R., Sivertsen, A., Solbø, A., Storvold, R., Wyatt, R., 2015. Literature Review: Understanding the Current State of Autonomous Technologies to Improve/Expand Observation and Detection of Marine Species.

Verfuss, U., Gillespie, D., Gordon, J., Marques, T., Miller, B., Plunkett, R., Theriault, J., Tollit, D., Zitterbart, D., Hubert, P., Thomas, L., 2016. Low Visibility Real-time Monitoring Techniques Review.

Verfuss, U.K., Gillespie, D., Gordon, J., Marques, T.A., Miller, B., Plunkett, R., Theriault, J.A., Tollit, D.J., Zitterbart, D.P., Hubert, P., Thomas, L., 2018. Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. Mar. Pollut. Bull. 126, 1–18.

Verhoeven, G.J., Loenders, J., Vermeulen, F., Docter, R., 2009. Helikite aerial photography–a versatile means of unmanned, radio controlled, low-altitude aerial archaeology. Archaeol. Prospect. 16, 125–138.

Voegeli, F.A., Smale, M.J., Webber, D.M., Andrade, Y., O'Dor, R.K., 2001. Ultrasonic telemetry, tracking and automated monitoring technology for sharks. In: The Behavior and Sensory Biology of Elasmobranch Fishes: An Anthology in Memory of Donald Richard Nelson. Springer, pp. 267–282.

Warren, V., Marques, T., Harris, D., Thomas, L., Tyack, P., Aguilar de Soto, N., Hickmott, L., Johnson, M., 2017. Spatio-temporal variation in click production rates of beaked whales: implications for passive acoustic density estimation. J. Acoust. Soc. Am. 141, 1962–1974.

Webb, D.C., Simonetti, P.J., Jones, C.P., 2001. SLOCUM: an underwater glider propelled by environmental energy. IEEE J. Ocean. Eng. 26, 447–452.

Weissenberger, J., Blees, M., Christensen, J., Hartin, K., Ireland, D., Zitterbart, D.P., 2011. Monitoring for Marine Mammals in Alaska Using a 360 Infrared Camera System.

Williams, S.B., Pizarro, O., Webster, J.M., Beaman, R.J., Mahon, I., Johnson-Roberson, M., Bridge, T.C., 2010. Autonomous underwater vehicle–assisted surveying of drowned reefs on the shelf edge of the Great Barrier Reef, Australia. J. Field Robot. 27, 675–697.

Wroblewski, J., Bailey, W.L., Howse, K.A., 1994. Observations of adult Atlantic cod (*Gadus morhua*) overwintering in nearshore waters of Trinity Bay, Newfoundland. Can. J. Fish. Aquat. Sci. 51, 142–150.

Wroblewski, J., Nolan, B.G., Rose, G.A., 2000. Response of individual shoaling Atlantic cod to ocean currents on the northeast Newfoundland Shelf. Fish. Res. 45, 51–59.

Wynn, R., Bett, B., Evans, A., Griffiths, G., Huvenne, V., Jones, A., Palmer, M., Dove, D., Howe, J., Boyd, T., 2013. Investigating the feasibility of utilizing AUV and Glider technology for mapping and monitoring of the UK MPA network. In: Final report for Defra project MB0118.

Wynn, R.B., Huvenne, V.A.I., Le Bas, T.P., Murton, B.J., Connelly, D.P., Bett, B.J., Ruhl, H.A., Morris, K.J., Peakall, J., Parsons, D.R., Sumner, E.J., Darby, S.E., Dorrell, R.M., Hunt, J.E., 2014. Autonomous Underwater Vehicles (AUVs): their past, present and future contributions to the advancement of marine geoscience. Mar. Geol. 352, 451–468.

Zitterbart, D.P., Kindermann, L., Burkhardt, E., Boebel, O., 2013. Automatic round-the-clock detection of whales for mitigation from underwater noise impacts. PLoS 8, 1–6.