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LITERATURE REVIEW:

UNDERSTANDING THE CURRENT STATE OF AUTONOMOUS TECHNOLOGIES TO IMPROVE/EXPAND OBSERVATION AND DETECTION OF MARINE SPECIES

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Cover photo: AutoNaut completing a PAM mission. © Peter Bromley.

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4 Executive Summary

4.1 Objectives

This report has been conducted to enhance the understanding of how autonomous vehicle systems can be used to monitor marine mammals and other marine animals in the frame of industrial activities of the oil and gas (O&G) industry. The purpose of such monitoring would be for mitigation measures, to estimate population status and trends in areas of interest, or to conduct fine-scale behavoiural studies to evaluate potential impacts of anthropogenic induced noise on these animals. Key objectives of the report include:

- An exhaustive review and evaluation of available platform and sensor technologies that are most pertinent to oil and gas operations for marine animal monitoring;
- Information on the key data types that can be obtained, addressing the technical challenges of managing, storing and analysing the large amount of data gathered by the autonomous systems; and
- Recommendations of platform technologies, sensors and data characteristics that would be most relevant for the O&G industry.

4.2 Approach

In order to address the objectives, the report provides a comprehensive evaluation of the status and potential of autonomous aerial and marine platforms and sensor technologies that are most pertinent to O&G operations for conducting mitigation monitoring, population surveys and/or tracking of marine animals such as marine mammals, sea turtles and fish. The main platforms and sensors considered in this review are:

- Unmanned Aerial Systems (UAS) including powered aircraft, gliders, kites and lighter-than-air aircraft;
- UAS sensors including thermal IR, Non-thermal IR, RGB and video cameras;
- Autonomous Underwater Vehicles (AUV) and Autonomous Surface Vehicles (ASV) including autonomous propeller driven craft, autonomous underwater buoyancy gliders, autonomous powered surface craft, self powered surface vehicles and drifting sensor packages;
- AUV / ASV sensors including Passive Acoustic Monitoring (PAM) and Active Acoustic Monitoring (AAM) sensors as well as animal-borne transponder tags.

Evaluation criteria and metrics were defined, which were used to evaluate the autonomous systems' applicability and suitability for various monitoring activities. Further criteria allowed the evaluation of potential platform and sensor combinations and considerations to be taken into account during project planning. The information gathered was compiled into matrices to allow a comparison of the different systems' operational capabilities, data processing and transfer aspects and their potential for mitigation monitoring and survey data collection. Further information was compiled and summarised to provide further insights into the following topics:

- Requirements of autonomous vehicles for marine animal monitoring;
- Current knowledge about autonomous vehicles;
- Operational aspects to consider;
- Regulatory / political barriers;

- Technical challenges of managing, storing and analysing large amount of data.

4.3 Outcome

The report illustrates that it is not possible to give simple 'one-size-fits-all' suggestions for choosing the appropriate autonomous vehicle to conduct different kinds of monitoring applications, as there are many project dependent factors that need to be considered. The large variety of target species requires the selection of the appropriate sensor type/platform type combination (rather than a specific system). The same is true for the different monitoring types (mitigation monitoring, density monitoring, focal-follow), combined with the choice of data relay system. Larger and more complex systems are generally more capable, but are likely to be more expensive and require greater supporting infrastructure. The technical and operational details of an autonomous platform will need to be tailored to the specific needs of the exploration and production (E&P) project, e.g. the area of interest, the properties of the platform that the autonomous vehicle will deployed from, the required survey length, project budget and more. Here we will give an overview of which platform types are best to use for various monitoring types by comparing each class of platform and highlighting their particular strengths relating to the specific monitoring types.

Once the details of an E&P project are known, the comparison and evaluation matrices in this report will then help to select the appropriate platform / sensor combination, and the discussion section will help to understand how well that system will address the task in hand. The establishment of a computer-based expert system based on this review and the preceding review on low visibility monitoring techniques as published in Verfuss et al., (2016) would be a helpful and appropriate tool to handle the vast amount of information gathered. This expert system should be based on the evaluation criteria established in both reviews, and should provide a list of the most appropriate systems and methods as an output based on the monitoring requirements fed into the expert system. The establishment of such a tool was, however, outside the scope of this review.

4.3.1 UAS

UAS have recently been introduced as alternative platforms to overcome some of the limitations of manned-aerial surveys, mainly for their ability to perform the same tasks more efficiently, safely, and at a fraction of the cost (Neininger and Hacker, 2011). Recent developments have turned present-day UAS into realistic alternatives to manned systems, such as longer flight durations, improved mission safety, flight repeatability due to improved autopilot systems, and reduced operational costs when compared to manned aircraft. The potential advantages of an unmanned platform, however, depend on factors such as aircraft flight capability, sensor type, mission objective, and current regulatory requirements for operations of the particular platform (Watts et al., 2010a). In recent years, UAS have been integrated into a variety of field studies involving a range of species and applications. However, there has been little focus on the application of these systems with a more O&G industrial approach, concentrating on their benefits for e.g. monitoring for mitigation purposes and their integration with other autonomous technologies (e.g. coordination of unmanned aerial, surface, and underwater vehicles to create a communication network that is capable of simultaneously surveying the same area using a variety of sensors in order to maximise the chances of detection and for data cross-validation between platforms).

The variety of UAS configurations currently available is a great advantage for offshore monitoring. Smaller platforms allow coverage of smaller areas at a low cost (e.g. exclusion zones during seismic operations), and larger platforms allow coverage of larger areas, providing valuable information both before, during, and after offshore operations. Hence, it is possible to cover a wide range of projects using different UAS models. Unfortunately, the complexity of the larger systems requires multiple experienced personnel to operate them and many of the systems are currently only available for military use. Larger platforms may also require runways similar to those required by manned-airplanes, which limits the possibility for deployments at sea. Conversely, the performance of smaller platforms may be limited by environmental conditions and payloads are limited, meaning that they may only be able to carry less sophisticated sensor equipment and / or operate for shorter periods of time.

Of the three classes of UAS platforms considered in this review, powered aircraft have many of the capabilities required for aerial surveys of marine animals. Kites and lighter-than-air aircraft, such as balloons, are cost-saving alternatives to some fixed and rotary wing systems, though they rely heavily on weather conditions and are difficult to control when following a predefined track. In terms of individual focal follows, however, lighter-than-air aircraft should be considered as a potential candidate platform, though their ability to follow animals will be restricted to the manoeuvrability of the support vessel to which they are tethered. Powered aircraft are good candidate platforms for individual-based monitoring as they can be piloted to follow animals (though fixed-wing systems may struggle to hover above stationary, or slow moving, focal animals), while kites have limited control. UAS are also suitable for mitigation monitoring provided they have real-time detection options. With long operational ranges, they are especially suited for monitoring the area ahead of a seismic vessel in order to detect marine animals within an exclusion zone around the anticipated start location of the sound source, as suggested by Verfuss et al. (2016).

This study makes the following short list of requirements for a UAS monitoring system: stabilised high-resolution video for detection, high resolution images for identification, real-time geocoding of image data and a computer system for efficient analysis of recorded data. If the data are to be transmitted to the ground, as needed for mitigation monitoring, a high bandwidth data link is also required.

4.3.2 AUV and ASV

Autonomous Underwater and Surface Vehicles (AUV and ASV) are divided in this report into five main categories: propeller driven underwater craft, underwater buoyancy gliders, powered surface vehicles, self-powered surface vehicles and drifters. The vehicles range from relatively small size, which can be lifted by one or two persons and deployed from shore or a small inflatable, to large diesel-powered surface vessels with bespoke launch and recovery systems (Griffiths, 2002). Many surface and underwater autonomous vehicles are now used on a regular basis by research institutions world-wide. Primarily, they are used for the collection of oceanographic data (e.g. sea surface or water column temperature and salinity for instance) while the detection of larger organisms, such as marine mammals and fish, generally remains a niche area of research. Powered underwater and surface vehicles have the advantage of greater control, but generally have limited deployment times (often hours to days). Buoyancy driven systems are generally small enough to be deployed manually from a small vessel and are capable of multi-month missions, giving them great potential for long term population monitoring. Wave driven systems tend to be slightly larger but can still often be deployed and recovered using modest facilities. The lowest cost systems are drifters, which have no control over where they go, but could be a cost-effective way of collecting large data samples.

A variety of active and passive acoustic sensors are available, which either have been, or have the potential to be, integrated into these platforms. While not every sensor is suitable for every platform, for each platform, there is at least one sensor which might be incorporated into it and vice-versa. A number of Passive Acoustic Monitoring (PAM) sensors are able to run automatic detection algorithms to automatically pick out marine mammal calls. However, these generally need checking by a human operator before they can be used in management decision making, so considerable quantities of PAM data must either be stored on the device for future analysis or transmitted to an operator if they are required in real-time. Solutions exist which can transport sufficient data over short ranges for real-time operation even for high frequency data. Most systems reviewed here only deploy a single hydrophone and are incapable of directly measuring bearings or ranges to detected sounds.

Automatic processing for Active Acoustic Monitoring (AAM) is less advanced than for PAM, with data generally being stored for future analysis. As with PAM, it should be possible to transmit sufficient data over short distances for real-time decision making. It is also possible to attach acoustic tags to target animals to identify and track individuals in real time with a receiving PAM system on an ASV or AUV. Obviously, a key requirement is that the animal is tagged in the first place.

The main restrictions governing the use of AUV and ASV for mitigation monitoring in the vicinity of seismic survey vessels are operational. The deployment of an autonomous vehicle close to an operational seismic survey vessel carries the risk that the vehicle may interfere with seismic operations and the industry would need to be willing to accept this risk when deploying an autonomous surface or underwater vehicle ahead of the survey vessel. It is therefore unlikely that AUV and ASV will have a role in monitoring around seismic vessels in the near future. On the plus side, seismic vessels have many competent technical personnel on board and the potential to deploy, service and operate autonomous platforms; however, depending on the circumstances there may not be room on board either for additional equipment or personnel required to operate autonomous platforms. AUV and ASV may have a role to play monitoring further ahead of seismic vessels as an aid to forward planning. This may be important in sensitive areas where PAM on the ASV / AUV could enhance detection capability of baleen whales and prompt mitigation monitoring by, for instance, thermal imaging. Additionally, ASV and AUV may be important when mitigating around static sources, such as rig operations where space for equipment and personnel may be limited. This might be of particular interest with regard to the use of explosives (such as for well-head decommissioning or removal of unexploded ordnance UXO) due to the clear requirement to remove personnel from the vicinity.

The long mission durations offered by self-powered surface vehicles and buoyancy gliders makes these systems particularly appealing for long term population monitoring. The choice of vehicle would depend on the characteristics of the area to be surveyed (e.g. size, water depth and current strength). For population monitoring, data need not be transmitted in real time, but can be archived to storage media. A particular advantage of low power vehicles for PAM is the low noise produced by the system itself, and more importantly, the consistency of noise between platforms. The main limitations to the use of this technology for population monitoring are the same as for vessel based acoustic surveys, namely the need to understand detection probability for different species as a function of range from the detector and the need for required behavioural data (e.g. group sizes or cue production rates) so that counts of animal detections can be translated into animal density estimates. The lower noise and mission duration capabilities of low power surface vessels also suggest an additional future role, not in mitigation, but in underwater sound measurement for verification of sound levels emitted from sound sources in the frame of E&P activities.

4.3.3 Future work

Autonomous systems have the potential to detect a wide variety of species in different operational scenarios. The primary limitations on the use of autonomous technologies during mitigation in the vicinity of seismic vessels are operational. If there is a desire on the part of industry to overcome these problems, then suitable engineering and environmental science teams both, inside and outside of industry, will need to further assess and find solutions to these quite significant problems. For population monitoring, technologies exist which can collect data for a wide range of species and development should be tailored to specific species groups and operational areas since this will guide the choice of technology. For specific scenarios, the cost and benefit of using autonomous vehicles should also be compared with more traditional methods of data collection (e.g. vessel or aerial visual survey).

Where multiple technologies have the potential to detect a particular species, we recommend that side-by-side comparisons should be conducted between current monitoring methods (e.g. visual vessel based or aerial surveys) and different autonomous solutions. This is valuable for evaluating the degree to which the data acquired by these technologies can be complementary. Particularly in the case of PAM, simultaneous deployments of various systems can help to estimate the detection probabilities of a given system by using the other platforms to conduct “trial-based” detection probability estimation. This would, however, demand a high degree of control over the conditions in which the equipment is deployed and a study may need to run for some time to obtain statistically useful sample sizes; nevertheless, it would be required to fully understand the relative capabilities of all these systems.

Real-time decision making and analysis of large data sets inevitably require the use of automatic detection algorithms for all sensor types. Automatic detection both reduces the amount of data that need to be checked by a human operator, and makes it more practical to send the data through lower bandwidth data relay systems. The development of detection algorithms is further advanced for PAM than for video and AAM, in most situations. Therefore, AAM and video future research should focus on developing detection algorithms and data compression techniques for returning summarised and/or raw data over low bandwidth communications. However, while detection and classification algorithms will always continue to improve, it must be understood that they will never be perfect and will continue to require a human operator at some point in the processing chain. This fundamental limitation should be taken into account as we move forward with developing these systems. While we would not suggest that further research into algorithms for automatic detection is not worthwhile, 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 also of high importance.

Finally, behavioural information on many marine animal species forms a huge data gap. Auxiliary behavioural data relating to the study species (e.g. group size, dive duration or call production rate) are required for abundance estimation and/or mitigation (in both cases where understanding probability of detection is crucial). Therefore, continued behavioural studies of all species of interest will be important for successful surveying and monitoring.

5 Quick guide for prospective users

Anyone wishing to use the information provided in this review to find an appropriate platform/sensor combination should start by answering the two questions below to narrow down the list of candidate technologies (see also Figure 1). Beneath each question, we point to the sections, figures and tables that contain background information, the important criteria and metrics as well as where to find information to address the most important points that need to be considered when deciding on the appropriate platform or sensor. An overview of the strengths and weaknesses of the different platforms is given in section 8.3.2.

When the most suitable platform and sensor type has been identified, and a short-list of the systems most suitable for the specific monitoring task is specified, the possible platform / sensor combination is mainly determined by the payload capacity of the platform (Table 17) and the operational size and weight of the sensor (Table 20). An overview of potential platform/sensor combinations is given in Table 29 and Table 30. The data relay class and system that should be used can be determined by reading section 8.1.4 and consulting Table 27 and Table 28, bearing in mind that operational size and weight need to fit the payload of the platform.

From this final short list of platforms, sensors and data relay systems, the final decision is dependent on the users demand and limitations, e.g. limited manning requirements (manning requirements information for platforms => Table 18, for sensors => Table 25) or limited budget (costs of platforms =>Table 15, sensors => Table 21, relay systems => Table 28). Once the platform, sensor and data relay systems have been selected, it is advisable to contact the corresponding suppliers (=> Table 31) to confirm the suitability of the chosen system for the demanded tasks and to retrieve potential updates on the information gathered in this review, as this is a rapidly developing field.

Q1: What kind of monitoring should be conducted?

a) Mitigation monitoring

- Most important points to consider:
    - Real-time detection of the animal of interest is obligatory, therefore only sensors with real-time options are appropriate (=> Table 23)
    - A high detection likelihood of the animal is required, which influences the choice of the sensor (=> Q2). Concurrent use of different methods increases the detection probability
    - Operational period and range need to be sufficient to meet the temporal and spatial requirements of the monitoring (=> Table 13)
    - Manoeuvrability is important to keep within the monitoring area (=> Table 16), which excludes drifters for the use of mitigation monitoring

    - In operationally busy areas, AUV and ASV are not recommended due to the risk of collision and entanglement with operational gear
    - Synchronised operation of a fleet widens the field of view and allows to cover a larger area (section 9.2.1)
- Requirements: section 9.1.1
- Which platform type to use: section 8.3.3, Figure 1, Table 4
- Criteria and metrics to consider: section 8.1.2
- Background information: section 7.1.1

b) Population survey

- Most important points to consider:
    - Operational period, speed and range need to be sufficient to meet the temporal and spatial requirements of the survey (=> Table 13), which excludes most powered systems for long-term monitoring
    - Track keeping is important, at least for short-term surveys (=> Table 16)
- Requirements: section 9.1.2
- Which platform type to use: section 8.3.4, Figure 1, Table 4
- Criteria and metrics to consider: section 8.1.1
- Background information: section 7.1.2

c) Focal-animal study

- Most important points to consider:
    - Tracking of the focal animal is required. System choice depends on the sensor capabilities to estimate bearing and range to the animal during stationary focal follows (i.e. animal is tracked within sensor's view) (=> Table 22) and the tracking ability of the platform during mobile focal follows (i.e. platform follows animal) (=> Table 16)
    - Manoeuvrability is important during mobile focal follows (=> Table 16)
    - Operational period, speed and range need to be sufficient to meet the temporal and spatial requirements (=> Table 13)
- Requirements: section 9.1.3
- Which platform type to use: section 8.3.4, Figure 1, Table 4

- Criteria and metrics to consider: section 8.1.1
- Background information: section 7.1.3

Q2: What kind of animal needs to be monitored?

a) Species regularly seen at or near the sea surface

- Sensor: Electro-optical imaging sensors (section 7.3.1)
- Animal types: Whales, dolphins/porpoises, seals, turtles, large solitary fish (e.g. basking sharks), swarm fish (specified for sensor systems in Table 22)
- Detection probability: increases with time spent at or near sea surface
- Most suitable platform(s) = UAS

b) Species in the water column

- Sensor: AAM sensors (section 7.3.3)
- Animal types: Whales, dolphins/porpoises, seals, turtles, large solitary fish (e.g. basking sharks), swarm fish (specified for sensor systems in Table 22)
- Detection probability: increases with size of animal or animal school
- Most suitable platform(s) = AUV/ASV

c) Species with frequent and distinctive vocalisations

- Sensor: PAM sensors (section 7.3.2)
- Animal types: Whales, dolphins/porpoises (specified for sensor systems in Table 22)
- Detection probability: increases with increased vocalisation rate and/or vocalisation duration
- Most suitable platform(s)= self-powered AUV/ASV, powered AUV/ASV with low self-noise

d) Animals suitable for tagging

- Sensor: Animal-born transponding acoustic tags in combination with a hydrophone (section 7.3.4)
- Animal types: Whales, dolphins/porpoises, seals, turtles, large solitary fish (e.g. basking sharks), swarm fish (specified for sensor systems in Table 22)
- Note: animal needs to be actively tagged; only suitable for focal-animal studies
- Most suitable platform(s) = self-powered AUV/ASV, powered AUV/ASV with low self-noise

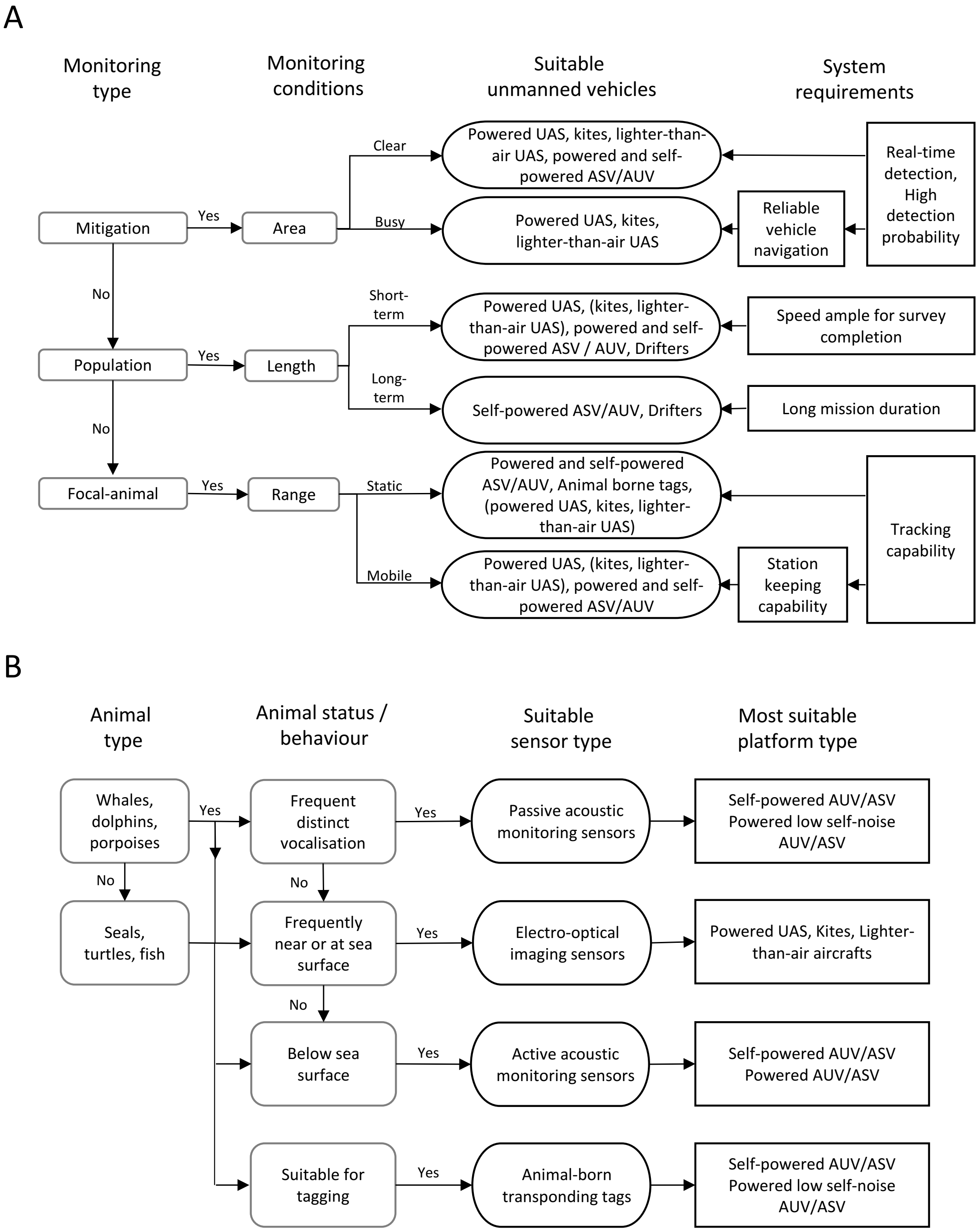

Figure 1. Decision tool for finding the appropriate platform/sensor combination for a specific monitoring task and animal type. The monitoring types are divided into Mitigation monitoring in areas either clear from or busy with other operational gear or traffic, Population monitoring in the short-term (hours, days) or long-term (weeks, months) and Focal-follows conducted with static or mobile systems. Answering questions Q1 (which monitoring type should be conducted) with diagram A and Q2 (which type of animal needs to be monitored) with diagram B will highlight the most important system requirements and the animal behaviour potentially triggering detection, leading to the sensor / platform combination best suited for a specific monitoring task.

6 Project framework and approach

This report was funded by the International Association of Oil & Gas Producers following the Request for Proposals (RFP) Number JIP III-15-02 "*Autonomous Aerial and Marine Technology Understanding - Literature review on understanding the current state of autonomous technologies to improve/expand observation and detection of marine species*" from the Joint Industry Programme on E&P Sound and Marine Life - Phase III, released on 24th February 2015.

The objectives outlined in the RFP were to enhance the understanding of how autonomous vehicle systems can be used for mitigation and impact monitoring and for estimating population status and trends.

Key objectives of the RFP included:

- An exhaustive review of available UAS and AUV platforms and sensors technologies that are most pertinent to oil and gas operations for monitoring of marine species, including details on cost of systems and sensors, current state of technology maturation, sensor performance, system lifespan, limits to operating conditions (weather, depth, currents, etc.), along with relevant references to field tests, sources of cited data and key points of contact for each system.
- Key data types (e.g. digital photographs, digital sound files, oceanographic data, e.g. temperature, salinity, depth, currents, bathymetry, GPS locations, etc.) and the data's potential uses for assessing the effects of oil and gas industry exploration and production (E&P) as well as geophysical operations (e.g. seismic surveys) on marine species. Technical challenges of managing, storing and analysing large amount of data produced by the autonomous systems should be addressed.
- Recommendations of platform technologies, sensors and data characteristics that would be most relevant for the E&P industry to pursue, either via further advancement of technology development or field trials of existing promising systems, including combinations of sensors/platforms best suited to particular species, geographic, and operational conditions.

SMRU Consulting teamed up with the Sea Mammal Research Unit (SMRU), Akvaplan-niva AS, the Northern Research Institute (NORUT), the Centre for Research into Ecological and Environmental Modelling (CREEM), Seiche Ltd and British Antarctic Survey (BAS) to form a team of highly experienced experts in the field of marine autonomous technologies and marine animal monitoring to undertake a comprehensive review on the status and potential of aerial and marine autonomous technologies for conducting marine animal mitigation monitoring and/or population surveys as well as monitoring animal movement and behavioural reactions.

The project team conducted an extensive literature review and information search combined with contacting suppliers and developers where the relevant information was not publically available. The literature search focused on specific information as requested by the RFP and outlined in this report, and criteria important for evaluating key features of the systems, such as

- platform applicability during E&P operations,
- operational requirements,
- data processing and transfer capabilities,
- platform ability to
    - conduct mitigation monitoring,
    - collect appropriate survey data for animal population monitoring,
    - monitor animal movement and behavioural reactions.

A subsequent evaluation of the gathered material provided a review of the state of the art of autonomous aerial and marine platforms and sensor technologies. Operational issues and data processing and transfer capabilities were reviewed and a comprehensive evaluation of the systems for impact monitoring and survey data acquisition was undertaken. This review identified knowledge gaps and areas for further development and research leading to recommendations on future studies.

The main platforms and sensors considered were :

- Unmanned Aerial Systems (UAS) including powered aircraft, gliders, kites and lighter-than-air aircraft (e.g. balloons);
- UAS sensors including thermal IR, Non-thermal IR, RGB and video cameras;
- Autonomous Underwater Vehicles (AUV) and Autonomous Surface Vehicles (ASV) including autonomous propeller driven craft, autonomous underwater buoyancy gliders, autonomous powered surface craft, self powered surface vehicles and drifting sensor packages;
- AUV / ASV sensors including Passive Acoustic Monitoring (PAM) and Active Acoustic Monitoring (AAM) sensors as well as animal-borne tags.

The report provides a short introduction into the different monitoring types considered in this review (section 7.1) as well as the considered autonomous platforms (section 7.2) and sensor types (section 7.3). The report then defines and explains the different criteria and metrics for the evaluation of the systems (section 7.1), gives the results of the evaluation (section 7.2) and discusses these (section 7.3).

In addition to the evaluation of the different systems, further information was compiled and summarised to provide insights into the following topics:

- Requirements of autonomous vehicles for marine animal monitoring (section 8.1);
- Current knowledge on autonomous vehicles (section 8.2);
- Operational aspects to consider (section 8.3);

- Regulatory / political barriers (section 8.4);
- Technical challenges of managing, storing and analysing large amount of data (section 8.5).

The appendix contains:

- Tables with the definitions of the criteria and metrics (section 10.1);
- Shortlists of platforms and sensors (section 10.2);
- Comparison (section 10.3) and evaluation (section 10.4) matrices;
- Supplier contacts (section 10.5);
- An explanatory section on surveying wildlife populations (section 10.6).

7 Introduction

Industrial activities that involve pile driving (such as the construction of offshore wind farms or oil-rigs) or activation of sound sources (such as seismic surveys) often involve the introduction of anthropogenic sound energy into the water. Concern has grown that underwater sound has the potential to impact marine mammals and other marine animals, which may result in auditory injury and/or behavioural changes (Gordon, 2003; Ketten, 1995; Lucke, 2009; Pirotta, 2014). There is a demand to increase monitoring efforts in order to contribute to baseline data for the region of interest as well as to assess and minimise anthropogenic impact on marine animals. Methods are required that can effectively be used for real-time or near real-time monitoring for timely decision making during operational environmental risk management and permit compliance (mitigation monitoring), for monitoring individual animal's response to direct impacts (focal-follows), and for exploring population size and distribution (population monitoring). Sound may influence marine animals at ranges that cannot be monitored from the immediate vicinity of an operational site. The use of autonomous vehicles for mitigation monitoring, population monitoring or focal-follows therefore represent potential advantages for such applications. Such vehicles can be deployed in the air (UAS) or in the water (AUV, ASV), and are therefore suitable for the detection of marine animals at the sea surface and underwater; Vehicles' applications reduce health and safety risks to human operators; and they can operate at long ranges far beyond the animal detection ranges of human observers. UAS platforms include powered aircraft, gliders, kites and lighter-than-air aircraft, which will mostly be used with sensors such as thermal infra-red (IR), non-thermal IR, Red Green Blue (RGB) and video cameras. AUVs include underwater buoyancy gliders and propeller driven craft, but exclude remotely operated vehicles (ROV), which are tethered underwater craft, from our definition of AUV. ASV include powered surface craft as well as self-powered surface vehicles and drifting sensor packages. For AUV and ASV the relevant sensors for marine animal monitoring with regards to E&P activity include Passive Acoustic Monitoring (PAM) and Active Acoustic Monitoring (AAM) sensors as well as animal-borne tags. IR, RGB and video cameras can be deployed on AUV and ASV, however are not useful for the kind of monitoring considered in this review due to their extremely low underwater visible range (unless in very clear waters).

In the following, the different types of monitoring methods relevant for marine animal monitoring with regards to E&P activities as well as the different types of platforms and sensors are described to provide background information on the topics discussed within this review.

7.1 Monitoring types

7.1.1 Mitigation monitoring

Mitigation monitoring is often required where anthropogenic activities involve the emission of sound that may impact marine vertebrates. It aims for a timely detection of marine animals within a pre-defined area around a sound source to allow for mitigation measures to be taken. Both the animal species and the size of the area to be monitored depend on the regulations that are to be met by the specific operation. For example, guidelines for the implementation of marine mammal mitigation during anthropogenic activities such as seismic surveys are often country specific. Most guidelines require monitoring for all marine mammals, though sometimes monitoring requirements are only in place for specific sub-groups (e.g. baleen whales, larger toothed whales, cetaceans) or specific species. Sea turtles, polar bears and walrus may also be of concern. The area that requires mitigation monitoring ranges from 500 m to 3,000 m and beyond, and also depends on the regulations. This area may include the exclusion zone only. The *exclusion zone* is the area within which mitigation measures have to be taken upon an animal sighting. Some regulations request the monitoring of a larger area around the exclusion zone for ensuring a timely detection of an animal before it enters the exclusion zone. The total area to be monitored (including the exclusion zone) is hereafter referred to as the *monitoring zone*. Another point to consider is the duration of the mitigation monitoring. Monitoring needs to be started a minimum of 30 minutes before the actual operation starts. Some guidelines specify a requirement for monitoring of 60 minutes or 120 minutes before the operation starts, depending on the situation or species of concern. For a comprehensive review of the guidelines please see Verfuss et al. (2016).

Marine mammal (and other animal) mitigation monitoring is traditionally performed by Marine Mammal Observers (MMOs) or Protected Species Observers (PSO) visually scanning the sea surface of the monitoring zone to detect target species. The MMO/PSOs are located either on the operating vessel or on satellite vessels accompanying the operation. To increase the probability of detecting some species, visual monitoring is often accompanied by acoustic monitoring with PAM systems. Thermal imaging systems have also been used, especially for the detection of animals in situations of low visibility, when MMO/PSOs will not be able to conduct visual monitoring e.g. due to lack of light. Imaging systems to date have been operated from vessels.

7.1.2 Animal population surveys

Surveys can aim to answer a wide range of questions about a population of interest. In this report, we focus on a few (linked) applications of relevance to the O&G industry: estimating absolute population abundance or density, assessing the spatial distribution of populations and how this may change over time and, finally, assessing behavioural responses to anthropogenic impacts. These applications are linked because spatial and/or temporal changes in the size and/or distribution of a population (which may be caused by anthropogenic factors) are typically best quantified by investigating changes in absolute abundance or density. Therefore, survey requirements to estimate absolute abundance or density will be initially considered before outlining what would also be required to detect spatial and temporal changes in these metrics over an area of interest for a species of interest, and identify whether any detected changes are due to anthropogenic impacts.

Marine mammal population sizes have been traditionally estimated using sightings data collected from vessel- or aerial-based surveys (e.g. Garner et al., 1999). In recent years, passive acoustic data have been increasingly collected from both vessel-towed instruments and static instruments (either fixed to a surface buoy or the seafloor), which have been used to estimate animal density or abundance (Marques et al., 2013b). Approaches to estimate fish population sizes include (1) conducting dedicated stock assessment surveys, (2) monitoring catch-per-unit-effort data or (3) tagging individuals with active acoustic tags that can be detected using passive acoustic receivers (Hilborn and Walters, 1992). However, the latter abundance estimation methods rely on catching fish. Active acoustic monitoring using echosounders (Simmonds and MacLennan, 2005) is an alternative approach for using distance sampling methodology that does not require animals to be caught and the collected data can readily be analysed in a similar framework to visual and passive acoustic survey data (e.g. see Cox et al., 2011 for a krill example). Larger fish, such as whale sharks and tuna, can also be surveyed from aircraft (e.g. Rowat et al., 2009; Bauer, 2015). Turtles are commonly visually surveyed from vessels and aircraft (e.g. Benson et al., 2007; Bresette et al., 2010), though land-based counts at nesting beaches and in-water methods using snorkelling observers also exist (e.g. Weber et al., 2013; Stadler et al., 2014). In recent years, the use of active acoustics to monitor turtles has been investigated. Turtles have been fitted with active acoustic transmitting tags (Thums et al., 2013) and the ability to use echosounders to detect turtles has also been recently explored (Pérez-Arjona, 2013).

Whether collecting sightings or acoustic (either active or passive) data during wildlife surveys, the aim is often to estimate the total number of animals in a given area based on some form of encounter with an animal, or group of animals and the movements of these animals. Numbers of visual or acoustic encounters are sometimes presented as indices of relative abundance or density. However, in order to link any spatial or temporal patterns present in such indices to changes in the underlying abundance or distribution of animals, it must be assumed that an equal proportion of animals remain undetected across space and time. This is a very strong assumption to make and, therefore, statistical data analysis methods have been developed that correct observed data for undetected animals, leading to absolute estimates of animal abundance or density (Borchers et al., 2002) (see section 11.6.1 for detailed information).

Surveys typically take place along planned survey transects or from static monitoring points. In some surveys, it may be possible to detect all animals within the transect lines or points. Such survey types are known as strip transect sampling (using transect lines) or plot sampling (using points). When animals are suspected to be missed within surveyed areas, there are several methods that can be used to estimate the probability of detection (detailed in section 11.6.2).

Once estimated, density and abundance estimates can be used to investigate spatial and temporal changes in animal distribution and population size. Spatial maps of animal abundance can be produced using density surface modelling (Miller et al., 2013; Borchers and Kidney, 2014), which can be used to assess potential impacts of anthropogenic activity (Scott-Hayward et al., 2013; Buckland et al., 2015). Time series of density or abundance estimates can be used in trend analyses, if sufficient data are available (Thomas et al., 2004). Power analyses can be conducted to assess the amount of data required to detect significant temporal and spatial trends in density or abundance across time (Thomas et al., 2004).

7.1.3 Focal-follows

There may be a requirement to assess potential anthropogenic impacts at a finer resolution by studying individual animals. Focal animal surveys have different attributes to population-focussed surveys. Conducting individual-based surveys of marine mammals, turtles and fish requires focal animals to be detected, assessed and tracked. Reactions of tracked animals to specific sounds (e.g. in play back experiments) or other stimuli can then be assessed (e.g. Antunes, 2014l; Miller, 2014). Marine mammals, turtles and fish have all been tracked using telemetry devices (e.g. marine mammals: Curé et al., 2015; turtles: Kobayashi et al., 2008; fish: Block et al., 2005), and visual focal follows of marine mammals are regularly conducted from vessels (e.g. Karniski et al., 2014). Marine mammals can also be tracked using passive acoustic monitoring whilst they are acoustically detectable (e.g. Gassmann et al., 2015), and underwater video has been used to monitor individual turtles and fish (turtles: Smolowitz et al., 2015; fish: Mellody, 2015).

7.2 Autonomous platform types

7.2.1 Powered aircraft (UAS)

Powered aircraft can either fly autonomously or be piloted remotely (Figure 2). The equipment can be launched from different platforms using, for example, catapult systems and recovered by using a hook and net system when deployed from a ship, or by landing on a flat surface when deployed from land or ship. The aircraft will autonomously follow the designed track based on prior uploaded flight plans, often relying on pilots for take-off and landing only. A ground station plays a key role in mission execution and planning, as it allows for control and monitoring of the aircraft and payload, and uploading and updating waypoints and flight plans before and during the flight. A typical ground station will have a telemetry link to the aircraft for monitoring and control, a visualisation of the aircraft and the flight plan and the ability to alter the flight plan during the mission. Here, we include fixed-wing systems and Vertical Take-Off and Landing (VTOL) systems. VTOL systems are gaining attention for their flexibility in deployment and recovery, which overcome some of the limitations of fixed-wing systems. VTOL unmanned aircraft categories include Multi-copters/Multi-rotors, Quadcopters, Hexacopters, Octocopters, and specialised Fixed-wing systems with multi-rotors installed which can be used for both take-off and landing. In general, the system payload is dependent on the size of the aircraft, with larger aircraft supporting heavier sensor systems such as single lens reflex (SLR) cameras and/or multi-spectral and thermal sensors. These systems can be valuable during animal surveys for E&P activities which heavily rely on the camera quality, maximum altitude and flight time (Koski et al., 2009a).

Figure 2. Examples for UAS: Left picture: Skyprowler UAS ©Krossblade Aerospace, right picture: Landing of CryoWing UAS. Photo by NORUT.

7.2.2 Motorized gliders (UAS)

Motorized gliders are a special class of fixed-wing aircraft capable of turning off the engine and performing (parts) of the flight through soaring on rising air. Unmanned gliders are rare, and are only used for specific scientific research in meteorology or atmosphere science, or military purposes (gliding bombs). As the column of air above an ocean can be regarded as a sink zone (which is the absence of weak atmospheric thermals to push the aircraft upwards or maintain altitude), motorised gliders are considered impractical for marine animal studies and monitoring in relation to E&P activities.

7.2.3 Kites (UAS)

Kites, which are essentially small parachutes (Figure 3), consist of a steel frame with an engine and parachute wing. These systems are easy to transport and are able to carry still, video and/or multi-spectral and thermal sensors. They can also operate with auto-pilot and conduct full coverage of the surveyed area with image overlap. However, this equipment can only be operated in wind speeds under 6 m/s, which may limit the locations in which they can be used. Adding to the dependency in environmental conditions, this equipment is often not stabilised, resulting in difficulties in hovering over an object or location of interest. This type of platform has been successfully used in Europe, Africa and Australia mainly for mapping, agriculture and forest management (Thamm, 2011). The limited amount of scientific literature concerning the applications of these systems in monitoring during offshore operations may indicate the lack of tests conducted. This is possibly associated with the weather limitations of this equipment. However, combined kites with lighter-than-air aircraft seem to have become a popular alternative (e.g. MacKellar et al., 2013; Verhoeven et al., 2009). These combined systems, so called "kitoons" have the qualities of both systems with few of their limitations. Though tethered, they are able to endure stronger winds while keeping a relatively stable position due to their balloon body and attached sail, which highlights their potential for marine data acquisition.

Figure 3. Kite SUSI 62 take-off. Photo by Thamm, 2011.

7.2.4 Lighter-than-air aircraft systems (UAS)

Lighter-than-air aircraft systems (blimps or balloons, Figure 4) consist of a buoyant gas-filled balloon (e.g. helium or hydrogen) with a connection to support imagery payload with straight-down or tilted views. The tethered balloon is then connected and towed by a vessel (Hodgson, 2007). The main difference between a blimp and a balloon is the lack of a tethering system in blimps, which makes them less stable in harsh weather conditions but enables them to conduct independent flights without relying on a support vessel. The required size of a blimp is dependent on the payload weight needed. Operating a smaller and lighter payload reduces the costs by minimising the amount of helium required, but may result in lower image quality. A mechanism to determine distance is not yet incorporated in these pieces of equipment (Hodgson, 2007). However, the systems are capable of carrying GPS technology that may improve position accuracy and estimate distance to the target object.

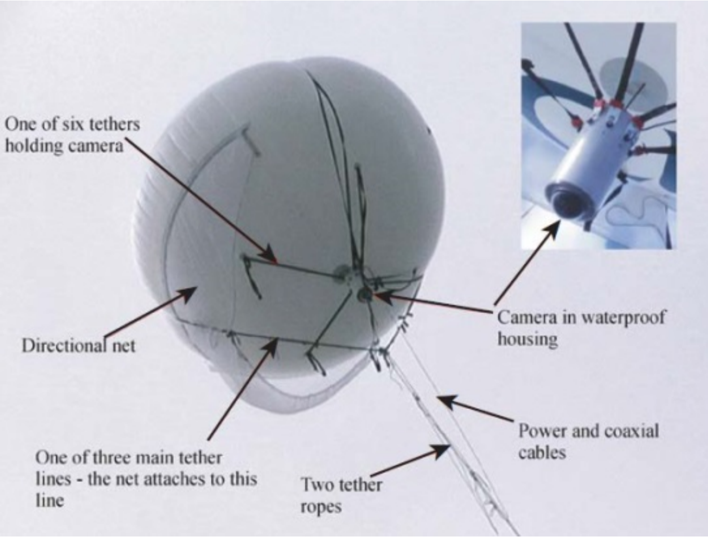

Figure 4. The lighter-than-air craft system "blimp-cam" and components necessary for flights. Photo by Hodgson, 2007.

7.2.5 Propeller driven underwater craft (AUV)

Propeller driven underwater craft are generally relatively small automated vehicles (see Figure 5), manoeuvrable in the water column in three dimensions by an on-board computer. Although these systems are normally deployed from a vessel, they are not physically linked to it (untethered) and perform the data collection in an autonomous manner (Wynn et al., 2013).

Most propelled AUV follow a traditional torpedo shape, which offers the best compromise between size, usable volume, hydrodynamic efficiency and ease of handling (Vijay, 2011). Other shapes found in propelled AUV are teardrop, oblate, rectangular or open space frame (typically twin-hull). They range in size from a portable lightweight AUV to large diameter vehicles over 10 m length (Vijay, 2011). The vehicle typically follows a precise pre-programmed course and can operate for periods of a few hours to several days in most environmental conditions. Some navy-developed models have been controlled via bidirectional radio or acoustic data links and some have been programmed to make "smart" navigation decisions based on their own sensor data. Propelled AUV operate in cruise mode (automated), collecting data while following a pre-planned route at speeds between 1 and 4 knots (Vijay, 2011). Travelling speeds of the propelled AUV are comparable to tidal currents, which can produce navigational drift and thereby affect the data quality. This makes propelled AUV less suited to shallow water operations (Wynn et al., 2013). Most propelled AUV can operate at depths of over 200 m, with some models able to reach 6,000 m depth. Propelled AUV keep a linear trajectory through the water, which is essential for seabed mapping and sub-bottom profiling. However, for optimal manoeuvrability, the weight and balance of a given AUV craft is a significant consideration.

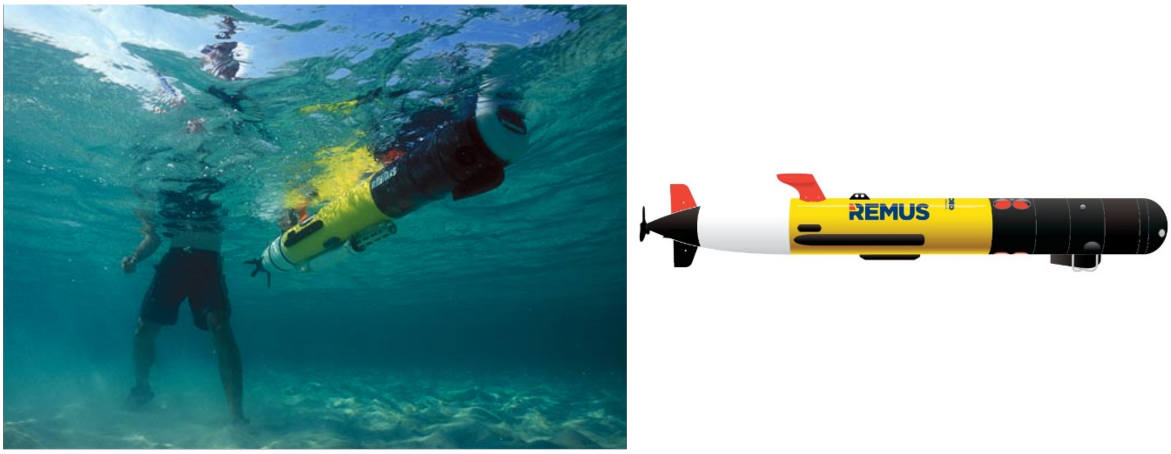

Figure 5. Propeller AUV REMUS 100 in a field study (left, by Anrey Shcherbina, WHOI) and detail of the model (right, Kongsberg Maritime website).

Propeller based thrusters, particularly Kort nozzles, are the most common propulsion systems used in AUV. These thrusters are usually driven by electric motors, powered by rechargeable batteries. Batteries can be used for extending the endurance (e.g. manganese alkaline, lithium), but this also increases the cost per mission. Some larger vehicles may be powered by aluminium based semi-fuel cells for a higher endurance and power output. Silver-zinc batteries allow the AUV to cover a longer distance, but lithium-ion batteries are the most cost-effective (longer life). Other types of rechargeable batteries are sealed lead acid, nickel cadmium and nickel hydride (Fernandes et al., 2003). Most of the internal space is used by the power source (e.g. batteries) and the navigation control instrumentation. However, AUV typically follow modular design to enable components to be changed easily by operators (Vijay, 2011).

7.2.6 Buoyancy gliders (AUV)

Autonomous underwater buoyancy gliders (hereafter UW gliders, Figure 6) are slow moving (~0.5 knots), typically small (<2 m), low power platforms that house sensors capable of making multidisciplinary oceanographic observations over months and hundreds to thousands of kilometres (Davis et al., 2002). Underwater buoyancy gliders move through the water column by changing their volume and buoyancy to profile vertically in the ocean. Variations in volume are achieved through inflating or deflating their oil or water filled bladder. Wings are used to convert vertical velocity into forward motion, so that the glider typically follows saw-tooth profiles. 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 perform a download of data.

There are currently three classes of underwater buoyancy gliders (Wood and Mierzwa, 2013): 1) those that use mechanical or electrical means of changing their buoyancy (i.e. drop weights or electrical power from batteries), 2) those that use the thermal gradient to harness the energy to change the vehicles buoyancy, and 3) hybrid vehicles that combine standard propulsion systems and buoyancy glider systems.

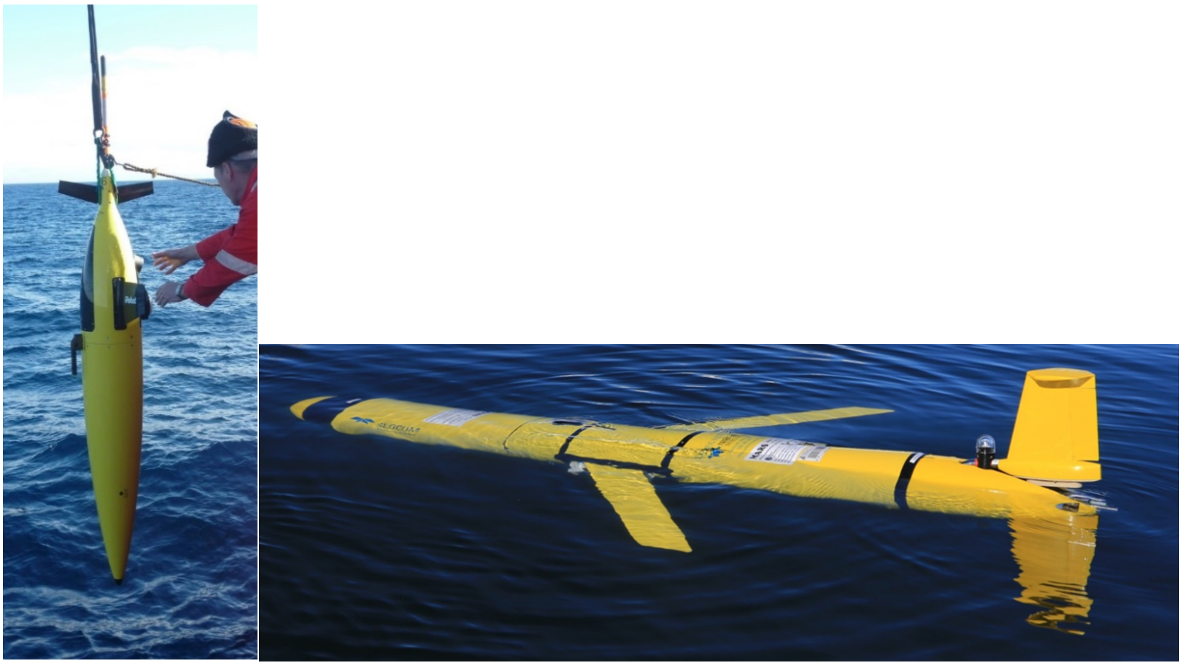

Figure 6. Underwater buoyancy gliders Seaglider (left) and Slocum (right) (images © Damien Guihen).

7.2.6.1 (Mechanical) Electric buoyancy gliders

Electric buoyancy gliders change their buoyancy by converting battery energy into a volume change with a hydraulic pump. Energy efficient movement is enabled through using only slight changes in buoyancy to minimize expended energy and moving slowly to reduce drag. Fairing (the external surface) shape is designed to decrease vehicle drag.

7.2.6.2 Thermal buoyancy gliders

In an electric buoyancy glider, approximately eighty percent of vehicle power may be used for ballast pumping to alter density (Graver, 2005). Thermal buoyancy gliders use the depth-related variation in oceanic temperature to effect changes in platform density. Volume change in a phase-change material such as wax is used to alter buoyancy as it varies between a liquid and a solid depending on temperature. Extrapolation of energy use during a short deployment of a Slocum thermal in March 2010 indicated a potential endurance of 3.4 years (Jones et al., 2011a), greater than three times the duration of the electric buoyancy glider. Initially just used for powering the buoyancy change, research and development is now examining the potential for harvesting thermal energy to power the sensors (Jones et al., 2011a; Buckle et al., 2013).

7.2.6.3 Hybrid buoyancy gliders

The hybrid buoyancy glider combines the buoyancy propulsion method with jet or propeller propulsion, where internal energy is converted to propeller or jet thrust. Buoyancy gliders are constrained by a requirement to undertake vertical saw tooth profiles when moving forward. Jet/propeller propulsion enables gliders to make constant altitude transits and can improve their ability to make progress against strong ocean currents, or navigate areas with restricted access to surface waters (Claus, 2009).

7.2.7 Powered surface crafts (ASV)

Unmanned powered surface craft offer great versatility and a number are now available. There is a diversity of approaches and designs and they take many forms. Most often these vehicles are operated remotely from shore or a support vessel. Such craft may also be known as “autonomous”. As a defining term, “unmanned” is more technically correct as none of these vehicles are autonomous in the sense of being wholly independent – all require some mission planning and/or remote operation by human hand. The following examples of autonomous powered surface craft are categorised into three groups based solely on hull shape: boats, catamarans and semi-submersibles.

7.2.7.1 Boat

Many such ASV bear a strong resemblance to an otherwise familiar craft, such as a rigid-hulled inflatable boat (RHIB) with an in board or outboard motor. Essentially, any small craft can be potentially converted into an ASV by the addition of controls, navigation and telemetry. For legal reasons, due to the potential for navigational risk to other craft, boats cannot be fully automated, and have to incorporate the possibility of 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). The advantage of this approach is that remote control brings a range of possibilities to familiar vessels of greater size large and complexity. The disadvantage is that the increased complexity may bring issues on mechanical reliability, which cannot be resolved remotely.

Figure 7. An AUV boat type Viknes designed and developed by the Norwegian University of Science and Technology in conjunction with Marine Robotics (image © Norwegian University of Science and Technology).

7.2.7.2 Catamarans

For autonomous operations, a catamaran based hull gives the ability to carry significant payload on a larger area of deck space. This enables ready access to the payload and a flexible modular build approach as well as supporting large top-heavy units, such as a telemetry mast. A catamaran gives a very stable at-sea platform but this may be at the expense of manoeuvrability – the main disadvantage cited of this hull-type. A catamaran shape is readily scalable in size however and this allows for scope in ambition and cost. Smaller models, such as the Springer (Figure 8 left), are ideal for research but have also been utilised for civil applications and education purposes. The larger ASV C-Enduro (Figure 8 right) utilises its shape and deck space to carry solar panels and support a three-blade wind turbine. Mission range is thereby increased and space still remains for the addition of sensor packages. This has included Seiche PAM which underwent trials in the Gulf of Mexico in 2015 and successfully detected animals remotely and in real-time.

Figure 8. Catamarans: Left picture: Springer, a catamaran based ASV developed by Plymouth University (image © Plymouth University), right picture: ASV C-Enduro, a large scale catamaran based ASV (image © ASV).

7.2.7.3 Semi-submersible

The main body of the semi-submersible vehicle (Figure 9) remains underwater. Only a small surface expression is given with the communications mast and air intake protruding above the waterline (Manley, 2008). The craft is necessarily bulky and the effect is to reduce the effects of waves and make it very tolerant in rough seas. The vehicle offers a particularly high level of sea-going capability given its relative small size and cost. It also enables excellent sea keeping capabilities, being able to remain at its design waterline in all operational speeds and conditions, without reliance on hydrofoil control. The semi-submersible's bulk also lends it high survivability. On the downside, physically managing the vehicle during launch and retrieval remains potentially challenging. The design is primarily intended for application in naval use but has potential for conducting bathymetric and hydrographic surveys in civil and commercial sectors (Wolking, 2011).

Figure 9. The semi-submersible ASV-6300 designed by C&C Technologies and ASV (image from Wolking, 2011).

7.2.8 Self-powered surface vehicles (ASV)

Self-powered surface vehicles such as wave and wind gliders use renewable energy from wave, wind or solar energy for generating forward motion or station keeping. The Liquid Robotics Waveglider (Figure 10), for example, is now a well-established autonomous surface vehicle. Its surface float contains solar panels to power the navigation systems and science payloads, while forward propulsion is provided by a rack of fins suspended 7 metres below the float which directly convert wave motion into forward power. The latest model of the Waveglider, the SV3, also has a small electrically driven propeller. The combination of wave and solar power means that these vehicles can stay at sea indefinitely and deployments of many months have been reported. Other wave and wind powered vehicles are also becoming commercially available such as the wind powered SailBuoy[1] and the wave powered Autonaut[2] and is likely that other vehicles will appear of the market in the coming years.

[1] http://www.sailbuoy.no/
[2] http://www.autonautusv.com/

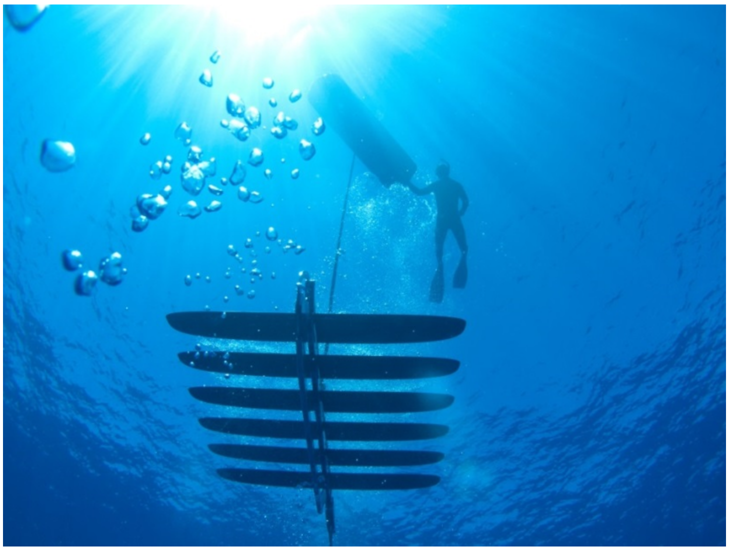

Figure 10. Underwater photograph of a Liquid Robotics Waveglider showing the sub unit, whose moveable fins convert vertical motion from waves into forward power and the surface float (photo, Liquid Robotics).

7.2.9 Drifter (ASV and AUV)

Drifting sensor packages have long been used by oceanographers, often because their low cost makes it possible to deploy many sensors at once, thereby increasing sample size. Many drifters simply stay at the surface and relay their positions via satellite link in order to study ocean currents. More sophisticated devices also carry sensor packages, and in the case of the ARGO floats[3], move up and down through the water column, sampling at varying depths, before transmitting their data to shore.

The classic example of a drifting PAM system is the sonobuoy. These have been used by the military since the 1940s, primarily for submarine detection. Modern sonobuoys generally consist of a cylindrical package thrown from an aircraft. When they hit the water, a hydrophone deploys to a set depth and a VHF transmitter is used to radio sounds back to the circling aircraft which must remain within line of sight of the buoy. Constellations of buoys can be used to localize sound sources, though life times are typically only a few hours.

Most autonomous drifter systems are non-recoverable, with all important data being telemetered to shore or satellite link, which presents a challenge for acoustic monitoring data due to the high volumes of data involved. Griffiths (2015) describes a low-cost drifting sensor package for passive acoustic monitoring which can be constructed for around $5,000. This system contains a two-channel recorder and data are stored on board the device, only available once it has been recovered.

[3] http://www.argo.ucsd.edu/

7.3 Sensor types

7.3.1 Electro-optical imaging sensors

There are four main imaging technologies that should be evaluated when considering detection of marine animals from aircraft; Red Green Blue (RGB), thermal Infra-Red (IR), non-thermal IR, and video cameras. These four sensor types differ mainly in what part of the electromagnetic spectrum they can register radiation from. Though RGB cameras are able to capture infrared wavelengths, for the purpose of this evaluation we assign infrared cameras to its specific category, including both thermal and non-thermal infrared, given that there are sensors developed for the single purpose of capturing IR wavelengths. Several sensors are currently available for UAS. Depending on the payload available, a single UAS may carry one or several sensors to increase accuracy of detections, which can provide information on object presence/absence and animal behaviour/movement. The information gathered by these sensors can be transmitted to the ground in near real-time or stored on-board the aircraft for post-processing. By utilising the data with regard to position and orientation of the camera, for each image or frame, it is possible to georeference each individual pixel in an image in relation to a geographic coordinate system. This is sometimes also referred to as geocoding. For detecting animals from an unmanned aircraft it is important to maximize the field of view while maintaining sufficient surface resolution and contrast. To detect small marine mammals such as porpoises while surfacing a surface resolution of approximately 20 cm/pixel is required.

7.3.1.1 RGB cameras

An RGB camera consists of millions of small electro-optical (EO) sensor elements, referred to as pixels, which register incoming radiation focused through a lens, and convert it to an electric charge. This charge is then digitised and stored on the camera or transmitted to a computer. Cameras can detect radiation in different parts of the spectrum but most commercial cameras only detect light in the visible range (VIS) of the electromagnetic spectrum between 400 to 700 nm. The two most common camera sensors today are the charge-coupled device (CCD) and the complementary metal-oxide semiconductor (CMOS). To be able to separate colours in an image using a single camera sensor, the individual sensor elements are fitted with a red, green or blue colour filter array. Cameras with no filter are referred to as monochrome cameras. They cannot separate colours but benefit from a much higher sensitivity than a colour camera. Commercial cameras come in a variety of different qualities, with regard to resolution, dynamic range and sensitivity. Cameras can record data with a high frame rate, which, combined with a high resolution, generates large amounts of data.

7.3.1.2 Thermal IR camera

Thermal cameras or sensors register thermal radiation emitted from an object. Thermal imagers are mainly divided in two categories based on the wavelength region they operate in (1) mid-wavelength infrared (MWIR) imagers operating in the range of 3 to 5 µm and (2) long-wavelength infrared (LWIR) imagers operating in the range of 8 to 15 µm. LWIR imagers are most common in small and medium size UAS due to their small size and relative low cost. However, the resolution is limited and a typical high end LWIR imager has a resolution of 640 x 512 pixels (Tau 640, FLIR Systems). The energy emitted from an object with regard to frequency or wavelength can be estimated using the Planck's law for black body radiation (Planck, 1914), where the energy is shifted to longer wavelength for lower temperatures. Hence, for objects such as marine animals, LWIR imagers would be the appropriate solution.

Water is non-transparent to thermal radiation, and a thermal IR system cannot see anything below the sea surface (even a few micrometres). Hence, the use of IR systems for marine animal observation and study is limited to surfacing animals only, resulting in the exclusion of fish and turtles as study objects (except for leatherback turtles, which seem to be an exception as they regulate their body temperature similar to mammals (Bostrom et al., 2010)). A thin layer of water often covers surfacing animals and experiments have shown that when a surfacing minke whale (*Balaenoptera acutorostrata*) is covered by a thin film of water, its thermal radiation is almost completely masked; the temperature difference between the animal and the surrounding water is usually less than 0.1°C (Baldacci et al., 2005). However, the blow and blowhole are easier to detect and temperature differences of over 4°C between blowhole and surrounding water have been reported (Baldacci et al., 2005). Several publications have investigated the use of IR cameras for detecting blows using thermal imagers; blows from large baleen whales were successfully detected up to 7 km away (Santhaseelan and Asari, 2015; Weissenberger et al., 2011; Zitterbart et al., 2013). These studies all applied a higher quality (third generation or later) thermal imager placed on a large ship or land-based installation, allowing a view of the blow against the water background. Additionally, studies from manned aerial surveys provide evidence that it is also possible to detect thermal "footprints" of animals surfacing, using the same type of equipment (Churnside, Ostrovsky, and Veenstra, 2009).

Using thermal IR from UAS for detection of marine animals seems plausible to detect marine mammals both, due to the large thermal difference between the cetacean blowhole and the surrounding sea (see also Verfuss et al., 2016), and differences in body temperature of smaller animals. In practice however, we have not found any publication documenting the use of thermal imagers on UAS for marine mammal detection. A whale's blowhole is comparatively small and would require a resolution of a couple of cm. For achieving a resolution of 2 cm/pixel, the resulting width of the scene covered by a thermal imager with 640 pixels would only be 12.8 m. To achieve an appropriate resolution, several cameras could be combined, which would result in a bulky solution not well suited for small or medium size UAS. Thermal IR is a promising technology, though the combination of payload requirements of UAS and camera resolution for aerial detection that is within reasonable price range for unmanned surveys, is possibly the main reason for why this has yet to be developed further.

7.3.1.3 Non-thermal IR camera

Non-thermal IR cameras operate in the low end of the IR spectrum and are often divided into two groups: near-infrared (NIR) in the range of 0.74 to 1.0 µm and short-wavelength infrared (SWIR) in the range of 1 to 3 µm

(Maldague, 2007). In this region of the spectrum very little energy is emitted from objects with normal body temperature and these cameras work similarly to RGB cameras, which are based on light reflected from the object. SWIR cameras excel in low light conditions, partly because these sensors are highly sensitive, but also due to a phenomenon referred to as night sky radiance. The night sky emits five to seven times more illumination than starlight, nearly all of it in the SWIR region. Hence, with a SWIR camera one can "see" objects with great clarity on moonless nights. SWIR cameras are available in small sizes, such as the TAU SWIR (FLIR Systems) weighting only 130 grams. However, SWIR cameras share similar limitations as thermal LWIR cameras with regards to relative low resolution (no more than 640 pixels). We have not found any work where SWIR cameras have been tested for the detection of marine mammals.

7.3.1.4 Video

The use of a HD video with a resolution of 1,920 x 1,080 pixels at an operational altitude of 122 m, and a ground resolution of 20 cm/pixel cross results in a cross-track distance of 384 m track (strip width), based on operations within the Visual Line of Sight (VLOS). Flights at higher altitudes will cover larger areas, though national authorities require special permits to operate at larger ranges and altitudes. One of the most important features for the detection of marine animals from UAS using live video is that the camera is stabilised using a gimbal (Koski et al., 2009a). This will reduce image vibration and improve the efficiency of the operator manually trying to identify animals in the video. Reducing image vibration will also reduce the video bit rate due to improved encoding efficiency. Though it is also possible to store the video collected for future analysis, the transmission of real-time data to the ground station can provide valuable information that can be used for both science and management (e.g. Hodgson et al., 2013; Koski et al., 2013; Koski et al., 2009a).

7.3.1.5 Other electro-optical imaging sensors

Sensors collecting LIDAR (Light-Detection and Ranging) remote sensing data use pulsed laser light to measure ranges to the Earth by using ultraviolet, visible or near infrared light to image objects (NOAA, 2015). This type of sensor has proven its value in surveys of manned aircraft and it is gaining interest in the UAS market. LIDAR has shown its relevance in fisheries and can detect fish at depths up to 16 meters (Butler, 1988) though the detection of marine organisms using such technology remains untested for UAS surveys, possibly due to the same limitations as for infrared equipment. Despite the interest in technologies using green light that can penetrate the water surface, this equipment use currently appears to mainly focus on topography (including sea floor elevations) and hydrodynamic modelling. Thus, the use of this type of equipment is not further dealt with in this report.

7.3.2 PAM systems

Passive acoustic monitoring relies on detecting the sounds produced by animals. Three groups of marine animals produce sound: crustaceans (predominantly shrimp), fish and marine mammals (Horne, 2000). Snapping shrimp are dominant sound producers in shallow waters at latitudes of less than 40° (Horne, 2000), a single snap can reach peak-to-peak source levels of 185 dB (re 1 µPa) with a broad frequency spectrum up to 200 kHz (Au and Banks, 1998). Soniferous (sound producing) fish are common, and can be used to identify specific species. Over 800 species of fish from 109 families worldwide are currently known to be soniferous (Kaatz, 2002). Fish produce sounds to communicate with each other while feeding, mating or aggressive displays as well as making incidental noises associated with feeding, swimming and other behaviours (Rountree et al., 2006). The sounds of fishes are rarely higher than 1 kHz, at least in the zones of maximum amplitude, and include those produced by friction between bones, contractions of sonic muscles, or hydrodynamic noises from swimming. A comprehensive review of sound and sound production in fishes can be found in Kasumyan (2008). It is generally considered that PAM could be used to monitor the distribution, abundance and behaviour of fish (Rountree et al., 2006). The use of PAM for the detection of fish is still very much a developing field of activity, and while there may be potential for monitoring some species and spawning events, active acoustic survey and tagging fish with ultrasonic sound emitting tags remain the more common methods used to study fish species.

The species group for which passive acoustic monitoring is most well developed is marine mammals, particularly cetaceans (whales and dolphins). All cetacean species are known to make sounds of some type or another, although for several species, sound production is limited to certain individuals at certain times of the year (for instance, male humpback whale singing during the breeding season). For some species, particularly deep diving odontocetes, individuals spend significantly more time vocally active and available for acoustic detection than they spend at the surface where they would be available for visual detection. On the other hand, many species, or important components of populations, are known to remain silent for extended periods, thus making them unavailable for acoustic detection.

The frequency range of marine mammals vocalisations span 14 octaves from the infrasonic sounds of large baleen whales, with each sound lasting for many seconds, to short (100 µs) ultrasonic echolocation signals from small odontocetes at frequencies ranging up to 150 kHz. For example, individual vocalisations of a blue whale may last 150,000 times longer than those of a harbour porpoise, and the frequency of a harbour porpoise click may be 15,000 times that of a blue whale call. This incredibly wide range of sound types creates particular problems for systems attempting to detect and localise multiple species types.

Vocalising animals can be detected so long as the PAM system has sufficient bandwidth to capture the sounds of interest. Sampling theory dictates that the sample rate must be at least twice the highest frequency of interest, so for small odontocetes, such as the harbour porpoise, sample rates in the several hundreds of kHz are required, with a 500 kHz sample rate being typical for many systems.

Detection range is governed by how loud the initial sound is, how much noise there is around the receiver in the frequency band of interest and transmission effects such as downward refraction and higher absorption of high frequency sounds. For large baleen whales, detection ranges in the tens or even hundreds of kilometres are possible and sperm whales are often tracked at ranges of several kilometres. Smaller species that produce higher frequency signals tend to have much shorter detection ranges, often in the low hundreds of metres even in low noise conditions. Detection range can be expected to vary dramatically depending on local industrial noise sources, such as airguns and vessel propulsion systems. Certainly a big potential advantage of small autonomous vehicles for PAM is that the local noise field can be expected to be both low and consistent between deployments, meaning that detection performance may be both better and better understood than it is for many vessel based deployments.

Acoustic sources can be localised using a number of techniques. Bearings to sounds can be obtained with small clusters of hydrophones and for some species, multiple bearings to individual animals, taken from a moving platform, can be used to estimate range as is demonstrated for sperm whales in Lewis et al. (2007). As a general rule, the lower the frequency of the sound of interest, the wider the separation between hydrophones needed. Separations of tens of centimetres are adequate to obtain bearings to broad band or high frequency odontocete clicks, but separations of many metres would be needed to estimate bearings to low frequency baleen whale calls. In order to measure range directly to the source of a single sound, widely spaced hydrophones are required and localisation will only be accurate within approximately 3 times the array dimension (i.e. if hydrophones were spread over 100 m, localisation would be accurate to about 300 m). Separating hydrophones by such distances can present technical challenges on board a vessel and would be particularly problematic on small low powered autonomous vehicle systems.

Most PAM systems include a human operator in any decision-making process, whether that be real-time decision making or post analysis of data. By their very nature, autonomous platforms do not accommodate a human operator, so data must be stored or transmitted in a form whereby it remains possible for an operator to view sufficient data for detection verification purposes.

PAM systems for autonomous data collection can broadly be divided into two categories:

1. Raw data systems
2. Systems with on board data processing.

The large size of modern hard drives, and more recently of flash memory cards, has led to the development of a wide variety of systems which simply stream raw data to storage media for later analysis. Fixed autonomous recorders for PAM were thoroughly reviewed in an industry-funded program in 2013 (Sousa-Lima et al., 2013) and it is not our intention to repeat this review process here. As is clear from this work, there is a general trade-off between size and capability in these systems. Many of these systems are now well established and are commercially available for hire or purchase. While intended for fixed use, many could potentially be adapted (e.g. through the addition of an external towed hydrophone) for use on moving autonomous platforms.

Packages with on board processing are less common, although the recent availability of powerful low power usage processors, often developed for the smart phone market, means that this is a rapidly developing field. When a glider is at the surface, summary information of candidate detections is sent to shore via satellite link where it can be verified by a human operator for near real-time detection. The system developed by Klink to detect beaked whales also sent back some summary information about detections during each dive, but insufficient data were sent to shore for data validation. Data validation was therefore only conducted once the vehicle was recovered and full recordings analysed. Similarly, Gillespie deployed a Decimus system on a Waveglider for the detection of harbour porpoises and although summary counts of detections were sent to shore via satellite, detailed data needed to confirm those detections were only available once the vehicle had been recovered.

As devices increase in acoustic bandwidth, so the pressures on data storage, data processing and power requirements become more acute. This can limit the practicalities of using these systems for long missions on small, low power vehicles.

7.3.3 AAM sensors

An active acoustic sensor acts by broadcasting a sound wave in the water and measuring the returned signal from encountered targets. The performance of the sonar system depends on the degree to which the beam of sound is focussed onto the target and hence the directivity of the array generating the sound beam. It is also dependent on the level of background noise. Active acoustic monitoring equipment typically includes fisheries sonar and echosounders that operate from ~18 kHz through to ~500 kHz. Targets that can be detected with AAM that are of interest for this review are marine mammals, turtles or fish. The animal is detected through target reflection rather than vocalisation. Therefore, active acoustic methods are not limited by poor light, visibility or most weather conditions and animal detection is not dependent on vocalisation or surfacing behaviour. The range and detection abilities of active sonar is frequency dependent; attenuation of sound amplitude increases with increasing frequency leading to shorter detection ranges. On the other hand, the resolution increases as frequency increases, therefore higher frequencies can detect smaller targets compared to lower frequencies.

In order to use AAM to detect marine mammals, turtles or fish two factors are required: a method of identifying the organism in the acoustic data and an estimate of the sensitivity of the instrument and effects of the physical environment on sound propagation (see Verfuss et al., 2016 for further details). Identifying the organism in the acoustic data can be done through either target strength (e.g. Bernasconi et al., 2013), target aggregation features (Fernandes, 2009), target movement (stationary fish schools versus moving whales; (Selivanovsky and Ezersky, 1996; Bernasconi et al., 2013) or multi-frequency responses (Korneliussen and Ona, 2003).

There are four types of echosounders/sonars used in active acoustic research: single-frequency echosounders (allowing for multiple transducers e.g. multi-frequency), multibeam echosounders, wideband/broadband echosounders and sonars. A generic feature of all these echosounders/sonars is that the amount of echo returned from a target is a function of the frequency used and the size, shape, composition and behaviour of the target (Horne, 2000).

7.3.3.1 Single-frequency / multifrequency echosounder

These are the standard fisheries echosounders, typically available from 18 kHz to >500 kHz, and normally have a focussed narrow beamwidth. The size of the transducer is related to the beamwidth, with a smaller beamwidth resulting from a larger transducer face at any particular frequency (MacLennan and Simmonds, 1992). The first echosounders only transmitted a single beam of sound, where the position of the target within the beam was unknown. Modern echosounders are split-beam, where the transducer has four quadrants, allowing the location of targets in three dimensions. The use of single-frequency acoustics is limited, as it cannot distinguish between size and target type and therefore has reduced capability for species identification. Multifrequency acoustics are required for species identification (Korneliussen and Ona, 2003), except where targets are simple or exhibit particular repetitive and recognisable patterns.

7.3.3.2 Multibeam echosounder

A multibeam echosounder emits sound waves in a fan shape. This greatly enhances the area and volume of the acoustic window, typically providing a horizontal swath of information with angular coverage to 150°, formed from hundreds of beams. They image a synoptic slice of the water column and can ensonify whole aggregations of fish, as well as discriminating and tracking the position of individual targets within the swath (Mayer, 2006; Colbo et al., 2014). Most recently, dedicated biological systems, which collect calibrated acoustic backscatter data throughout a whole fan of 500 beams have been developed (e.g. the MS70, Korneliussen et al., 2009). For the detection of marine mammals and sharks, multibeam echosounders (vertically downward looking) and multibeam imaging sonars (horizontally looking) have almost exclusively been used.

7.3.3.3 Wideband / broadband echosounder

Wideband echosounders make use of a chirp pulse to cover a wide frequency band in a single ping, thereby providing echo strength measurements over a wide frequency range. Wideband equipment[4] currently represents the forefront of technical developments in fisheries acoustics. It has four advantages over narrowband systems: (1) spectral information for species identification, (2) improved target detection, (3) more stable estimate of signal and (4) improved target resolution.

7.3.3.4 Omnidirectional sonar

An omnidirectional sonar emits sound waves in all directions in a horizontal plane. This greatly enhances the area of the acoustic window, and allows detection of marine mammals and fish from directions not immediately under the ship.

[4] www.simrad.com/ek80

7.3.4 Animal-borne tags

Identity and movements of individual organisms (marine mammals, turtles and fish) can be monitored using transponding acoustic tags (e.g., Voegeli et al., 2001). A miniature electronic pinger can be placed on an animal and followed using hydrophones (e.g. Wroblewski et al., 1994; Wroblewski et al., 2000). Tags transmit at specific frequencies to provide a unique marker for each individual. Detections are generally made with bespoke receiving equipment from the tag manufacturer. Tag detection range and transmission duration are proportional to tag size. Obviously, a key requirement is that the animal is tagged in the first place.

8 Evaluation of autonomous systems

8.1 Criteria and metrics

There are several examples in published literature of complete autonomous systems (see section 9.2), which combine a platform (or vehicle) with a sensor and data relay system in order to achieve a specific task. For the evaluation we have separated platforms, sensors and data relay systems to enable a comparative analysis of the various parts. However, the main emphasis of the analysis is assessing the suitability of the platforms, sensors and data relay systems (and any of their combinations) for mitigation and/or population monitoring or monitoring of individual animals.

Many of the platforms reviewed at least claim to be highly flexible in how they are fitted out with sensors and data relay systems, and data relay systems in particular must often be chosen for particular applications. Therefore, as well as defining what is required in terms of performance, we have gathered practical information to inform which platform-sensor-transmission system combinations may be feasible in the future. General information on the platforms and sensors was collected as well as details such as technical data and operating figures, expenses, main properties determining mitigation monitoring and marine animal survey capabilities, operational information and data sources. To collect this information in a comparable manner, evaluation criteria were chosen. This chapter provides explanations on how these criteria were defined and why they were chosen. To generate the comparison matrices in section11.3, these criteria were grouped into the following categories: general information, technical details, costs, survey capabilities, operational aspects and manning requirements for both the platforms and sensors. These general categories facilitated the organisation of the huge amount of information gathered for each system. Section 11.1 gives a bullet point list overview of the criteria defined in this chapter as well as a link to the corresponding comparison matrix table.

How a platform and sensor are configured and used depends very much on the purpose of the collected data. Platform, sensor and data relay requirements for mitigation monitoring as well as operational aspects are quite different to those for population monitoring and these differences are highlighted in the sections below. When mitigating, the priority is generally on the delivery of near real-time data and high detection efficiency, whereas for long term monitoring real-time data are often not required and detection efficiency need not be high, so long as it is reasonably quantified.

8.1.1 Collection of survey data

To achieve the survey design, data collection and analysis requirements outlined in section 11.6, the following evaluation criteria were identified, which are discussed below.

The majority of the platform criteria are linked to survey design. As with mitigation monitoring, platform **mission duration** and any **factors limiting** it, and **speed** are key criteria that must be assessed to ensure that a planned survey can be completed in the desired timeframe. The **minimum and maximum vertical range** a platform can cover (height above sea level for aerial vehicles and depth for underwater vehicles) are also important. For each considered platform, it is important to know whether a system has **track setting options** to follow a pre-designed track, and whether the track is implemented using pre-programmed coordinates, through manual piloting, a combination of both or some other method. **Environmental limitations** that would potentially affect a system **keeping** to its **track** are also investigated. Some systems have the ability to **self-correct** if deviation from a planned track occurs. It is important to consider whether a system can self-correct for two reasons. Firstly, self-correction will improve the ability of a system to adhere to a planned survey design but, secondly, self-correction may increase system noise, which may negatively impact data collection. The ability of a system to remain stationary (or at least perform turns to stay in the same location) is also considered. **Station-keeping** (as this behaviour is known) is useful for (1) making vehicles act as fixed platforms or (2) having vehicles interact with other fixed platforms over a small spatial scale or (3) potentially collecting fine-scale animal behavioural information. The capability of a given system to make **autonomous decisions** and, therefore, potentially have multiple survey modes is also investigated. The ability to switch between survey modes would allow a survey to be adapted either through interactions with other vehicles or due to some detections/measurements encountered during the survey. Finally, whether or not **clock synchronisation** with other systems is possible is also a useful consideration. Clock synchronisation may be required if the same detections needed to be identified across multiple platforms (this is also relevant to specific sensors).

Unlike mitigation monitoring, it is not necessary that the probability of detection of a given animal or group of animals is high during surveys. Instead, criteria relating to surveying capabilities are primarily concerned with the potential to estimate the probability of detection, using any of the methods discussed in section 11.6.2. The first criterion for the sensors, however, provides a general assessment of what **environmental factors** would prevent optimal **sensor performance**. The **type of data collected** and stored by the sensor is also ascertained. It is important to know whether the sensor stores raw data or whether there is some on-board processing. If only processed data are stored, then it is more difficult to assess, for example, the proportion of false detections. It is also critical to know whether the resolution of the stored data is sufficient to identify the observed species. In order to assess the potential of a given sensor to store data that could be used to estimate detection probabilities, it is necessary to ascertain whether the data could be used to estimate (1) **bearings** to observations or (2) **direct ranges** where absolute location of the animal may not be known or (3) **horizontal ranges** to animals (where some bearing ambiguity may exist). In order to estimate horizontal range using AUV systems, it would be necessary to know animal depth. For estimating horizontal range from UAS systems, it would be necessary to be able to estimate the horizontal distance from the vehicle's trackline to the animal. Also linked to detection probability estimation, but only relevant for PAM data, are the following criteria: can (1) **received levels** of the detected animal sounds, and (2) **ambient noise levels** be estimated from the data. In the absence of any other information about acoustic detections (i.e. no range or bearing estimates), such information becomes increasingly useful. Received levels and ambient noise levels (in the frequency band of interest) can be used to calculate signal to noise ratios. In addition, **CTD data** will allow accurate sound speed profiles to be estimated, which can be used in sound propagation modelling to estimate transmission loss. Transmission loss is another acoustic measure that can be used in non-standard detection probability estimation methods. **Clock synchronisation** is also a relevant criterion to assess; clock synchronisation will be key if the same detection needed to be identified across multiple sensors. The accuracy of the synchronisation will also determine whether multiple systems or sensors can be used to create instrument arrays that can potentially estimate bearings to, or localise, animals.

8.1.2 Mitigation monitoring

To identify which system is suitable for which kind of mitigation monitoring requirements, the operational aspects of a platform need to be evaluated in combination with sensor criteria. Some of the points to be considered are also important for population surveys but, as has been discussed in section 7.1, there are also some very different requirements between population surveys and mitigation monitoring, so separate sets of evaluation criteria were constructed.

The most basic requirements for mitigation monitoring are that data retrieved by the sensor must be available in near **real-time** and that detection efficiency over the mitigation zone should be sufficiently high that the chance of missing an animal is low. Each detection methodology has its advantages and disadvantages, e.g. PAM can only detect vocalising animals while any optical method relies on animals near or breaking through the sea surface. Therefore, the **system class** of the sensors (e.g. AAM or PAM) is the most important criteria when it comes to which marine animal species actually can be detected and in which situations. This has been intensively discussed in Verfuss et al. (2016). For evaluating the detection efficiency, the **collected data type** and related data processing is important to know. The system class as well as certain technical details of the sensor will also determine which **species or species groups** are able to be **classified**. To determine whether an animal is about to enter or is present in the exclusion zone, localisation of the animal in relation to the sound source needs to be possible, which can be done by evaluating information on **bearing** and **direct** or **horizontal range** of animal to the platform (with possible ambiguity regarding bearing and uncertainty on the animal's swimming depth where only direct range is estimable) or at least the determination of the **range** between animal and sound source. Furthermore, it is likely that there will be associated uncertainty with the localisation or range estimate.

Ways in which to minimise such measurement error need to be considered at the survey planning stage to make sure that the measurements are suitably reliable for use in mitigation decisions

Unless highly reliable automatic detectors are running on the autonomous platform, it will be necessary to transfer large quantities of unprocessed data in near real time. If automatic detectors are used then it will still be necessary to transfer sufficient data for human verification in order to avoid false alarms. It may also be necessary to demonstrate that on-board detectors are running with sufficient efficiency such that no animals are missed.

The **maximum mission duration** as well as the **factors limiting its duration** is one limiting factor that determines which monitoring requirements a system can fulfil. Also, the **minimum, maximum and typical speed** of a platform is important for understanding the potential to cover a monitoring area and design, as well as the environmental factors limiting the platform performance.

The **payload capacity** (see section 8.1.3) as well as the **type of interface** determines what kind of sensor fits onto the platform. That determines many other factors important for mitigation monitoring: High **noise levels** created by the platform or sensor may interfere with the detection probability or have an effect on animal behaviour. The **data relay system** may influence if real-time detections are at all feasible but, together with its **transmission range, also determines** the maximum range a system can operate at. This, in turn, determines the size of the monitoring area that can be covered. The **vertical ranges** a platform can cover also determines the dimensions of monitoring area coverage, which for some systems have to be combined with certain sensor properties for meeting the requirements needed for mitigation monitoring. For example, a high flying UAS will need to be combined with a high-resolution camera to retrieve qualitative sufficient data for animal detection, while a low flying UAS can be coupled with a sensor of lower resolution.

8.1.3 Operational aspects

Selecting the most appropriate platform and sensor solely based on the criteria outlined in sections 8.1.1 and 8.1.2 for conducting a certain kind of marine animal monitoring is not enough to produce a sufficiently running system. There are further operational criteria that are necessary to consider. For instance, most platforms will have some maximum payload space and power availability, which informs as to which sensors may fit into those payload spaces and how long they might operate for. Therefore, defining the **payload power, capacity weight and space** for both, platform and sensor, allows an assessment of which sensor systems a platform can feasibly carry. By payload power we mean the power supply necessary for a given sensor package to operate – though this balance is likely to be configurable to specific mission requirements. Capacity weight and space identifies the necessary physical dimensions and limitations of a sensor/platform combination. This may have two aspects: the space with the platform and that positioned outside. For sensors, the payload capacity was divided into two further aspects: the **internal payload capacity**, which is the space that would be required if the electronics is removed from the standard deployment package and incorporated into the vehicle payload bay, and the

external payload capacity, which is the space required for the standard manufactures package. Operationally it is necessary to understand the **deployment and recovery procedures** for the platform and sensor, as well as the **manning requirements for deployment and recovery** and the **level of training needed** in order to be able to deploy, recover and interpret data from the sensors. With deployment and recovery procedures it is important to note any requirements in terms of number of crewmen for manual handling and the need for any lifting equipment at sea. Specialist training may be required for deployment/retrieval and, more pertinently, operation of the craft – potentially remotely from an onshore base as well as personnel requirements for interpretation of data. It is also important to understand the **failsafe modes** the platform incorporates and the **transponder, detect and avoid capacities** the platform has. We define the failsafe mode as the default functionality of a system that allows it to operate should major problems emerge. This is of particular importance regarding navigational and positioning ability within a field of industry operations. Failsafe mode options therefore encompass: *Bearing*, to define the heading of the craft. *Location*, to define its geographic position. *End point*, noting its final waypoint for retrieval. *Keep track*, describing the course to be adhered to or stop. Worst case scenarios will have to be considered and the ability of a platform to "limp home" and avoid being a serious hazard requires close scrutiny. Consideration of transponder, detect and avoid capacities takes into account abilities of sensor/platform to safely navigate and respond to its surroundings. Further criteria requested were **fuel type** for the platforms and their **level of autonomy**. Fuel type varies greatly between platforms, and individual craft may have a number of options. This is highly relevant when considering mission duration, safety and means of re-fuelling/recharging. Understanding the level of autonomy is key to the success of any given ASV/AUV/UAS if it is to prove worth over and above existing "manned" methods, particularly in terms of ability to meet waypoints and remain under continuous control.

8.1.4 Data relay

Data transfer requires power and often also infrastructure such as mobile phone masts or satellites. Offshore, where mobile phone infrastructure is generally unavailable, the principle methods of data relay are covered by the following **data relay system classes:**

- Wireless modems. These vary from something similar to home or office wifi (high data rate, but short range) to systems which have ranges in the tens of km, but lower bandwidth. They are generally operated as peer to peer networks and incur no data transmission costs.
- Satellite systems. These come in many varieties from small, low power, but also low bandwidth devices up to physically large, high power and high bandwidth systems. These relay systems are reliant on satellite infrastructure and therefore incur significant usage costs.
- Analog systems. These are relative simple and a somewhat dated technology, but can be used to relay audio and video data over short ranges.

The **data bandwidth** is one of the most fundamental parameters governing the choice of data relay system. Generally, bandwidth is quoted in bits per second, or bps. Mbps means a million bits per second and kbps 1,000 bits per second. Note that most of us tend to think about data in terms of "bytes", e.g. "My memory stick has an 8 GByte capacity". There are 8 bits to a byte and this needs to be taken into consideration when evaluating these data.

For instance, a vehicle collecting long term monitoring data far from shore will have little choice but to communicate through satellite link and it may be acceptable to receive either no real-time data, or only very basic summary information on the system status. The same vehicle and sensor combination, when used for mitigation, might opt for a much higher bandwidth radio communication system to nearby ships, which would allow much greater real-time throughput at negligible cost.

The other fundamental parameter is **range**. Transmitting data over greater ranges requires more power. All of us are used to office and home WiFi systems which have excellent data throughput, often in the hundreds of Mbps. Going into the next room cause data rates to drop and disconnection will occur at ranges in the low tens of metres. **Data delay** will give an understanding on how long one needs to wait from sending data to receiving it. Another criterion **is power consumption**: the more data you want to send and the greater the distance, the more power you're going to need. For small, low power autonomous systems, power consumption can be critical.

Clearly, the transmitter unit needs to physically fit within the autonomous platform. This is why the operational size is important. Also, weight is an issue that is however less important for surface and underwater vehicles, but essential information if systems are to be incorporated into autonomous aircraft. **Platform requirements** that might be necessary to install a data relay systems also need to be considered as well as the knowledge on any **training needs** necessary to run the systems.

For the economic side, it is important to investigate the **purchase cost** of transmitters and receivers, as well as their **operational cost**. For some systems using free spectrum, where you buy your own receiver, operational costs are zero (apart from power). For satellite based systems, data costs can be considerable. **Packaged size** and **weight** of the system may also be important for overviewing upcoming costs for transportation if needed.

Potential **usage restrictions** are also important to investigate as some radio based technologies may be restricted in certain areas / countries.

Environmental limitations to optimal system performance such as current or weather (wind, rain) were requested to understand in which situations performance may drop.

8.1.5 Further information gathered

General information requested for the comparison matrix include the type of platform, platform name and the manufacturer and/or the designers. Next to the evaluation criteria as outlined above, further criteria were specified that are important to note for any monitoring and project plans, influencing the time planning, the budget or allowing for additional data to be retrieved while performing animal monitoring.

The **technology readiness level** as defined in Table 10 is important to assess whether or not the system is available for commercial use or its current stage of development. It was also prudent to determine which platforms the sensors have already been integrated into, or where there are plans to integrate them, as this will impact on the level of testing and development required for use in autonomous monitoring abilities in the near future.

Operational and package size and weight of the platforms are important to know in terms of space and cost of shipping as well as space needed on a survey vessel. This information is also requested for the sensors and data relay systems to understand related shipping costs and implementation potential into a platform (as mentioned above). The hazard class of platform and sensor as defined in Table 11 are especially important for shipping and transport issues. Here the hazard class levels related to battery or fuel type of an evaluated system was evaluated. One has to bear in mind that oils or other materials used in the manufacturing of systems may also have hazard levels associated with them, but these could not be considered in this review.

The **presence or absence of additional sensors** may help to gather additional data but may, on the other hand, also be a **factor limiting the performance** of the platform or sensor used for animal monitoring. One other factor interesting to know is the **deployment type of the CTD sensor** if present. This sensor can be mounted either as a fixed sensor or profiling sensor on an AUV / ASV. A fixed sensor can only measure CTD data at the location of the vehicle. A profiling CTD sensor can measure CTD profile of the water column. This is of particularly important for ASV, where CTD profiles of the water column can only be retrieved with a profiling CTD.

For project planning purposes, it is of course also important to investigate the costs related to the purchase of the equipment, or alternatively the rental price. Operational costs and maintenance costs are also considered for platform and sensor.

8.2 Evaluation results

8.2.1 UAS platforms

There are a number of different types of UAS, which we divided into powered aircrafts, motorized gliders, lighter-than-air aircrafts and kites. These are described in detail in the introductory part of this review (see section 7.2). For this review, we included powered aircrafts and motorized gliders with fixed wing and rotary wing-type systems which enable operations from land and vessels, and allow for enough payload to be carried for conducting animal surveys offshore for long term monitoring and real-time detection. Lighter-than-air aircraft considered here include tethered and remotely operated balloons and blimps, respectively. Tethered balloons are also occasionally called blimps, but, in the context of this review, these will be kept separate. Only kites that can be remotely operated were included in this review. For the sensors, those not exceeding 2 kg and able to provide an image resolution that allows for the detection of animals with at least 1 m length were considered.

Based on the recommendations of (Koski et al., 2009a), we defined a set of characteristics relevant to wildlife monitoring offshore to understand which UAS to include into this review. Flight duration and communication range with the ground station should be sufficiently long to allow for deployments from land and from vessels. We defined that detection of objects as small as one meter in length should be possible, which includes sharks, turtles, fish shoals, and smaller marine mammals. This will allow UAS to be versatile in any environment, regardless of the species present in any region. Additionally, to include both timely decision making and population surveys, we considered a minimum horizontal operational range of 500 m from vessels and 200 km from land, considering the JNCC definition of high risk zone in marine mammal monitoring for industrial operations offshore. The land range for UAS operations defined here allows for future comparison studies to determine whether these systems can perform similarly to manned aerial surveys. This also requires that the flight time should be at least 30 minutes if the UAS is operated from a vessel, and 4 hours if operated from land.

Due to the large amount of UAS, we focused the comparison of UAS systems to those that can be deployed rapidly and with the need of no more than 3 to 4 persons to operate. These are all in the class of small to medium size UAS and with a maximum take-off weight (MTOW) of less than 80 kg. We consider characteristics that are relevant for animal detection and deployments with both space and time constraints.

The selection of platforms included different range, payload and deployment capabilities, which may serve different purposes depending on the studies of interest. We included systems that can be applied for population and mitigation monitoring as well as monitoring of individual animals for the application in the O&G industry.

8.2.1.1 Powered aircrafts

Powered platforms have been most widely tested in the UAS field. The capabilities of these systems allow them to be considered as alternative methods for work developed both at sea and on land. Depending on the study design, there is currently a wide variety of platforms available at the moment that can overcome many limitations that human observers and other aerial platforms (e.g. digital surveys using manned aircraft) experience. The versatility of these systems highlights the potential applications of this equipment both for research and management.

In most commercially available systems, the manufacturer is able to provide a fully integrated package that can satisfy the needs of operators and clients. However, listed sensor systems in the comparison matrix (Appendix 11.3.8) have similar characteristics, especially for thermal IR and RGB (Red Green Blue) cameras, which may be applicable to platforms that have gimbal capacity.

Neither of the largest UAS manufacturers listed in this report, such as Insitu and Arcturus UAV, provided a price on their system upon request. Specific requests for price estimates or price ranges were unsuccessful. In other occasions, quotes were given on a specific system with details regarding the quote, such as price, being under a strict Non-Disclosure Agreement. The military market clearly is the biggest market for these systems today, therefore keeping the price of such systems a secret may be beneficial with regard to price differentiation among different customers. However, according to (Thamm et al., 2013), these systems tend to vary in price between US$ 27,360 to US$ 76,577. Systems based on military applications, such as the ScanEagle for instance, may reach higher costs due to the demand for more complex launching and landing equipment, and contracts with certified operators.

UAS platforms are generally very versatile. Depending on the study design and main goals of a survey, it is possible to use a wide array of systems that can provide different data types. Two of the main aspects that should be considered are flight duration and range from the ground station and the main pilot. This point alone will help define the UAS that suits a study in the best way possible and from there, restrict the selection of sensors that are applicable. Using Iridium satellite, most systems considered can be piloted globally. However, for live data streaming, the payload can be limited (unless the operator has access to a satellite data link, or cell phone coverage). The choice of datalink, and hence range varies depending on location, as regulations regarding frequency bands and transmitter power varies from country to country.

Most UAS are able to conduct transect-based surveys. Both fixed-wing and VTOL platforms are able to conduct waypoint flights (transects) and focal follows. However, fixed-wing platforms may have difficulties in hovering and rely on gimbal sensors to lock the camera on the point or object of interest while loitering around the target. The choice between data in the form of photo or video will also be dependent on the study's goal and the resolution that is required. However, as with any other visual method of observation, UAS are only capable of detecting animals that are visible at the surface or in the top layers of water, which may prove to be efficient for studies concerning animals that spend long periods of time at the surface. For animals with long dive duration (e.g. beaked whales), the flight time required is much greater and studies for those species would probably rely on a combination of survey methods to aid detection. As UAS evolve, so do their carrying capacity (payload), which could include the deployment of acoustic technology during flight while at the same time conducting visual surveys. The combination and comparison of different systems is a topic which has been under discussion, as all current methods have advantages and limitations, and may provide more accurate estimates of animal positioning, size, and more detailed descriptions of animal behaviour in animal studies at sea.

The only two full electric powered aircraft proposed in this review are the Trimble UX5 and the Bramor C4EYE. These systems benefit from the lightweight, ease of use and the low operational cost, requiring only 1 to 2 persons for operating. They both can land in confined areas and are well suited for short missions close to the shoreline. The Bramor C4EYE has the longest flight duration (up to three hours) and has also the capacity for streaming live data back to the operator, while the data has to be downloaded from the Trimble UX5 after the mission has ended. Four fuel-powered aircrafts are proposed, where the Arcturus Jump-20 is the only aircraft with VTOL capabilities. This is a clear benefit when operating from ships or in areas without a suitable landing strip, and requires no extra infrastructure other than a flat surface, such as a helipad. The Insitu Scaneagle and

Thales Fulmar both have capabilities for wire or net landing on ship or land. The Penguin B is the only aircraft that require an airfield to land. With duration of 24 hours it has a long range, and should be considered in cases where one can operate from an airfield. The Thales Fulmar is the only proposed aircraft which can land on sea and is well suited for the harsh environment of marine operations.

With more than 800,000 proven flight hours[5] the Insitu ScanEagle is in a class of its own when it comes to medium sized UAS. It has the capabilities to operate from ships and rugged terrain and has previously been evaluated for surveying of marine mammals and marine fauna. With a mission duration of 24+ hours and its capacity for streaming live data back to the ground station it can be used for continuously monitoring of large areas. However, a possible limitation for all currently available medium size UAS is the lack of an integrated de-icing system.

In powered aircraft, the data can be stored in the form of SD cards and then downloaded to a local computer for analysis. Images and video may be edited a posteriori and processed using analysis software (Ireland et al., 2015) and human visual inspection. Live streaming may also be possible, with storage and further analyses occurring at the receiving end. The only proposed system without this capability is the Trimble UX5.

8.2.1.2 Gliders

Glider platforms tend to be less versatile than powered aircraft, given that they are designed to harvest the energy present in rising air. Hence, they do not prioritize maintaining altitude or flying in straight trajectories. Further, the capabilities are the same as fixed wing powered aircraft. These systems were not found suitable for marine animal studies due to the sink zone above the ocean. Hence, no glider systems were considered in this evaluation.

8.2.1.3 Kites

Kites are generally limited to wind speeds under 6 ms-1, which may limit the locations in which they can operate (Thamm et al., 2013). Adding to the dependency in environmental conditions, this equipment is not often stabilized, resulting in difficulties in hovering over an object or location of interest. The number of available platforms is limited. Often, parafoil kites may be used and the parts collected to create a system used for surveys. There are online platforms available where the construction of these systems is advised and guided, making these platforms highly personalised. These systems are not well suited for marine animal studies due to their wind limitations. There are few commercially available systems or systems that are becoming available as a complete package, and we have therefore selected the single kite platform that is able to conduct surveys of marine animals in flexible weather conditions.

[5] www.insitu.com

Based on the estimates by Thamm et al., (2013), it is estimated that the price ranges for kite systems range between ~US$ 20,000 and ~US$ 44,000.

Kites are similar to fixed wing powered aircraft, except that the wings are not rigid. The advantages are

- Easier to carry in a backpack than compared to a fixed wing with same payload capacity.
- Need no runway for take offs and landings and can be operated from a ship.

The disadvantage is the extremely low weather maxima and limited control during flight, which makes them unusable for offshore applications such as monitoring of marine mammals.

Kites are more weather-dependent than the other systems above. They are particularly sensitive to wind and rain, as these can affect the stability of the equipment lead to difficulties in maintaining a specific survey track. These UAS may conduct transect-based surveys for animal population studies, but struggle in maintaining hovering position to perform more focal assessments. Wind speed may have a strong effect on kite stability and also on the amount of overlap that may result from a survey, and should then be taken into consideration during flight preparations. As with other types of UAS, it is possible to choose between data in the form of photo or video, and as any other visual detection methods kite systems maintain the same limitations concerning detectability of animals. The payload capacity of these systems will depend on the size of the system, though it has yet to be tested at sea.

Kite systems have a flight time that can go up to a few hours, though it seems to require slightly less training time for pilots and operators (Thamm et al., 2013). Similar to powered aircraft, the size of the kite will provide an indication of the payload that it can carry, though smaller kites may prove to be more unstable in strong wings than larger ones. These platforms require runways for take-off and landing, thus making them difficult to operate from vessels in areas distant from the coast. See section 7.2.3 for details.

For these systems, the data can be stored in the same format as for the previous aircraft. Images and video may be also edited *a posteriori* and processed using both analysis software (Ireland *et al*., 2015) and human visual inspection.

8.2.1.4 Lighter-than-air aircraft systems

Similar to kites, these systems may be dependent on weather conditions to provide adequate images of the area surveyed. However, new systems are being developed that may overcome this limitation. We therefore include these platforms in the list of methods for marine animal monitoring.

The OceanEye is supplied with a triple sensor unit (EO/IR/AIS) and is capable of real-time, night video, and imagery. The elevated AIS receiver allows for increased ship detection range, which is of value when conducting studies of animals with a strong perception of vessel presence. The compact camera is attached to the balloon, improving the stability of the sensor unit and quality of the footage. The Helikite platform is able to carry Gyro-stabilised and standard PTZ (pan-tilt-zoom) and modular video cameras, which can be remotely operated to provide a wider view, or store information on-board. Both can be attached in any position of the tethering line, allowing for an exchange of batteries without landing the balloon.

No price information was requested from the manufacturer for the OceanEye system. Based on the price ranges of the Helikite we estimate that the price ranges for balloon platforms range between US$ 147 and US$ 7,362.

These UAS may be less weather-dependent than kites, as they are generally tethered to a vessel. They are also sensitive to wind and rain, but are able to maintain a certain distance from the survey track or the study animals due to the presence of a cable that stabilizes (up to a limit) wind disturbance. These UAS may conduct transect-based surveys for animal population studies, and can be controlled to maintain a hovering position and perform more focal assessments. However, this equipment is dependent on the presence of the support vessel, which may affect animal presence and thus create biased studies.

Tethered balloons can, at standard temperature and pressure, carry about a few kilograms of payload depending mainly on their helium (or hydrogen) capacity. However, though not generally acknowledged, the weight of the required length of line must be taken into account to make accurate assumptions about the actual sensor capacity of the balloon or blimp. Additionally, weather conditions, particularly heat and humidity may affect the lift of the balloon, which in conditions of rain, snow, and mist can get extra weight from the accumulated precipitation on top of the platform. This type of platform is generally sensitive to wind conditions. Helikite managed to overcome this limitation by incorporating a tethered helium balloon with a kite wing. Furthermore, given that they are tethered, the length of the line can be adjusted to cover different heights and distances from the attached vessel.

In lighter-than-air aircraft, the data can be stored on-board the aircraft and downloaded to a local computer for analysis after the survey has been completed, or directly transmitted to a ground station present on-board the supporting vessel. Through real-time transmission of video images, it is also possible to trigger a camera to select photos of the target objects, rather than storing the whole video (Hodgson, 2007).

8.2.2 UAS-sensors

From the discussion above, we limit the sensor survey to stabilized camera systems (i.e. gimbal systems) capable of acquiring HD video (or better). Most gimbal systems on the market come pre-assembled with sensors, and the manufacturers gives the customer a choice from a selection of different sensors to suit the customer's application and needs. As the systems listed below are expensive, high performance gimbals, most manufacturers deliver the same camera sensors, or cameras with similar characteristics. Hence the choice of gimbal system often comes down to what the UAS system provider can deliver as standard options.

The biggest gimbals (like Cloudcap TASE 400) are only needed for exotic (combinations of) cameras, such as the VIS + LWIR + SWIR, or for heavy optical zoom (which we probably do not need for marine animals, as we most often wish to fly below 120 meters due to aviation requirements for VLOS operations).

- Cloudcap Technology: Tase 400 & Tase 310
- UAV Vision: CM 202 & CM 100. The CM100 Gimbal is the smallest and lightest in the study, hence it is possible to fit most UAS systems
- DST: OTUS U135 HIGH DEF & OTUS-L205 HIGH DEF.

In addition, there are specialized gimbals from Insitu and C-ASTRAL which are compatible with the ScanEagle and Bramor systems, respectively.

Most platforms considered in this evaluation are available as a set. It is possible to exchange the sensors for a single platform but it will depend on the availability of compatible sensors developed by the same manufacturer. It may also be possible to deploy sensors such as DSLR cameras as given in the study examples of Table 7, but it has to be taken into consideration the payload capacity of the platform and data transmission compatibility. It is therefore recommended to follow manufacturers' advice on the possibility of using alternative sensors.

Given that for a turn-key (fully integrated/assembled and ready-to-go) UAS system the sensors and stabilizing gimbal are purchased as a package, and the information publically available is limited, it was not possible to obtain price ranges for single sensors.

Imaging sensors such as high resolution still or video camera, operating in the visible spectrum or the non-thermal region of the infrared spectrum are the most relevant sensors for marine animal studies. For video, it is important that the camera is gyro stabilised. This will improve the efficiency of operator analysing the data and will also reduce the required bit rate when doing video encoding/compression. It is also important that the image frames are geocoded, so that the location and size of a spotted animal can easily be determined from the image. A future system combining gyro stabilised geocoded video with corresponding high resolution, geocoded and overlapping still images seems to be an effective system for near-real-time detection and identification of marine animals from UAS data. In such a system, one could imagine the operator identifying potential sightings in the video stream by point and click, and using the corresponding high resolution still image from this area for verifying and identification.

UAS sensors are positioned below the survey platform either providing a straight or angled view. The choice of video (real-time or on-board stored) or still image, and ground resolution will rely on the objectives of the study, but the choice of the type of sensor has to be taken with consideration for the payload capacity of the UAS to be used. Some manufacturers such as ARCTURUS UAV and TRIMBLE provide only complete packages, in which case one can only operate using the sensors provided in the package or produced specifically by that manufacturer.

An integrated system for analysing the data from the UAS is required. Some data processing capabilities, such as object tracking or motion detection, can be included in the sensor or gimbal. This has mostly been used in systems designed for surveillance purposes, and may be useful for marine animal monitoring, especially for focal follows and mitigation purposes. The communication system, used for transferring data from the sensor and to the ground is often an integrated part of the UAS and also used for the main or secondary telemetry link for monitoring and control of the aircraft. Depending on the aim of the study, it is possible to create mosaics (overlapping the photos and creating a chart), analyse each photo or video individually, or for real-time detection, using a system such as the one developed by Ireland et al., (2015). Given that the data may be stored at all times, there will be no data losses unless the sensor is not properly connected to the aircraft or there is equipment failure. Analysing each photo or video individually can be quite time consuming, and we therefore urge the development and public availability of detection algorithms that can be used to triage the photos.

8.2.3 AUV / ASV platforms

8.2.3.1 Propeller driven underwater craft and powered surface craft

As is made apparent in the matrix given in section 11.4, the range of potential combinations is extensive. Dominant factors in shaping options are the payload size and power budget. Mission duration and whether the data is transferred or recorded are early questions in defining the exact specifications for any given mission. Whilst a "low cost, off the shelf" approach is slowly emerging (more rapidly in AUV than ASV), in almost all instances specific requirements can be tailored to a particular survey. On the practical side, self-noise is a key issue to be addresses by all crafts if applied to PAM or AAM. The craft itself may be very quiet but the deployment/attachment method of acoustic sensor is all important here. Self-propelled AUV have a particular challenge in this. Also to note, that cameras, both HD and IR can be attached to ASV which, though it offers a very low observation platform, may have an application in the detection of surface animals, e.g. marine mammals, turtles, seabirds.

The purchase price range of the above AUV and ASV for existing models with integrated sensor packages included spans from tens of thousands of pounds for smaller AUV to several hundred thousands, even millions, of pounds for higher specification instruments. Another model is rental. This is usually by the day and costs here are estimated to be low hundreds of pounds per day for lower specification AUV up to several thousand per day for more. Pricing, especially for rental, may be subject to deployment length and exact requirements. Manufacturers typically have been open to integrating new sensors and tailoring specifications for a given project, but this incurs research and development (R & D) costs – which can be significant. It is worth noting that as this technology emerges out of R & D laboratories to seek an entrance into the commercial market, an exact "price point" of the product is often still to form. Additionally, associated costs such as transportation and service arrangements should be kept in mind.

All above AUV / ASV are designed to follow a track line by waypoint setting. Variation emerges with operator capability to alter course. All ASV claim this ability, but questions arise on responsiveness. Iridium, freewave, wifi and acoustic modem command and control enable buoyancy gliders to be directed in real-time. As a result they are targeted platforms, and can be used to investigate ambiguous observations, or to change survey areas rapidly if required. Station-keeping abilities vary widely. It is claimed by some AUV but there is uncertainty here as to exact capabilities. Powered ASV have the potential to stay on point more dynamically, but this has implications on power/fuel. The method of staying in position by close circling has more flexibility but, by definition, provides less positioning precision. More clearly known on mobility is that all AUV / ASV move very slowly. Except, that is, for the powered boat-style RIBs, some of which are capable of very high speeds indeed.

All AUV / ASV are theoretically capable of conducting PAM and AAM surveys, but project specifics must be borne in mind. Data transfer capabilities will determine whether this is for purposes of logging data only, near-real-time or genuine real-time (i.e. for mitigation monitoring). Additionally, self-noise may be an issue in some (such as propeller driven AUV).

When considering operational practicalities of ASV/AUV, a guiding theme is safety. Any risk of, for instance, AUV / ASV breakdown ahead of a seismic vessel and associated equipment would have massive implications for the whole operation. Before usage in industrial field of operations, extensive trials and proven track record will be required for all crafts to provide assurance on technical reliability. High confidence in ability to complete mission duration and genuine independence are also high priority attributes. In-field support, such as by a chase vessel, may be available but not guaranteed and exact requirements will vary by application. Any ASV/AUV must demonstrate full capability in these areas. Logistical factors must be taken into account, such as ease of deployment/retrieval. Safety concerns are paramount, but also implications on cost (such as freight to overseas locations).

Regarding remote operation, technical and safety assurances will be required on the dependability of the link and responsive ability of remote operation. The control, handling and maintenance of ASV and AUV may require specialist knowledge, provided either by additional AUV / ASV experts heading offshore or by training of existing crew. A clear code of practice is likely to be required and disseminated in advance to potential marine/airspace users, including third parties, in the area.

8.2.3.2 Autonomous underwater buoyancy gliders

There are, to our knowledge, currently four commercially available electric buoyancy gliders: the Slocum electric (Webb et al., 2001) manufactured by Teledyne Webb, the Seaglider (Eriksen et al., 2001) manufactured by Kongsberg, the Coastal glider (Imlach and Mahr, 2012) manufactured by Exocetus, and the Sea Explorer (ACSA, 2013) manufactured by ACSA. In addition, there are several underwater gliders that are in use or development, including Spray (Sherman et al., 2001), Deep glider (Osse and Eriksen, 2007), Tsukuyomi (Asakawa et al., 2011) and the Liberdade Xray/Zray (D'Spain et al., 2011; D'Spain, 2009). 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 is designed to glide to depths of 6,000 m (Osse and Eriksen, 2007), the Sea Explorer is designed to be faster (1 knot) and powered by rechargeable batteries, 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 carrying large and high-data-rate payloads (D'Spain, 2009). Currently there is one manufacturer of a thermal glider (Teledyne Webb), and four hybrid vehicles currently advertised or in-use, the Slocum hybrid (Jones et al., 2011a) manufactured by Teledyne Webb (note, all new Slocum G2 gliders have the hybrid capability), the eFòlaga (Alvarez et al., 2009) manufactured by Graal-tech, the SeaExplorer (Rochet, 2015) manufactured by ACSA, and the experimental SeaBird (Araki and Ishii, 2007). We have limited the descriptions below to those gliders that are currently (or have been) commercially available.

The first ocean-proven electrical buoyancy gliders were Slocum, Seaglider and Spray with similar features (Table 1). The more recent designs typically focus on particular improvements/applications.

Table 1. Common design features of electric buoyancy gliders (from Davis et al., 2002 and Wood and Mierzwa, 2013).

Feature	Design
Endurance	Endurance of months to year, at slow horizontal speed (~0.3 m/s) to minimise drag and vertical velocities of ~0.1 m/s Ballast system that uses a hydraulic pump to move oil between an external bladder and an internal reservoir.
Portability and versatility	A similar size, shape and weight (~2 m length, ~60 kg in weight), that permit deployment and recovery by 1 to 3 people and a small rib
Economy in use	Construction costs in the order of $50,000 to $100,000 and refuelling costs $3,000 to $15,000 per deployment.
Real-time control and data relay	GPS navigation, on-board PC-level internal data processing, and an ability to receive commands and transmit data timely.

In most commercially available systems, the manufacturer is able to provide a fully integrated package that integrates a passive or active acoustic system into the underwater glider. Selection of a specific sensor may be limited by the vehicle payload size (which is small but comparable between the gliders), the communication method employed by the glider, and suitability to a platform undertaking a saw-tooth profile.

The price range for all underwater buoyancy gliders spans ~$50,000 to $200,000 for existing gliders and pre-integrated sensor packages. The manufacturers have typically been open to integrating new sensors, although these have incurred research and development costs. New lithium batteries, sensor calibration and re-ballasting for a mission are in the order of £5,000 to £15,000. Piloting telemetry costs are ~£2 / day, although data transmission costs can be significant on top of this.

Buoyancy gliders typically undulate in the upper 1,000 m of the water column, thereby making subsurface measurements. Traditional visual survey methods involving aircraft or ships are expensive and can be ineffective at detecting small aggregations of animals that spend significant periods of time submerged and out of view of the sea surface. Visual methods are also naturally limited by factors that affect visibility, such as rough seas, fog, rain, snow, and darkness (Baumgartner et al., 2013). The buoyancy glider can therefore undertake marine animal surveys in conditions not suitable for visual methods.

Different makes of buoyancy gliders have different mission durations but typically, once deployed, they are operational 24 hours a day. Assuming the method of detection does not require light, then marine animal observations are undertaken continually throughout the mission duration (6 hours to >1 year).

Iridium, freewave, wifi and acoustic modem command and control enable buoyancy gliders to be directed in real-time. As a result, they are targeted platforms, and can be used to investigate ambiguous observations, or to change survey areas rapidly if required.

Ships and aircraft are operationally expensive to run. With a purchase cost of ~£100,000 per platform and running costs of ~£10,000 to £20,000 per mission (battery, piloting communication and CTD calibration), buoyancy gliders are a scalable economy for a survey. New methods for controlling multiple vehicles enable a multi-vehicle approach to surveys that may compensate for the slow-moving nature of the platform (Greene, 2014).

Buoyancy gliders are acoustically quiet platforms, since they do not have thrusters and use internal actuators, making them ideal platforms for acoustic monitoring (both AAM and PAM). However, acoustic platform noise (self-noise) generation does occurs (predictably) when the buoyancy change and trim adjustments mechanisms are activated, causing potential periods of masking during PAM (Ferguson, 2010).

Buoyancy gliders are designed for slow speeds to reduce drag and extend endurance. Typical speeds are ~0.3 m/s, with the addition of thrusters this can increase speeds to ~1 m/s. The ability of a glider to perform a transect, or to pass through a waypoint is dependent on the ocean currents and their variability within the survey region. The operator can specify how close to a waypoint the platform should achieve before it is accepted to have reached its goal, however the route to that waypoint can be convoluted and straight-line transects may therefore not be achievable in dynamic ocean environments.

There is limited information on the reliability of gliders, due to their relative newness. Brito et al., (2014) investigated the reliability of gliders using 205 missions made by 56 gliders undertaken by the EU GROOM (Gliders for Research, Ocean Observation and Management[6]) programme. The probability of a deep (1,000 m) underwater glider, independent of manufacturer, surviving a 90-day mission without a premature mission end is approximately 0.5. The probability of a shallow underwater glider surviving a 30-day mission without a premature mission end is 0.59.

8.2.3.3 Self-powered surface vehicles and drifting sensor packages

In recent years, several self-powered surface vehicles have become available. These vehicles mostly extract energy from wave motion and convert it into forward motion. Some vehicles supplement this with solar or wind powered electricity generation which is then used to drive a propeller. By extracting energy from their

[6] http://www.groom-fp7.eu/doku.php

environment, the vehicles can often stay at sea almost indefinitely. Electrical power for payloads is supplied by batteries charged by solar panels. Control is similar for all vehicles. GPS and on-board software navigate the vehicle between waypoints. Vehicle position and be monitored via satellite and new instructions can be uploaded at any time.

Self-powered and drifting surface vehicles are relatively quiet, having no propeller noise. This makes them highly suitable for PAM as well as AAM. Some researchers have also attached cameras to these vehicles and have detected birds and marine mammals. Purchase prices are in the $100,000's for the Wavegliders while the smallest of the MOST Autonaut vehicles costs less than $100,000.

All of the self-powered surface vehicles can follow a track line. However, in calm conditions, when wave-power is unavailable, they will not be able to do so accurately and in flat calm conditions, will drift with the current. The exception is the SV3, which has a propeller that can be switched on at these times, so long as sufficient solar power is available. Due to their sub-sea structure which descends 7 m below the surface, wavegliders can only be operated in at least 12 – 15 m water depth (shallower-water versions can be available on request). This generally requires deployment from a vessel equipped with a small crane to lower the float and sub-unit over the side. Wavegliders can be deployed from a slip if the sub-unit is tied up to the float and the vehicle is towed out to deep water prior to the sub unit being released.

The Autonaut vehicles have a small draft and can therefore also be easily deployed from a slipway or beach as well as from a small vessel. Once deployed, the vehicles can stay at sea for many months and both Wavegliders and Autonauts are known to have survived severe storms. Communication with shore via satellite is provided on all Waveglider and Autonaut vehicles except for the smaller Autonaut 2 which only has UHF and Wifi communication. Where satellite links provide insufficient bandwidth for data transfer, it is possible to fit additional radio links to these vehicles for high volume / short range communication.

8.2.3.4 Data processing and transfer in AUV and ASV

Data processing and transfer issues are generic to AUV and ASV platforms. Basic communication (piloting telemetry) with vehicles is undertaken with ease through the current satellite or RF modem options since data volumes are relatively small. However, data relay generally requires considerably more bandwidth and may be impossible to achieve unless a high level of automated processing can be implemented in order to reduce data volume. Challenges occur depending on the sensors fitted to the buoyancy gliders, and what information is required to be transmitted. Therefore, these issues are related to the sensor fitted to the platform

8.2.4 AUV / ASV-sensors

The review of sensors has been limited to those which have been deployed on autonomous platforms or which perform a high level of processing, making them suitable for real-time detection. This review therefore excludes most of the PAM systems designed for fixed autonomous monitoring reviewed in Sousa-Lima et al., (2013).

8.2.4.1 PAM

To date, most interest from researchers has been in the lower cost submarine gliders and self-powered surface vehicles in the hope that they will provide quiet, persistent platforms, capable of collecting PAM data on large temporal and spatial scales. The only PAM systems which are suitable for use on small lower powered autonomous vehicles such as underwater gliders are the SoundTrap, the DMON and the WISPR board. Indeed, 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 since they have fewer space restrictions and generally have more power available. However, there may still be trade-offs between power consumption, power availability and mission duration for many possible combinations.

The larger powered vehicles could also accommodate wide band satellite communications systems and could in principle, provide more real-time monitoring when operating remotely.

We are unaware of any PAM systems being used on the range of powered underwater vehicles. There is nothing fundamental preventing this from happening beyond the obvious possibility of noise interference from propulsion systems. Most likely researchers have shown little interest in this due to the short mission duration of these vehicles which would make them impractical for the collection of marine animal survey data (which generally requires data collection over long time periods in order to obtain sufficient sample size).

Where given, price ranges for PAM systems were all in the $2,000 to $10,000 price range. However, it should be noted that there may be engineering costs associated with mounting any of the systems into specific vehicles. These additional costs may be needed to cover installation of the monitoring device into a secure dry space, mounting of hydrophones, supply of power and interfacing of any communications systems. These costs are, however, likely to remain low compared to the purchase and operational costs of most vehicles.

Several of the PAM systems are recording only, whereas others purport to offer real-time detection. Perhaps the most succinctly useful comment came in a reply from Cornell University regarding the automatic detection capabilities of their Auto Detection buoys: "… any species for which a trusted algorithm exists". As discussed in section 9.5.2, an increasingly wide array of automatic detection algorithms is appearing in the literature, however, most of these are tuned for very specific analysis of historical data and are unlikely to perform well in many situations. PAM systems generally require a human operator to verify detection data and without a considerable quantity of data available for human verification the chances of false alarms from automatic detectors can be high.

For long term monitoring, the most practical solutions are probably the lowest power system available which can record as much data as possible and perhaps perform a minimum of data reduction. Key to any mission planning is defining the required upper frequency limit of the system since this will control the mission duration available with a given data storage capacity. Either all raw data can be stored, or simple algorithms (employed to run at both high efficiency and high false alarm rate) can be used to reduce the quantity of stored data, which is particularly useful when working with high frequency species.

For mitigation monitoring, then mission duration may be of less importance and priority may be given to data relay, on-board processing and ease of connectivity, which is provided by the higher power systems. Underwater vehicle systems clearly have a disadvantage for mitigation monitoring given the time delays incurred while they return to the surface to transmit data. However, for some mitigation scenarios, where species are known to move slowly, there may still be a use for these vehicles in mapping out areas unlikely to contain marine mammals so that operations can minimise the likelihood of incurring a shut-down whilst real-time monitoring around those operations.

None of the systems reviewed had any significant operational requirements. However, for real-time interpretation of incoming data, training and expertise would be required of a similar level as is required for PAM operators on seismic vessels.

Physical dimensions of the systems varied from 9.5 x 4 x 2.5 cm for the smallest system to 56 x 13 x 11 cm for the largest. Weights ranged from 120 g to 1.5 kg. Power requirement was also highly variable, with several systems using less than 100 mW, the lowest being 35 mW for the single channel SoundTrap HF. The highest power systems used between 2 and 4 W of electrical power.

Most systems have the ability to store recorded data, mostly using lossless compression algorithms such as FLAC. However, even with terabytes of internal storage, this does not overcome the fundamental limitations of storing data acquired at high sample rate outlined in section 9.5. However, as storage capacity continues to increase it is likely that full recordings of even high frequency sound will become increasingly accessible in the coming years.

Raw PAM data comes in at a rate of a megabyte per second for high frequency species, 100 kilobytes per second for mid-frequency sounds such as sperm whale clicks and dolphin whistles and a few kilobytes per second for low frequency sounds, such as baleen whale calls. Some of the data relay systems using either analogue transmission or Wi-Fi based digital technology are capable of transmitting that data volume over several kilometres using free spectrum (i.e. no data relay costs beyond equipment purchase). Power consumption for these data relay systems s between 10 and 30 W, which is many times higher than the power consumption of the monitoring systems themselves and would impact on the lifetime of most vehicle deployments. However, for mitigation monitoring, where deployments durations of hours to days may be acceptable, this may not be a problem.

The highest power satellite based systems can relay data at 128 kbps or 16 kBytes per second. This would be insufficient for transmission of anything but 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. Smaller, low power satellite systems, such as the Iridium L-Band, are available which are more suitable for mounting on autonomous platforms and only consume 2.5 W power. However, the low power systems have an even more restricted bandwidth of 2,400 bps (300 bytes per second, or a raw acoustic bandwidth of 150 Hz).

The only systems we are aware of which have achieved sufficiently reliable algorithms such that adequate data can be sent to shore via low bandwidth satellite links are the underwater glider based DMON (Baumgartner et al., 2013) and the Cornell Auto Detection buoys. However, both of these systems only achieve that level of data reduction for certain species of baleen whale. None of the systems reviewed have to date sent adequate information via satellite links for high frequency odontocete sounds for reliable real-time detection with low false alarm rates. Several of the systems offer serial and Ethernet based connectivity and the SA Instrumentation Ltd Decimus and the Seiche system can both be used with wireless modem systems to send enough data in real-time for mitigation monitoring of a wide range of species.

To summarise: for real-time mitigation monitoring, high frequency real-time data can be sent over short distances (up to a few kilometres) using free spectrum radio links. Where local radio links are not possible, accurate identification of marine mammals is currently only practical for some baleen whale species. For population monitoring, where it is unlikely that radio links can be used, raw data, or partially processed data should be stored for analysis post recovery, with only summary and status data being sent through satellite links.

8.2.4.2 AAM

Currently there are selected AAM sensors and AUV glider platforms that have already been integrated. These include: the Imagenex ES853 and Nortek ADCP sensor into both the Slocum G2 glider and the Seaglider (ogive), as well as the Imagenex ES853 sensor into the Slocum G2 hybrid and the Sontek ADP sensor into the SCRIPPS Spray. The comparison matrices showed that the Imagenex ES853, Kongsberg/Simrad WBT mini, Sontek ADP, Nortek ADCP and the Vemco modular VR2C currently have the capacity to be integrated into any of the listed AUV glider systems. The Biosonics DT-X-Sub, mini WBAT and the ASL AZFP could potentially be integrated into any of the listed AUV glider systems whilst these systems and the Simrad WBAT could be integrated into larger AUV. A Biosonics multifrequency instrument has been integrated into a Waveglider (Greene, 2014).

Where given, price ranges for AAM systems were all in the $2,000 to $100,000 price range. However, this is the purchase price for the sensor and there will likely be additional costs associated with mounting any of the systems into specific vehicles. Of the sensors that are available to rent, the price for a three-month rental ranged between $5,000 and $20,000.

The data collected by the AAM system is raw, unprocessed data, with the exception of the Biosonics DT-X-Sub which has on-board processors that produces data summaries which can be viewed as simplified echograms and is able to provide alerts triggered by acoustic events. Most of the AAM systems are able to identify fish and zooplankton from the raw data collected, as well as provide a bearing and direct range estimate to the animal from a single device. Conversely, the Vemco modular VR2C and VMT can only be used to detect species which are large enough to be tagged with an acoustic tag and cannot provide either a bearing and direct range estimate to the animal from a single device. Real-time data transmission is partly possible for all AAM devices (apart from the Vemco VMT) where a ping can be transmitted in real time. However single pings have limited value except to indicate the instrument is working, analyses are typically undertaken on multiple pings.

Where provided, the level of automation for the AAM sensors was categorised as self-logging with a fixed ping rate or programmed intervals.

The raw data volume varies greatly between AAM sensors, depending on their complexity. For example, the raw data volume for the Imagenex ES853 is 256 bytes per ping, compared to the 32 bytes per ping for the Sontek ADP and 5,6124 to 1,159 bytes per ping for the ASL AZFP (depending on the number of frequencies, bin size and range). More information on the data processing and transfer information was provided for the Biosonics DT-X-sub, which has a raw data volume of 30 MB/sec, the ability to provide low bandwidth summary reporting as a method of real-time data reduction, a power usage of 30 watts and a required external power feed of 12 to 24 volts DC.

8.2.4.3 Animal-borne tags

It is possible to integrate tag receivers into an AUV or ASV to provide real-time / near-real-time (depending on glider communication strategy) information (e.g. Waveglider, Slocum or REMUS). Vemco tag locators have been integrated into a Slocum glider (Haulsee et al., 2015), REMUS AUV (Eiler et al., 2013) and a Waveglider[7]. PAM systems as evaluated in section 8.2.4.1 can potentially be used to detect the signature of acoustic tags (Sparling et al., 2016). We did not consider these systems further as it has a minor role in monitoring with regards to noise impact.

8.3 Discussion

8.3.1 How to use the evaluation results to find the appropriate autonomous platform / sensor combination

This review presents a large variety of autonomous vehicles and sensors that are suitable for marine animal monitoring during E&P activities. The requirements for marine animal monitoring were the drivers behind the information that was gathered for each of these systems. The compiled comparison and evaluation matrices (see sections 11.3 and 11.4 as well as Table 2, Table 3 and Table 4) help to select the appropriate platform/sensor combination, and the following discussion points out what capabilities are required from the platforms and sensors in various monitoring situations. Anyone wishing to use the information provided in this review should define the objectives and requirements of the monitoring first. For example (this is not a comprehensive list of questions):

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[7] http://oceantrackingnetwork.org/otn-tests-new-wave-glider-technology/#prettyPhoto

- Which animal species or species group shall be monitored?
- Is it mitigation monitoring / population monitoring / fine-scale behavioural monitoring?
- If during E&P activity, what kind of activity?
- Is the monitoring area near shore or offshore?
- What is the size of the monitoring area?

Species or species group will determine the kind of sensor that can be used for monitoring. An extensive review on which sensor is best suitable for which type of animal in which environmental conditions (including geographical location) was recently conducted for IOGP and summarised in Verfuss et al., (2016) and is therefore kept to a minimum in the current review.

AAM can detect anything with a large enough target strength to be captured by its receiving elements, i.e. enough energy from the emitted sonar pulses needs to be reflected by the animals' body to be imaged on the sonar screen. This is why any large "body", from zooplankton patches and fishes up to large whales can be detected (Table 2). Classification of the animal species or species group is, however, 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 with the Tritech SeaTec system have been developed or are still in development (as discussed in section 7.3.3). 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.

PAM only detects vocalising animals and is mainly developed for whale and dolphin detection. Which cetacean species can be monitored depends mainly on the frequency range of the system, the kind of detector used and whether tonal calls or echolocation clicks can be captured. Species identification is restricted to animals with very distinctive calls or clicks that can be distinguished from other species and depends on the software used with the system and the entailed classification algorithms. Detection algorithms can often be used for data reduction, filtering the most likely detections out of the huge amount of data retrieved, but generally require visual confirmation, especially for mitigation monitoring, where false alarms may cause delays in operations.

While PAM and AAM are sensors that are used with AUV / ASV and are therefore specialised to under water life, video sensors are coupled with UAS and work well for animals surfacing frequently. This means that video sensors may be inefficient for deep and long diving species, at least for mitigation purposes where the detection probability would need to be high (see Verfuss et al., 2016). With appropriately trained human observers monitoring the video stream, classification of animals with this kind of sensor is possible. In order to reduce the huge amount of data collected by video sensors, algorithms can be used to present likely detections to the observer, thus decreasing the potential workload and increasing observer efficiency.

The kind of monitoring determines the platform requirements. These are detailed in section 9.1. Mitigation monitoring, for example, relies on continuous real-time detection capabilities in order to enable a timely decision on whether mitigation measures are to be taken or not (section 9.1.1). For population monitoring, sending data in real-time is not required but may be advantageous (section 9.1.2). Focal-follows may or may not require real-time option, depending on whether the vehicles are being piloted manually or using detect-and-track capabilities (section 9.1.3).

Table 2 gives an evaluation of those sensors included in this review with real-time detection capabilities, and which species group they are able to detect or even classify.

For mitigation monitoring, where the continuous real-time monitoring is required, the sensor alone is not the determining factor. The platform needs to be continuously in contact with the data relay system. Any sensor mounted on an underwater autonomous vehicle can only send data back when at the sea surface and in contact with the relay system. Therefore, only surface or aerial systems would be feasible in monitoring and mitigation instances when continuous real-time detection is required.

Table 2. Evaluation matrix of detection/classification capabilities of sensors (included in this review) capable of real-time detection. With the help of these sensors, one is capable of detecting (Detect) or not capable of detecting (No) marine animals. Some of the sensors deliver data with which marine animals can be classified (to some extent) to species or species groups (Classify).

<table>
<tr><th>System class</th><th>System name</th><th>Real time</th><th>Zooplankton /Fish</th><th>Whales</th><th>Dolphins/ Porpoises</th><th>Seals</th><th>Turtles</th><th>Large fish</th></tr>
<tr><td rowspan="10">AAM</td><td>Aquadopp</td><td>Partly</td><td rowspan="5" colspan="6">Detect</td></tr>
<tr><td>ADP</td><td>Partly</td></tr>
<tr><td>AZFP</td><td>Partly</td></tr>
<tr><td>DT-X SUB</td><td>Partly</td></tr>
<tr><td>ES853</td><td>Partly</td></tr>
<tr><td>Gemini 720i</td><td>Yes</td><td rowspan="2" colspan="2">Detect</td><td rowspan="2" colspan="2">Classify</td><td rowspan="2">Detect</td><td rowspan="2">Classify</td></tr>
<tr><td>Gemini 720is</td><td>Yes</td></tr>
<tr><td>Modular VR2C + tag</td><td>Yes</td><td colspan="6">Classify</td></tr>
<tr><td>WBAT</td><td>Partly</td><td rowspan="2">Classify</td><td rowspan="2" colspan="5">Detect</td></tr>
<tr><td>WBT mini</td><td>Partly</td></tr>
<tr><td rowspan="8">PAM</td><td>C-POD-F</td><td>Yes</td><td rowspan="8">No</td><td>No</td><td rowspan="3">Classify</td><td rowspan="8" colspan="3">No</td></tr>
<tr><td>Cornell / AutoBuoys</td><td>Yes</td><td rowspan="7">Classify</td></tr>
<tr><td>Decimus</td><td>Yes</td></tr>
<tr><td>DMON</td><td>Yes
(Whales only)</td><td>Detect</td></tr>
<tr><td>SDA14</td><td>Yes</td><td rowspan="4">Classify</td></tr>
<tr><td>SDA416</td><td>Yes</td></tr>
<tr><td>Seiche real-time transmission system</td><td>Yes</td></tr>
<tr><td>WISPR</td><td>Partly</td></tr>
<tr><td rowspan="8">VIDEO</td><td>CM100</td><td>Yes</td><td rowspan="8">Detect</td><td rowspan="8" colspan="5">Classify</td></tr>
<tr><td>CM202</td><td>Yes</td></tr>
<tr><td>Dual Imager</td><td>Yes</td></tr>
<tr><td>EO900</td><td>Yes</td></tr>
<tr><td>OTUS U135 HIGH DEF</td><td>Yes</td></tr>
<tr><td>OTUS-L205 HIGH DEF</td><td>Yes</td></tr>
<tr><td>TASE 310</td><td>Yes</td></tr>
<tr><td>TASE 400HD</td><td>Yes</td></tr>
</table>

The **kind of E&P activity** would furthermore determine the choice of platform, e.g. any AUV / ASV around seismic survey vessels would create a significant safety risk (see section 9.3.5) and would therefore not be suitable for mitigation monitoring in these areas (Table 4). On the other hand, deployment of an AUV / ASV in the vicinity of an explosive removal operation for a period of monitoring prior to detonation might be relatively straightforward. The location of the monitoring area will determine which data relay system to be used as will the monitoring kind. Mitigation monitoring often requires the transmission of a large amount of data to a human observer for the purpose of verifying detections. Therefore, a high bandwidth is required, such as is provided by a wireless system. For locations further offshore however, wireless systems are often unavailable (Table 3). Satellite systems, by contrast, have an unlimited communication range that would assist the data transfer, however, the disadvantage is the low bandwidth that satellite systems employ in general. The installation of a wireless system on a vessel accompanying the autonomous vehicle would be another solution for short range, high bandwidth communication offshore (for more information, see section 9.5).

Table 3. Properties generally applying for autonomous vehicles for the data relay systems satellite links and wireless systems

Property	Satellite links	Wireless system
Bandwidth	Low	High
Communication range	Unlimited	Short

The **size of the area monitored** will determine the technical requirements of a platform class. Large areas will demand larger and more robust vehicles while smaller and more agile systems may be more appropriate for smaller monitoring areas. For example, in the context of offshore seismic surveys: small low-range UAS may be used to monitor marine species within the exclusion or high-risk zone; while long range UAS may be used to obtain information before and after the arrival of seismic vessels, thus gathering information on animal density and distribution in the specific region targeted for operations (baseline monitoring) (Watts et al., 2010).

The above text is an example for how to approach the data gathered in this review. The subsequent sections will discuss and explain further details to be considered. This overview of autonomous vehicles will support the selection of the appropriate combination of systems for data acquisition and processing, considering the different qualities of platforms and sensors that are applicable to different types of surveys.

As highlighted above, the diversity of applications for autonomous vehicles means that specific survey scenarios are required in order to provide specific recommendations on which platform and sensor combination might be best to use in a specific scenario. Given the large number of target species, selection of the appropriate sensor/platform type is possible rather than selecting specific individual systems. The same is true for the differing monitoring types, combined with the choice of data relay system. The technical and operational details will need to be tailored to the specific needs of the E&P project, e.g. the area of interest, the platform an autonomous vehicle will start and finish operating from, the required survey length, project budget and more. Here we give an overview of which platform types are best for which monitoring type by comparing each class of platforms and highlighting their particular strengths relating to the specific monitoring types. The results are summarised in Table 4. Examples of specific E&P project or operations needs will be given to narrow the choice of platforms best suited to a specific application. One could then choose the appropriate platform and sensor from the short lists given in section 11.2, based on the technical details and operational aspects given in the comparison matrices in section 11.1 that suit the monitoring application considered. The evaluation matrices in section 11.4, showing which sensor may fit into which platform, then helps to find the appropriate combination of those systems.

It is, however, important to note that the use of autonomous vehicles for animal surveying will encounter many of the same survey design, data collection and analysis issues currently experienced when using standard manned survey vehicles or static PAM. For example, it should be shown that any automatic detectors used are able to perform adequately given the surveying conditions e.g. in poor weather conditions (for both visual and acoustic data) or in the presence of local industrial or ambient noise sources (acoustic data). Furthermore, suitable hardware should be selected if estimation of detection probabilities, or other multipliers, is required.

Table 4. Evaluation matrix of monitoring capabilities of sensor/platform types. Given they meet the criteria as outlined in section 8, the specific sensor/platform types listed are in general well suited (✓), suited (x) or not applicable (-) for the certain monitoring types (exceptions may be possible). 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) population monitoring and focal-follows conducted with static or mobile systems. L-t-a = Lighter-than-air aircraft.

			Monitoring type					
			Mitigation		Population		Focal-follow	
Sensor	Vehicle		Clear	Busy	Short-Term	Long-Term	Static	Mobile
Electro-optical	Powered aircraft		✓	✓	✓	-	x	✓
	Motorised gliders		-	-	-	-	-	-
	Kites		✓	✓	x	-	x	x
	L-t-a aircraft		✓	✓	x	-	x	x
PAM	Powered	AUV	✓	-	✓	-	✓	x/-
		ASV	✓	-	✓	-	✓	x/-
	Self-powered	AUV	✓	-	✓	✓	✓	-
		ASV	✓	-	✓	✓	✓	-
	Drifter		-	-	✓	✓	-	-
AAM	Powered	AUV	✓	-	✓	✓	✓	✓
		ASV	✓	-	✓	✓	✓	✓
	Self-powered	AUV	✓	-	✓	✓	✓	✓
		ASV	✓	-	✓	✓	✓	✓
	Drifter		-	-	✓	✓	-	-

8.3.2 Strength and weaknesses of autonomous vehicle types

8.3.2.1 UAS

UAS generally operate at a lower speed than manned aircraft and with a smaller field of view. UAS may, however, compensate for this by surveying for longer periods of time and reaching areas inaccessible to manned aircraft. Weather conditions, such as sea state, have been reported to affect sighting rate of medium-sized mammals less when using UAS imaging compared to human observers, which is one of the main limiting factors known to decrease sighting rates in manned surveys (Hodgson, 2013). The variability in UAS sizes currently available is also a great advantage for offshore monitoring, since smaller aircraft allow for monitoring of smaller areas at a low cost (e.g. exclusion zones during seismic operations), and larger aircraft can cover larger areas and provide valuable information both before, during, and after offshore operations. The long operational range of UAS mean that they are also quite suitable for mitigation monitoring of the area ahead of a seismic vessel for detecting marine mammals within an exclusion zone around the anticipated start location of the sound source, as suggested by Verfuss et al., (2016).

In addition to the potential use for monitoring marine organisms using visual systems, UAS may also be used to drop various types of autonomous monitoring systems at pre-determined locations. In the case of marine mammal mitigation in relation to seismic surveys, it may be possible to drop hydrophones with a built-in radio link (e.g. sonobuoys[8]) to acoustically monitor areas prior to the arrival of the seismic exploration vessel. This would allow the operators to optimise operations planning given this "early warning" of potential marine mammal presence.

Hence, it is possible to cover a wide range of studies using the same technology. However, there are some shortcomings to the use of UAS, such as the restricted field of view of an image and the image resolution required to compensate for this at higher altitudes, and the time to analyse the data after the survey. For this last factor, real-time data transmission and/or automated detection of animals would help to reduce post-survey image analysis time.

The advantages of using unmanned systems not only cover health and safety issues but also the quality of the data that can be acquired. Data from digital surveys overcome the issues related to observer bias and accuracy of the information concerning flight operation data (altitude, speed, field of view accuracy). Acquiring the GPS location of every image provides greater accuracy in the location of a detection than for manned surveys where

[8] See http://www.uasvision.com/2015/07/22/ultra-electronics-studies-uav-drop-options-for-sonobuoys, https://www.google.com/patents/US3986159 (last accessed 03.02.2016)

observers report the sightings. Using the GPS location of an image, it is possible to obtain the coordinates for the image corners, and thus of each animal sighted within it (software Vadar[9]).

The success rate in the use of UAS is highly dependent on the main aims for its use. Circumstances that demand long range operations with higher sensor quality will thus be pricier than in circumstances where focal monitoring of single individuals or groups of animals is needed, which may provide valuable results with smaller and less costly platforms. Although there are several hundreds of platforms and sensors on the market, and new systems continuously being developed, it is obvious that many systems produce good quality data regardless of the platform used. The combination between platform and sensor should be chosen based on the operational needs and the capacity for the platform to carry a specific sensor for the amount of time or distance required.

Depending on the payload, a low-cost camera with high or low stability and quality can be mounted into the system, providing valuable information about animal distribution, abundance, and behaviour. Balloons and kites are cost-saving alternatives for some fixed and rotary wing systems (Thamm and Judex, 2006; Altan et al., 2004; Fotinopoulos, 2004; Grenzdörffer et al., 2008; Scheritz et al., 2008), though they rely heavily on weather conditions and are difficult to control when attempting to follow a predefined track. In terms of data analysis, it is often sufficient to have a quick overview of images or videos acquired using low-cost sensors, whereas for accurate measurements with more precise methods (e.g. differential GPS), data require a more detailed review and evaluation. In recent investigations, the trend seems to be directed to fast processing such as online triangulation and direct geo-referencing, which may facilitate imagery analysis and reduce personnel costs. In addition, the sensors and systems are getting smaller, at a fraction of the price, and operating with open source platforms that are continuously being developed in photogrammetry. Data integration of various sensors and high precision and resolution of specific applications and near real-time applications has also been under focus recently, with continuous progress.

This study makes the following short list of requirements for a UAS monitoring system: Stabilised high-resolution video for detection, high resolution images for identification, real-time geocoding of image data and a computer system for efficient analysis of recorded data and localisation of animals. If the data are to be transmitted to the ground a high bandwidth data link is also required.

8.3.2.2 AUV / ASV

There is a broad range of AUV and ASV models and sensors that will meet most needs. The platform should be chosen based on the size, endurance, payload and depth capabilities required for each application. Larger powered AUV are generally more suitable for deep water, open sea tasks, than small powered AUV which are more suited to shorter missions, where the reduced cost is a must and the smaller payload is not a limitation.

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[9] www.cyclopstracker.com

Underwater buoyancy gliders offer similar capabilities for sensor combinations as powered AUV. However, they have reduced payload capabilities, reduced manoeuvrability in fast currents and operate at slow speeds. On the positive side, they have long mission durations, independence from a mother ship and the ability to profile the vertical range of the ocean. The integration of both active and passive sensors into underwater buoyancy gliders is also relatively well advanced in the scientific community.

Self-powered craft such as the Waveglider offer largely similar capabilities as powered ASV but there are some main differences. Reduced payload capabilities in self-powered craft may be a limiting factor but the longer mission duration and greater independence (in terms of minimised mechanical maintenance) of simpler self-powered ASV has significant appeal (particularly for longer term environmental monitoring).

8.3.3 Platform types for mitigation monitoring

Mitigation monitoring generally takes place in the presence of some kind of E&P activity meaning that it is highly likely that a number of vessels are operating in the area. These vessels may have competent technical personnel on board with the ability to deploy, service and operate autonomous platforms. However, in many circumstances, vessel operations are already working close to the limit of what is practically feasible in terms of equipment deployment, personnel are already assigned to challenging and all-consuming tasks and there may not be room on board either for additional equipment or for additional personnel to operate it.

Unmanned vehicles have so far not been used for mitigation monitoring but bring potential into this field. Some systems may well be placed for the use of mitigation monitoring as they allow for (near) real-time detection, which is necessary for timely decision making. These systems would need to operate for long enough periods and cover wide enough ranges to meet the temporal and spatial requirements of the various guidelines. Synchronised operation of a small or larger fleet of vehicles has the potential to obtain a wider field of view to cover larger areas than single vehicles. The concurrent use of different mitigation monitoring methods, e.g. different autonomous sensor/platform types combined with monitoring methods installed on a manned platform (e.g. MMO/PSO, thermal-IR) will increase the probability of animal detection, which is an important factor in mitigation monitoring.

Mitigation monitoring is usually conducted close to the mitigation zone astern of the seismic vessel – an area where no vessel, let alone an autonomous one, can safely operate. Other support vessels do operate ahead and to the sides of seismic vessels, but, as outlined in section 9.2.1, there would be severe problems in deploying additional autonomous sea based vehicles in these areas. This is why AUV and ASV are not considered suitable for mitigation monitoring in operationally busy areas (Table 4). Aerial systems however, may be suited if they meet the requirements outlined in section 9.1.1.

In dynamic operations (e.g. a seismic vessel) there is great potential for autonomous system, especially UAS, to scope ahead, to operate as an alert system to mitigation monitoring methods on the source vessel. In many operations, the unmanned systems would be at a stand-off distance from the source, which may (but not necessarily) limit the ability to establish the animal's positon relative to the monitoring zone or sound source, respectively. However, one big advantage of autonomous systems is that they give the opportunity to cover great distances and large areas, especially when using multiple systems that coordinate their movements through a co-operative communication system. However, as discussed above, there are significant logistical and safety constraints which would need to be overcome before sea based autonomous vehicles could be operated in the vicinity of a seismic survey.

As discussed in section 9.1.1.1, the localisation of the target animal would be a great advantage. The experimental autonomous PAM systems have tended to use only one or a small number of hydrophones close together. In most cases, these can only provide animal presence; some may be able to provide bearing information to the animal, but none could provide animal range. The only example of an exception to this is the simultaneous deployment of three submarine gliders off the US East Coast (Fucil et al., 2006), where time of arrival difference of the signal at the three vehicles was used to estimate animal location. While this technique could be implemented using multiple surface vehicles, if the deployment of one vehicle in the vicinity of a seismic survey is problematic, then deploying three (or more) vehicles would clearly require careful consideration. A vehicle capable of towing more than one array or equipped with beamforming capability or vector sensors could also resolve left-right ambiguities and localize in near real time.

If it were possible to deploy vehicles close to a seismic survey vessel, automatic detectors can be used with some species, but false alarm rates are rarely low enough for action to be taken without some verification, so significant amounts of data need to be relayed back to an operator. The relay of significant quantities of data back to the vessel is a problem, but not an insurmountable one, since a number of wireless radio systems exist which can send wide bandwidth data over short distances.

In operations such as unexploded ordnance device (UXO) removal or well-head decommissioning, where the source is in a fixed position but an MMO/PSO or detection technology cannot be placed close enough to the source to provide adequate monitoring, autonomous vehicles would provide a safe and effective solution, particularly, as they do not place humans within a dangerous working area.

Trials with PAM on ASV C-Worker and C-Enduro showed promising results with successful real-time detections. An appealing idea is for the ASV to scope ahead of the seismic vessel for marine mammals. This offers the benefit of operating in lower noise environment (away from the vessel), and would enhance ability to detect low frequency baleen whale vocalisations, which are hard to detect with PAM installed from a seismic vessel (Verfuss et al., 2016). However, this would not cover the monitoring zone (operating instead as an early warning system). So it would not replace existing methods, but would be complimentary, or could be used for assessing a monitoring zone located around the anticipated start of sound source operation (e.g. during seismic surveys) as suggested by Verfuss et al. (2016). This task could also be achieved using UAS.

8.3.4 Platform types for population monitoring and focal-follows

8.3.4.1 UAS

Of the three classes of aerial platforms considered in this review, powered aircraft have many of the capabilities required for aerial surveys of marine animals. Kites share many of the same attributes as powered aircraft and they are easier to transport and, in some cases, deploy than fixed wing aircraft. However, they are less robust to bad weather, which is a major disadvantage for wildlife monitoring, especially during offshore operations (see Table 4 for this and any further discussion). Sensor data from these platforms can be geo-referenced using data from a GPS and flight data recorder, which greatly improves the accuracy of measurements related to the individual animal's position when sighted.

Lighter-than-air platforms also have capabilities to perform marine animal surveys but, due to their requirement for a tether, several would either have to be moored to static buoys to create a series of monitoring points, or attached to a moving vessel (which could, in theory, also be autonomous) to conduct a line transect survey. However, both of these scenarios (moored and tethered) are potentially more logistically complex than using fixed wing UAS and, therefore, powered aircraft appear to be the optimal candidate platform for aerial transect-based surveys using autonomous vehicles.

In terms of individual focal follows, however, lighter-than-air aircraft should be considered as a potential candidate platform, though their ability to follow animals will be restricted to the manoeuvrability of the support vessel to which they are tethered. Powered aircraft can be piloted to follow animals, rotary wing vehicles have performed well in existing studies (Durban et al., 2015), though fixed-wing aircraft may struggle to hover above stationary, or slow moving, focal animals. Therefore, powered aircraft and lighter-than-air aircraft could be good candidate platforms for individual-based monitoring, depending on the exact goals of the monitoring.

In conclusion, the studies mentioned previously and systems evaluated for this review highlight the potential of UAS in marine wildlife monitoring. Koski et al., (2009a) and Hodgson et al., (2013) support the use of unmanned aircraft in marine monitoring and its potential to replace current methods employing human observers posted on the source vessel or in an aircraft. However, as mentioned in Koski et al., (2009a), this can only really be achieved when surveying large individuals or large groups of small animals if the search area is small. For larger areas and detection of smaller animals, higher resolution video is required if one is to compare both manned and unmanned aerial detection. Therefore, the next steps in establishing the efficacy of replacing manned aerial surveys with UAS is to conduct a direct comparison and determine whether the proportion of animals available for detection from the air is equivalent for both methods. This would need to be conducted under a variety of conditions, ranging from Arctic summer/winter to temperate and tropical regions, where both the detectability and endurance of UAS is expected to vary. Additionally, testing at different locations could also include a range of different species, which would assist in determining the limitations of species identification, particularly in regions with long-diving and evasive species.

8.3.4.2 AUV / ASV

The five classes of AUV / ASV reviewed in this report are all capable of completing marine animal surveys of various kinds (see Table 4 for this and any further discussion). Some classes of platform share similar characteristics, though there are also clear different strengths and weaknesses between classes relating to marine animal surveying.

The potential to increase spatial and temporal survey coverage is a major benefit of using autonomous vehicles. To that end, the fact that powered surface craft and propeller driven underwater craft have survey duration times on the order of hours, rather than the months that unpowered vehicles can be deployed for, is a disadvantage for long-term wildlife surveying (though a notable exception was the ASV C-Enduro, with a maximum survey duration of 90 days). However, these platforms may be more suitable for individual focal-follows, especially those with increased manoeuvrability.

The autonomous underwater buoyancy gliders and the self-powered surface vehicles generally have much longer survey durations, which make them very attractive for long-term wildlife monitoring. Furthermore, the ability of underwater gliders to vertically profile the water column (which may also aid detection of different marine animals that occur at varying depths) is a further advantage of these vehicles. Reduced payload capabilities may be a limiting factor but the longer mission duration and greater independence (in terms of minimised mechanical maintenance) of simpler self-powered ASV has significant appeal, particularly for longer term environmental monitoring.

An important advantage of the smaller, low powered autonomous vehicles is their low noise floor which can provide at least some level of confidence when comparing survey results from different regions since a) masking of animal sounds will be both low and stable across platforms, and b) animal reaction to the smaller platforms is likely to be low and consistent. The varying noise output from vessels can both mask sounds and cause changes in animal behaviour making it difficult to compare data collected from different survey vessels. The use of large vessels for marine mammal surveys also poses the risk of collision with the animals under study. Powered AUV are less likely to play a role in population monitoring due to their limited deployment lifetimes and likely noise interference, particularly for PAM sensors. Although relatively quiet compared to research vessels, propeller driven AUV may disturb marine fauna in sensitive regions, especially when running geophysical sensors with a high acoustic output (Wynn, 2013). The noise generated by the propeller in propeller-driven AUV has the potential to mask low level signals in the same frequency range, thereby limiting the use of this type of AUV for PAM purposes.

Another limitation of the AUV / ASV platforms is their sensitivity to environmental conditions, particularly currents, and how this affects survey design. Though information was not available for all platforms, the powered instruments are likely to have most resistance to currents (for example, the REMUS propeller driven AUV can hold station in strong currents). Clearly the drifting buoys are the most affected by currents, though their major benefit is their low price compared to other platforms. As discussed in section 11.6.2, current research is focussing on how much deviation from a planned track is needed before the survey design cannot be used to make inferences about animal density/abundance in the wider study area. In the case of self-powered platforms, it may be that the extended survey duration is a suitable trade-off for some track line deviation, particularly if the altered course changes are minor compared to the overall survey design.

For the use of PAM sensors on AUV / ASV, hydrophone arrays which can localise animals may be required for detection probability. Auxiliary behavioural studies may be needed to estimate vocal production rates and/or group sizes. For some regions data on group size or vocalization rates may be available from past studies, or might be extrapolated from similar species and regions in the absence of directly relevant data to supply vocalization rate and group size values. Regarding range estimation using PAM, ship-based surveys often use hydrophone arrays and the appropriate software to estimate bearings to animals. As the ship moves, multiple bearings to the same animal or group of animals will cross over time to provide an estimate of range (i.e. target motion analysis). In the case of slow moving autonomous vehicles, target motion analysis will not work if animals' positions change quickly relative to the vehicle as bearings to the same animal/group are unlikely to cross. Therefore, more complex hydrophone arrays will be needed that can estimate range, which, in turn, can be used to estimate detection probabilities. However, the versatility of autonomous vehicles is an advantage here; if a multi-element passive acoustic array (capable of estimating range to a calling animal) cannot be deployed on a single platform, then multiple vehicles could be deployed as an array. Furthermore, a mobile array could be relocated and also its configuration could be adjusted depending on the target species. The ability of an array to be reconfigured would be an advantage over current fixed arrays, which often have to have spacing for range estimation that is species (or groups of species) specific due to the wide range of frequencies at which marine animals vocalise.

Although an advantage of self-powered platforms is that they can be deployed for long durations, the consequence is that they are slow-moving. As discussed, this has some analytical implications (i.e. the need to implement cue-counting or snapshot methods to make sure that animal movement does not create bias). It also has logistical implications – a smaller area is likely to be covered by an AUV / ASV than by a ship in the same timeframe. Furthermore, an autonomous vehicle may need an additional support vessel, so this cost needs to be factored in to the survey budget. However, despite these additional considerations, the fact that autonomous vehicles be deployed for extended periods is a major advantage for marine animal surveys. By having the ability to thoroughly monitor a specific area through time, but also being able to efficiently move to other parts of the study area make them a powerful asset to use.

8.3.5 Technologies that might be used in future field trials

This section describes (sections below) and summarises (Table 5) the technologies that might be used in future trials.

8.3.5.1 UAS

All systems reviewed in this evaluation appear to have the capabilities to monitor marine animals in offshore regions. Future trials should attempt to focus on the versatility of each system (platform and sensor) in detecting species of various sizes, under variable conditions. Since UAS may have different qualities and applications, it is recommended to assess the conditions to which each system may be most suited. For instance, for long-range experiments, it is necessary to operate vehicles with higher endurance and range, which may demand special flight permits and operating costs. Abundance and distribution studies focusing on the use of UAS in areas relevant to Oil and Gas related operations, will provide not only information about animal distribution, but also seasonal data that can be used for the O&G industry to conduct environmentally-conscious decisions in the operations conducted (e.g. restricting E&P activities temporally/spatially to avoid sensitive times/areas). Additionally, studies using UAS for behavioural experiments, such as controlled-exposure experiments during seismic activity, can result in scientifically valuable knowledge that can also be useful for the industry.

Side-by-side comparisons between different autonomous vehicles (AUV, ASV and UAS) can be valuable to evaluate the degree to which the data acquired by these technologies can be complementary. Simultaneous deployments of various systems may help to estimate detection probabilities of a given system by using the other platforms to conduct "trial"-based detection probability estimation. This would, however, demand a high degree of control over the conditions in which the equipment is deployed, but it would be nevertheless highly relevant for a greater understanding of the capabilities of all these systems.

8.3.5.2 AUV / ASV

Several PAM and AAM systems have already been combined with several different autonomous vehicles and shown themselves capable of collecting data. Which technologies might be used in a trial would very much depend on the specific aims of that trial. Unless logistical and safety constraints can be overcome, it seems highly unlikely that AUV or ASV will be deployed in the vicinity of a seismic survey vessel for real-time mitigation. For population monitoring, the choice of both vehicle and sensor would be governed by the specific species of interest, the geographic area, the water depth, local current strengths, shipping density, are the obvious questions which would need to be answered before selecting a platform, but there are also other factors such as the expected animal encounter rate and the precision required of the study which might affect platform choice. Given PAM systems' inability to distinguish some species groups (e.g. accurately separating dolphin whistles to species), it would be necessary to determine what level of species sub division would be required. Answers to these questions would guide the type of sensor required, the duration for which monitoring may be required and the number of vehicles (or listening stations) that should be deployed.

AUV and ASV may also be suitable tools for sound measurement, particularly in remote areas where data is harder to obtain. Underwater buoyancy gliders and the Waveglider are suitable for this task if a vessel can deploy them nearby. Alternatively, the Autonaut in particular would be well suited to this task due to long mission duration and independence.

Table 5. Recommended technology types that might be used in future 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.

			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	Waveglider		
	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* *see population monitoring	NONE				
	Self-powered	AUV	NONE	NONE				
		ASV	NONE	NONE				
	Drifter		NONE	NONE	All		NONE	

8.3.6 Data gaps and recommendations

This section provides a description (sections below) and summary (Table 6) of the data gaps and recommendations identified in this report. One overarching recommendation directly connected to this review is the establishment of a computer based expert system that uses the vast amount of information gathered in this review and the preceding review on low visibility monitoring techniques as published in Verfuss et al., (2016). This expert system should be based on the evaluation criteria established in both reviews, and should provide a list of the most appropriate systems and methods as an output based on the monitoring requirements fed into the expert system. A cost/benefit-analysis tool could also be implemented. This system would need to be based on a live database that will be updated on a regular basis to keep the information from this rapidly developing field up to date.

8.3.6.1 UAS

As new systems arise, additional testing is required to further validate the quality of the data acquired during unmanned aerial surveys. Side-by-side comparisons with current monitoring methods still represent a large data gap, which are of high relevance particularly when considering the replacement of current methods. Additionally, the amount of information provided by UAS producers is limited, which restricts the information provided in this report. However, even with limited information, it is already possible to see that the systems have a high potential for application to offshore monitoring of marine mammals, turtles, and fish.

Though the systems show great promise, the development of automatic detection algorithms applicable to the variety of data gathered using UAS, is one of the key areas that requires further development. Detection algorithms need to be adaptable to the varying environmental conditions to which they are applied, and the number of false detections needs to be well quantified (and minimised for real-time mitigation purposes). Real-time data transfer may improve data filtering and acquisition, but it remains dependent on a human observer to verify an animal detection, which may not always be easy if the aircraft is flying at high speed. Finally, there is a trade-off between the degree of false positives and the probability of missing a detection– a more sensitive algorithm will allow a higher degree of false positives but with a less sensitive algorithm there is a higher chance of missing a detection. For any particular application, the balance between these may differ depending on the consequence of missed detections – for example in real-time mitigation there is likely to be more of a need to implement a more sensitive algorithm than for population monitoring.

As platforms and sensors vary in their capabilities, it would be worth assessing the potential use of each type for specific applications. For instance, testing the difference in data quality between video and IR, or still-photo and IR, particularly when monitoring large areas and presence of small species. The detection of marine turtles and large fish should also be under focus, since most monitoring studies using UAS involve either terrestrial mapping or marine mammal detections.

Though there has been an increase in the use of UAS in marine mammal research, relatively few studies have reported their effects on marine animal behaviour (Smith, 2016). Altitude plays a key role in assessing the potential effects of UAS on marine animals, but it has not yet been established whether there is a distinction between disturbances from noise versus visual disturbance as a function of altitude (Smith, 2016). As altitude decreases, it is most likely that the triggers for behavioural responses change from acoustic to both acoustic and visual ones. For cetaceans in general, a behavioural disturbance may be triggered during low altitude UAS operations. When compared to manned aircraft, several studies have documented that UAS cause a smaller degree of disturbance and avoidance behaviour (Acevedo-Whitehouse, 2010; Mulaca, 2011; Moreland, 2015). This is possibly as the noise levels produced by UAS are far below those from manned aircraft (Jones, 2006; van Polanen Petel, 2006; NMFS, 2008; Hodgson, 2013; Goebel, 2015; Pomeroy, 2015). Overall, as UAS technology improves we are likely to expect a further spike in UAS operations with an application in animal monitoring, particularly in marine regions. It is therefore relevant to understand the effects of this technology itself and compared with current monitoring methods for various species and locations before it is accepted to replace or complement other methods using a precautionary principle.

The evaluation presented here provides a glimpse at how UAS may efficiently collect valuable data and transform operations for the oil and gas industry. The value of UAS for reduced risk and increased cost avoidance is visible across the tests conducted over time and the progress of this technology. Lower UAS operating costs, for example, allow more frequent aerial inspections resulting in enhanced awareness and more proactive maintenance. As industries attempt to fully understand the benefits of employing UAS, they require thorough planning to utilise the best technology to meet their needs (i.e. take in consideration regulatory and technology updates that may affect data acquisition and analysis), and effectively harness the increased volume of data to make informed decisions (Gibbens, 2014).

8.3.6.2 AUV / ASV

There are a number of platforms and sensors at a high state of technological readiness which can be used for the collection of PAM and AAM data from autonomous platforms. With a little effort, many of these sensors could be combined with many of the platforms and they could be sent out to collect monitoring data. The problems that limit the use of these systems also often apply to surveys conducted from ships in that it is data interpretation rather than data collection which is the fundamental limitation. These problems can however be more acute on smaller lower powered autonomous vehicles than they are on ships for a number of reasons.

For PAM, the current trend is to deploy more sophisticated hydrophone arrays that can at least determine bearings to sound sources. Fast moving vessels can also use target motion analysis to determine range to some species, and the possibilities of combining visual and acoustic methods on the same platform can help to understand overall detection probability. The development of PAM systems for autonomous platforms that can employ more sophisticated arrays therefore requires consideration.

Although the development of detection algorithms is further developed for PAM than for video and AAM, in most situations, the reliability of these algorithms means that human observers continue to play an important role in data analysis whether it be for mitigation or population monitoring. While detection and classification algorithms will always continue to improve, it must be understood that they will never be perfect and are unlikely to ever provide simple red/green stop/go traffic light like systems for mitigation in most situations. This fundamental limitation should be taken into account as we move forward with developing these systems and while we would not suggest that further research into algorithms for automatic detection is not worthwhile, research into both the magnitude and the effects of mis-detection and mis-classification and investment in systems which make it possible for humans to continue to play a role in decision processes is probably of high importance.

AAM future research should focus on developing detection algorithms and data compression techniques for returning summarised and/or raw data over low bandwidth communications. Simultaneous application of the different sensor types may help quantify false detection rates and estimate detection probabilities for different platform/sensor combination as discussed in section 8.3.5.2 and as outlined in Verfuss et al. (2016). As for all platforms, well-annotated datasets that can be used to test detection and classification algorithms are essential. The performance of the detectors used with AUV and ASV will also need to be tested/proven in the presence of local industrial or ambient noise sources.

The use of PAM sensors for marine animal monitoring in recent years has highlighted the need for continued behavioural research to better understand the contexts in which animals produce sound (Marques, 2013). This is key to inferring animal density from acoustic data. Optimal survey design for passive acoustic surveys is also an ongoing area of research (Marques, 2013) but, as mentioned in Section 8.3.5.2, these investigations will rely on specific survey scenarios in which to test different configurations of platforms and sensors.

In general, behavioural information on many animal species forms a huge data gap. Therefore, auxiliary studies on animal behaviour such as the vocal production rates, group sizes, diving behaviour or surfacing rates will help to quantify detection probabilities of the target species and reduce the surrounding uncertainties.

8.3.6.3 Operational aspects

Health and safety is the highest priority with regards to the operation of autonomous vehicles. Technical reliability for these systems is a key issue for any craft that is considered for marine animal monitoring, and not all autonomous vehicles have a proven track record of their technical reliability. Any considered craft should therefore be trialled extensively to ensure their reliability during operation to ensure sufficient safety.

Further promotion of the HSE procedures would be the development of an industry-wide “code of practice” for operation of autonomous vehicles in industrial operational fields to ensure safe interaction with other marine/airspace users. There are many issues concerning the regulations, which differ among countries and lack international harmonisation on both standards and regulations. This can create some resistance from current air or water space users and public apprehension. This should, therefore, be further developed in order to create a smoother transition to, and acceptance of, autonomous vehicle use. Therefore, one recommendation is to construct a framework governing rules and regulations that are flexible and amendable to the specifics of an industrial project and to the rapid development of autonomous vehicles. This framework should allow for the range of application abilities of autonomous vehicles. A further step would be the international harmonisation on both standards and regulations.

Further research into "detect-and-avoid" systems for autonomous vehicles is another step towards safe operation of autonomous vehicles. There are, for example, safety and regulatory issues associated with operating a UAS in civil airspace, which need to be addressed by the aviation and airspace authorities in the countries where unmanned surveys are to be conducted. The lack of systems with see-and-avoid technology that would prevent the UAS from colliding with an aircraft limits the ability to conduct studies in remote areas and is also one of the main concerns raised by aviation authorities. The mandatory inclusion of see-and-avoid technology in UAS is under discussion at the moment to help achieve technology acceptance and safety.

Table 6. Shortlist of recommendations with medium (M) or high (H) priority and with medium (M) or high (H) urgency, along with the related topic and data gap.

Topic	Recommendation	Priority	Urgency	Data gap / issue
ALL	Studies comparing MMO/PSO, PAM, UAS, AUV, ASV and tagging to assess the capabilities of each systems, determine to which extent they may complement each other, and provide accuracy in animal distribution and behaviour studies	H	M	Need for assessment of technology capabilities in relation to all monitoring methods
AAM	Focus on developing detection algorithms and data compression techniques for returning summarised and/or raw data over low bandwidth communications	M	M	Detection algorithms and data compression techniques not well developed
PAM	Development of PAM system for employing sophisticated arrays for bearing and distance measurement	M	M	Limitation in data interpretation
PAM	Testing of performance of systems in the presence of local industrial/ambient noise sources	M	M	Applicability of PAM in a noisy environment
Behavioural data	Improve knowledge of target species behaviour through dedicated behavioural studies	H	H	Multipliers such as group size/ call production rates are often important in population monitoring and also relevant for mitigation monitoring.
Operational safety	Extensive testing of systems to ensure reliability during operation	H	H	Reliability of systems often not known
Operational safety	Development of an industry-wide "code of practice" to ensure safe interaction with other marine / airspace users	M	M	No "code of practice" existing for interaction between autonomous vehicles and other marine / airspace users
Operational safety	Construction of a framework governing rules and regulations that are flexible and amendable to specifics of industrial project and development of autonomous vehicles	M	M	Regulations differ among countries, lack international harmonization on both standards and regulations.
Operational safety	Research into collision risk and integration of "detect-and-avoid" systems into autonomous vehicles for safe operation of autonomous vehicles	H	H	Integration of "detect-and-avoid" systems often not given.
Sensors	Improvement of algorithms for (real-time) detection, classification, localisation	M	M	Detection algorithm for marine animal species not always implemented, lack of classification

Topic	Recommendation	Priority	Urgency	Data gap / issue
				of many species, localisation option may be missing
Sensors	Identification of the magnitude and effects of miss-detections and miss-classifications. Simultaneous application of different sensor types to quantify false detection rates and estimate detection probabilities for different platform/sensor combinations	H	H	False alarm rates and rate of misses not well known.
UAS	Further studies for technology testing in offshore regions before, during and after seismic operation. Comparison with current (manned) methods in assessing animal distribution and density in areas of interest for the petroleum industry	H	M	Technology capabilities in relation to current aerial and ship-borne mitigation monitoring methods not known
UAS	Use current available UAS data to develop versatile detection algorithms that can be used both during real-time transmission and for post-processing of the data acquired.	H	H	Automatic detection algorithms generally non-existing or at basic level.
UAS	Development of real-time detection systems and support for further development of existing real-time detection systems.	H	H	Hardly any real-time detection systems existing.
UAS	Investigate further capabilities of UAS that can be combined with surveillance, such as deployment of other equipment at sea	M	M	Need for further investigation of the capabilities of sensor and aircraft systems
UAS	Compare different sensor systems for species such as fish and marine turtles, tackling both the testing of sensor types and need for more knowledge about sensitive species in regions of interest for the petroleum industry.	M	M	Need for further investigation of the capabilities of sensor systems

9 Further information

9.1 Requirements of autonomous vehicles for marine animal monitoring

The ocean can be a hostile environment and the use of autonomous systems will not only decrease the risk to survey personnel, but also enable surveying of hard-to-reach study areas, such as areas affected by ice cover (Dickey et al., 2008). The use of autonomous vehicles may be more cost-effective and able to generate more robust survey data and results than traditional ship and aerial-based surveys. Depending on the sensors used with an autonomous platform, round-the-clock monitoring may be possible, in contrast to manned surveys that collect visual sightings, which can only be conducted in daylight hours. The use of autonomous vehicles creates opportunities to study the vertical variability in the world's oceans (using diving AUV systems), while traditional visual survey methods can be ineffective at detecting small aggregations of animals that spend significant periods of time submerged and out of view at the sea surface (Baumgartner et al., 2013). In general, autonomous systems have great potential to improve the spatial and temporal coverage of marine animal surveys (e.g. Van Parijs et al., 2009).

There are several existing examples of the use of autonomous vehicles for marine animal surveys, which are summarised in section 9.2 as well as Table 7 and Table 8. However, it is important to assess these technologies and consider whether the instruments are compatible with existing animal survey methodologies, or whether new surveying methods are required.

There is a wide range of autonomous vehicles (outlined in sections 7.2), thus, their capabilities to collect suitable data for marine animal monitoring will vary. This section will provide a general discussion of marine animal monitoring, identifying key features of survey design, data collection and data analysis which need to be considered in relation to using autonomous systems as monitoring platforms. These features will be used to assess the potential suitability of the various autonomous vehicles for monitoring marine animals for the O&G industry.

The key considerations when assessing whether autonomous technologies are suitable for mitigation monitoring and surveying marine animals for both population-level and individual-level studies, can be split into the following topics:

- Survey design
- Data collection
- Data analysis.

In this section, each topic will be discussed in relation to autonomous technologies to understand which capabilities an autonomous system needs to cover to be regarded as suitable for a certain monitoring task (see also section 8.3.1). Examples on the current use of autonomous systems used for marine animal monitoring can be found in section 9.2.

9.1.1 Mitigation monitoring

9.1.1.1 Survey design

In terms of mitigation monitoring (section 7.1.1), the survey needs to be designed so that the monitoring ensures a timely detection of a target animal within the monitoring zone. Continuous real-time or near real-time monitoring is required to achieve a timely detection so that the time between a target animal entering a monitoring zone, its detection and the subsequent mitigation decision is sufficient to enable an effective mitigation cascade (see Verfuss et al., 2016 for further discussion).

It is also important that the probability of detecting a target species is high. Key to maximising detection probability results in the choice of the appropriate sensor technology. Electro-optical sensors combined with aerial vehicles can only detect animals present above, at, or close to the sea surface (an exception is in case of thermal IR, which cannot detect sub-surface animals), PAM sensors combined with AUV / ASV require that animals vocalise and that those vocalisations are distinguishable from background noise in order to be able to detect them, and AAM sensors only work under water. An extensive evaluation of which target species is best detected with which sensor type, and the influence of environmental factors on the detection probability, is given in Verfuss et al., (2016) and will therefore be omitted in this review.

A second consideration is the resolution of the spatial and temporal survey coverage of the monitoring zone. The coverage needs to be such that the chances of detecting an animal present within the monitoring zone are maximised.

The ability of a system to classify and/or localise an animal is also useful. Classification and/or localisation is not necessarily essential for mitigation monitoring but will decrease the likelihood of mitigation processes conducted based on false alarms. The ability to classify detections so that target species (or species groups) can be discriminated from non-target species will decrease the amount of false-detections. Regarding the level of classification and detail required about a given detection, in many situations, species identification is either not required at all, or is only required to the level of broad species groups (e.g. a dolphin or a large whale). The sensor types included in this review have classification abilities to some degree. An extensive evaluation of this matter is given in Verfuss et al., (2016), and will be reconsidered in the discussion of this review (section 8.3.1).

The ability to localise a target animal will also decrease the amount of false-detections, given that mitigation measures will only be taken when a target animal is present in the monitoring zone. Animals outside the monitoring zone should either not be detected, or it should be possible to localise them with sufficient accuracy to be sure that they are outside the zone. Localisation depends on the configuration of a sensor system. Electro-optical systems will need to have (at a minimum) reference points to allow the monitoring zone border to be identified on the recorded images. In most circumstances, single hydrophone PAM systems cannot determine range. Small arrays, as might be deployed from a single vehicle, can determine bearing to sound sources and for some species, multiple bearings from different points along the trackline can be used to estimate range. In certain well understood propagation conditions, range can be determined using multipath arrivals of signals (e.g. surface and bottom echoes) or dispersive mode propagation models. Most AAM systems have excellent range determination capabilities and high angular resolution. Further discussions on this matter can be found in Verfuss et al., (2016).

9.1.1.2 Data collection

For real time, or near real-time applications, such as mitigation monitoring, considerable amounts of data need to be transmitted to an operator if accurate decisions are to be made. In a limited number of cases, this has been possible using low bandwidth satellite links where summary information or short sound clips from automatic detectors are sent to shore to be checked by a human operator. For most operational scenarios, the quantities of data that need to be presented to an operator are currently too large to send through low bandwidth. However, for short range communication, free spectrum wireless systems can be used to send high bandwidth data over ranges of several kilometres. Acoustic processing is an active area of research and it is possible that for some situations the amount of data that need to be sent in order that an effective mitigation decision can be made could be significantly reduced.

For mitigation monitoring, the most practical option is therefore to use a free spectrum radio modem link to send data to a nearby base station (which might be on one of the operational vessels) where an operator can view and verify detection data.

9.1.1.3 Data analysis

For mitigation monitoring it is advisable to have a trained human operator to check detections identified by a system's detector before mitigation procedures are implemented. Detectors can be used to reduce data volumes that need to be stored or transmitted, but none have yet been sufficiently validated as being capable of accurately making a complete decision concerning animal presence with a high degree of certainly and low false alarm rate. Detector performance may also become poor in the presence of noise (industrial, biological, weather generated, etc.). Automatic detection and classification is generally more advanced for PAM than for AAM and optical methods. However, there are no systems of any type where detection is so automatic that automatic detectors can be relied upon on their own.

9.1.2 Animal population monitoring

9.1.2.1 Survey design

As outlined in sections 7.1 and 11.6, survey design is an important feature, firstly, to be able to infer density and/or abundance in the study area and, secondly, for detection probability estimation. Therefore, autonomous vehicles that can adhere to designed survey transect lines, or remain stationary to create a monitoring point, would be particularly suited for acquiring survey data. Technical terms used in this section are explained in section 11.6.

If pilot study information is available on the expected encounter rate in the region, the amount of line length or the number of points needed to achieve an acceptable level of variance in the results can be estimated (Buckland et al., 2001). For moving systems, the power and speed of the system will need to be considered to ensure that it is logistically possible to complete the survey in the required timeframe. Deployment duration and communication range with the ground station should be of sufficient length to allow for successful deployments from and returns to land or a survey vessel (as noted by Koski et al., 2009a in a review of UAS).

If systems were to be used as stationary monitoring points then, ideally, enough systems would need to be available to achieve simultaneous monitoring at all points. It would be possible to split the survey area into smaller blocks to survey with fewer systems at any one time, but then the ability to tease apart spatial and temporal factors that may affect animal density/abundance would be reduced or lost.

During the survey design stage, every effort should be made to keep the number of multiplying parameters (or “multipliers” - see section 11.6 for explanation) required to estimate absolute animal density or abundance to a minimum. For every extra estimated multiplier, such as detection probability, additional uncertainty is added to the analysis, increasing the overall variance estimates. Furthermore, there is the possibility that a multiplier estimate may be biased (e.g. an incorrectly applied call production rate), which may result in biased density/abundance estimates. Therefore, an ideal design would be one where all animals in the monitored area were certain to be detected and individual animals could be counted (so no group size or cue production multiplier would be required, for example). Detection probability estimation may not always be required, if it can be assumed that all available animals within a surveyed transect or point are detected (as may be the case in UAS surveys where recorded images are collected and analysed post-survey). However, most population–level surveys will require some form of multiplier so substantial effort should be dedicated to planning the optimal survey given the study area, the study species and logistical constraints. It is important to note that the survey design required to achieve certain, or as high as possible, detection probabilities for real-time detection with the aim of mitigation monitoring will be different from the survey design for population surveys (Verfuss, et al., 2016).

For every required multiplier, an appropriate estimation approach should be planned at the survey design stage, and may involve the collection of auxiliary data. Probability of detection should be estimated using one of the "standard" density estimation methods, such as distance sampling or SECR, so the design of the survey should ensure that appropriate data are generated for these analyses (i.e., estimated horizontal ranges to animals for line or point transect sampling, or associating the same acoustic events across hydrophones or re-identifying individuals across surveying occasions for SECR). Particularly for UAS technology, implementing methods to account for missing animals directly on the transect line or at the point due to non-constant availability should be considered (see Chapter 11, Buckland et al., 2015 for a recent review of methods to address this issue). Altitude and speed of the UAS will be of importance when determining the availability bias; the temporal and spatial field of view of the UAS may be too narrow to allow a second detection of an animal when resurfacing, so alternative approaches may have to be considered for deeper diving species. In the case of AUV technologies that collect passive acoustic data, it is likely that call production rate, or proportion of time animals are vocally active, will be required as a multiplier. The exact metric will depend on the exact form of the density estimator. Therefore, an assessment of the availability of suitable data from the existing literature needs to be conducted, or associated behavioural studies will need to be planned as well as the main survey. Given that behaviour-linked multipliers are likely to be context-specific, it is recommended that multipliers are estimated at the same time and place as the main survey (Marques et al., 2013a).

Furthermore, if it is suspected that model-based inference (see Section 11.6.2) will be required to estimate abundance in the whole study area (e.g. if the chosen vehicle may deviate from its planned track), or density surface modelling is required, then appropriate covariate datasets will have to be obtained from other existing datasets or collected from the study area.

Given the number of available AUV and UAS platforms, it is possible that there may be several options at the survey design stage. Different combinations of system and sensor may be suitable for the same survey. For example, smaller animals or animals with little surface contrast can either be detected with high-resolution cameras mounted on a UAS operating at a higher altitude and speed, or with lower resolution cameras operated by smaller UAS flying at a lower altitude and speed. The size of target, light conditions, sea state, operational altitude, speed and contrast between target and background are also important factors to consider when determining which imaging system is required for an operation. All survey design options will likely involve different pros and cons that will be survey-specific.

In order to assess animal population sizes, real-time detection is not required. However, there would be advantages to systems that could relay data back in real, or almost-real, time. For example, survey designs could be updated or adapted, depending on what species were detected – this may be very useful if multiple AUV / ASV instruments were deployed to form an array, which could have altered spacing depending on the types of species being acoustically encountered.

9.1.2.2 Survey data collection

Regardless of the particular methodological protocol that a survey may follow, there are basic data collection requirements for any survey. Firstly, a temporal and spatial record of the system's survey route is essential. Secondly, systems should collect either visual or acoustic data that can be used to identify species. In the case of UAS surveys, stabilization of the camera, especially with regard to pitch and roll of the aircraft, has been identified as being important, particularly when using video for the detection of marine mammals (Koski et al., 2009a). AUV and ASV systems that use on-board processing of acoustic data ought to keep examples of raw data so that false detection proportions can be assessed.

Clearly, whatever system is used, in most situations it is desirable to store and present to a competent operator as much raw data as possible if accurate management decisions are to be made. For long term monitoring, considerable amounts of data can be stored on high capacity memory cards or hard drives and it is only the lowest power and long duration vehicles (such as submarine gliders) that require significant real-time data reduction for this application. Our recommendation for long term monitoring is to store all data, or as much data as is practically possible and to send a minimal amount of data to shore primarily as a system status and health check. The detailed data processing can then be conducted once the system has been recovered.

9.1.2.3 Survey data analysis

The development of algorithms to detect marine animals automatically from aerial images is an area of active research (Ireland et al., 2015). Image processing for fisheries stock assessments is also being investigated (Mellody, 2015). Therefore, at present, the vast majority of recorded sightings data will be manually analysed by an operator, either in near real-time or after the vehicle is recovered. In any autonomous vehicle survey, the particular abundance estimation methodology used will determine what analyses are required. For example, estimation of horizontal perpendicular distance for line or point-transect sampling, individual (re)identification for spatially-explicit capture-recapture (SECR) and group size estimation (see section 11.6 for further details). Where multiplier estimation analyses are required, such as group size estimation, collected data can be subsampled if sample sizes are prohibitively large. However, a systematic random subsample (i.e., evenly spaced samples with a random start point) of the data must be taken so that the subsample is a true representation of the full dataset.

The data analysis considerations outlined above are not significantly different from current considerations for collecting visual or acoustic data for wildlife surveying. However, the differences of UAS/AUV platforms to currently used platforms (i.e., ships, aircraft, or moored acoustic instruments) mean that there are some data analysis considerations relating to autonomous vehicles that are current areas of research. These are discussed here, though definitive conclusions and/or recommendations are not yet available.

The first issue relates to survey effort and animal movement. Typically, survey effort is defined as line length travelled for line transect surveys and time spent monitoring for point transect surveys. However, it can be considered that slow moving platforms, although they move along transect lines, are essentially completing point transect surveys, where the point moves slowly through space. The slow movement of platforms has implications for (1) how survey effort is defined in the density estimator and (2) whether animal movement may be problematic or not (Glennie, 2015). If a platform moves considerably slower than the study animals (or is stationary), any bias caused by animal movement can be avoided by either counting cues (e.g. acoustic cues, or visual cues such as whale blows) or treating the survey as a series of "snapshot" moments through time. The latter method works by estimating density in short periods of time (i.e., a snapshot) where animal movement is deemed to be minimal (e.g. Ward, 2012; Hildebrand, 2015). Survey effort is then defined as the number of snapshots used in the analysis. Current research is investigating the effect of snapshot window length on density estimation using data from slow moving autonomous vehicle, specifically gliders and drifting platforms. In addition, work is currently ongoing to determine how much deviation from a planned survey is needed before model-based inference is required to estimate abundance in the whole study area.

9.1.3 Focal animal studies

In the case of focal animal studies, survey design, data collection and analysis need to be specifically tailored to the study objectives. We therefore highlight some general key considerations in this section.

Autonomous vehicles will need to be either (1) mobile in order to follow an individual of interest (via manual or automatic piloting) or (2) remain static with a field of view such that an animal can be monitored for a period of time. When using a manually piloted system, real-time detection feedback is necessary for the pilot to track the animal. Automatic piloted systems would need to have a detect-and-track routine that allows for automatic tracking of a detected animal. Mobile systems would additionally need to have a geo-referencing system that allows the determination of the target animal's location. An associated time-depth recorder may also be of interest for obtaining dive-profiles of the animal.

During the focal follow, detection probability should remain certain, so that a complete record of the animal's behaviour during the focal study is recorded. This is more difficult to achieve with PAM systems, because an animal is only 'observable' when it is vocalising. The ability to perform focal follows will also be limited by the communication system and the operational range of the system.

9.2 Current knowledge on autonomous vehicles

9.2.1 Independent systems

9.2.1.1 Unmanned aerial systems

UAS have recently been introduced as alternative platforms to overcome the limitations of manned-aerial surveys for marine studies, with the ultimate benefit being their ability to perform "dull, dirty, dangerous[10]" tasks more efficiently and at a fraction of the cost of manned-aerial surveys (Neininger and Hacker, 2011). These systems have evolved rapidly over the past decade, a process driven primarily by their various uses in military operations. Only recently have they become available for civilian and scientific uses, for instance for earth sensing reconnaissance and scientific data collection (Watts et al., 2010). Recent developments that have turned present-day UAS into realistic alternatives to manned systems are longer flight durations, improved mission safety, flight repeatability due to improved autopilot systems, and reduced operational costs when compared to manned aircraft. Advances in quadcopter systems have proven to reduce the need for extensive operator training and operating difficulties compared with fixed-wing aircraft, particularly in flights with short ranges that may require lower speeds and altitudes. The actual advantages of an unmanned platform, however, depend on many factors, such as aircraft flight capabilities, sensor types, mission objectives, and the current UAS regulatory requirements for operations of the particular platform (outlined in section 9.4.1) (Watts et al., 2010).

UAS have been widely used for different purposes both for research and industry surveys. Some of the work developed in research has included studies such as meteorological data (e.g. Funaki and Hirasawa, 2008), sea ice monitoring (e.g. Inoue et al., 2008), and wildlife monitoring (e.g. Hodgson et al., 2010). Shell has conducted a few studies in offshore Arctic regions in the last decade, some showing the full potential of this type of equipment for industrial operations (Koski et al., 2009a; Lyons et al., 2006). Additionally, different studies have been conducted to test individual systems and sensors in a way to better understand their capabilities (Table 7). In offshore areas, there has been an intense focus on sea ice monitoring, pipeline inspection and wildlife surveys with UAS, which reduces the risk to human personnel and are completed at a fraction of the cost compared to the use of manned aerial platforms. The availability of commercial and small UAS has also prompted the use of this type of equipment in research, without requiring large budgets or instructed personnel. However, with the continuous development of platforms and sensors the capabilities of these systems to monitor offshore regions and detect marine organisms evolve.

[10] *Dull* as marine mammal surveys can be considered dull – spending hours looking for an animal either from plane or ship, most of the time not seeing anything. *Dirty* as fieldwork can be dirty – sea sickness or plane sickness, few clothes, maybe no access to shower and clean toilet conditions, bad weather and sea salt can affect equipment and log sheets, etc. *Dangerous* because if there is bad weather at sea it can easily affect navigation and risk people's lives.

In recent years, UAS operations have been integrated into a variety of field studies involving a range of species and applications of UAS, including the use of UAS to deter birds from feeding in commercially important agricultural areas (Grimm et al., 2012), monitoring habitat and biodiversity loss (Koh and Wich, 2012), and monitoring illegal poaching activities (Olivares-Mendez et al., 2013; Mulero-Pázmány et al., 2014; Smith et al., 2016). Under the Marine Mammal Protection Act (MMPA), NOAA's National Marine Fisheries Service (NMFS) is challenged with developing further research and stock assessments for both cetaceans and pinnipeds, and has been developing a UAS program to improve scientific applications. Most of the published research programs and activities are on the applications, capabilities, and inventory of UAS technology. However, there remains a missing component on the application of these systems with a more industrial approach focusing on their benefits in management issues and their integration with other autonomous technologies (coordination of unmanned vehicles aerial, surface, and underwater, as a communication network).

There are a variety of UAS systems, including remotely controlled aircraft (e.g. operated by a pilot at a ground control station) and aircraft that can fly autonomously based on pre-programmed flight plans or more complex dynamic automation systems, such as for search and rescue where the aircraft is programmed to find an object or its cue in a specific area. They can also include various tethered systems that are either stationary or stationary relative to a mobile anchor point. The great potential of UAS systems lie mainly in their comparative cost effectiveness compared to manned aircraft, but also stem from the fact that these systems are generally safer and operationally simpler to use. Their usefulness for marine-based surveys will depend greatly on their flight capabilities (speed, range, altitude) and on their payload capacity in relation to suitable sensor packages (e. g. cameras, thermal sensors) (Campoy et al., 2009). Payload includes everything that is not part of the aircraft structure itself, ranging from the fuel and battery type to the different cameras an aircraft can carry. Though it is often not specified, it is generally assumed that the payload associated with UAS represents solely the weight of the imaging equipment. However, this should be specified by the manufacturers, as some may define their payload as all the components that are external to the aircraft and others may only include the imaging equipment.

Several studies have been conducted to test the capabilities of different aerial systems, such as powered aircrafts (e.g. Hodgson et al., 2013; Koski et al., 2009b), kites (Fraser et al., 1999; Vorontsova, 2015) and lighter-than-air aircrafts (e.g. Flamm et al., 2000; Hodgson, 2007). Each system may have a different applicability, depending on the weather conditions to which it is exposed and the payload sensors that it can carry. While the understanding of the advantages and limitations of powered systems for marine monitoring has increased in recent years, there is also an interest in exploring the applicability of kites and lighter-than-air aircraft, since these systems are quieter and therefore potentially less disturbing to animals. Furthermore, they can be considered more environmentally friendly than fuel powered systems. However, there is much less information about the performance of such systems in marine applications, and no comprehensive overview of the different systems and their application to marine organism monitoring has been carried out up to date. The extent to which these systems can provide useful scientific or operational data is currently uncertain, and the use of UAS for monitoring and mitigation purposes in relation to marine organisms is therefore very much at an early test stage.

There is a wide range of different UAS with sizes as small as 18 grams (PD-100 by Proxdynamics) to 14,000 kg (Global Hawk by Northrop Grumman). However, the complexity of the larger systems requires a lot of personnel to operate and many of the systems are only available for military use. Larger platforms may also require runways similar to those required by manned-airplanes, which in turn limits the possibility for deployments at sea. Smaller platforms, on the other hand, may have a stronger sensitivity to environmental conditions, and are limited in the payload weight they can carry. Tethered systems may overcome some of these problems, but in turn are limited in their operational range.

9.2.1.2 Autonomous Underwater and Surface Vehicles

AUV and ASV are unmanned, self-propelled vehicles that can operate independently for periods of a few hours to several months or even years. A wide variety of AUV and ASV are now available for purchase and hire. These range from relatively small vehicles, which can be lifted by one or two persons and deployed from a small inflatable, to large diesel-powered surface vessels with bespoke launch and recovery systems (Griffiths, 2002). The smaller vessels are often operated with a high level of autonomy and can stay at sea for several months at a time. The larger surface vehicles tend to be more closely controlled, although this restriction is most often for regulatory and safety reasons rather than a fundamental operational constraint.

Many AUV's and ASV's were initially developed for military applications (e.g. mine sweeping, battle space preparation) and long term academic surveys. They have also been extensively used in O&G operations such as for subsea equipment inspections, leak detection, dynamic positioning, etc. It is timely to consider the use of AUV and ASV in the environmental commercial sector, specifically oil and gas operations. Key issues are the vehicles' deployment duration, health and safety concerns associated with the hazards of refuelling at sea, and deployment, recovery and control of the vehicles in adverse conditions. Autonomous vehicles may have particular advantages in areas where they can be easily deployed and recovered from land. However, for long-term deployment at sea involving maintenance refuelling, more frequent data collection and support staff may be required, introducing a range of complex logistical problems. Additionally, deployment risk is more significant in busy areas of high military, shipping or fishing activity, due to acoustic interference, collision risk and net entanglement (Wynn et al., 2013). However, the potential of AUV and ASV is clearly given in their ability to acquire data in inaccessible parts of the ocean at short notice (given that hiring vessels or survey-planes may require long lead times) and provide improved temporal and spatial resolution of a broad range of marine measurements.

In the naval sector, niche applications have been identified to give clear developmental guidance on craft and sensor type requirements. In the research world, application aims remain much more open. Scores of platforms (particularly ASV) exist in the developmental stages and trialling tends to remain geared toward system improvement as a general aim in itself. Within the industry sector, very few craft (particularly ASV) appear to be genuinely available with commercially viable applications still being established. In comparison, AUV are slightly more advanced commercially. Though there is clear potential, the combination of craft and sensor(s) that meets a niche is currently in the pioneer stage. The presence of ASV in the market is certainly growing, especially as they are increasingly recognised as a valid alternative to AUV in many applications. Relative to AUV however, regulatory uncertainty are a constraint to the wider use of ASV (see section 9.4.2 for further details). The relationship between ASV and AUV is also complementary however and there is growing interest in the use of ASV to support AUV in navigation and as a data relay / transmission station.

Many surface and underwater autonomous vehicles are used on a regular basis for the collection of oceanographic data by research institutions world-wide (e.g. Figure 11). Primarily, they are used for the collection of oceanographic data and the detection of higher organisms, such as marine mammals and fish, generally remains a niche area of research. Several published papers describe field trials of AUV and ASV for environmental and oceanographic applications (summarised in Table 8), but most of the published work focuses on technical aspects of automated navigation and collaborative performance of AUV.

Figure 11. The UK National Oceanography Centres Autonomous Vehicle Fleet[11]

AUV and ASV are capable of carrying a variety of sensors for e.g. seabed mapping and acoustic related data collection, including, but not limited to, Multi-Beam EchoSounders, Sub-Bottom Profilers (SBP), side-scan sonars (SSS), magnetometers, geochemical instruments, imaging systems (HD cameras), oceanographic instruments (Conductivity-Temperature-Depth units (CTD), echosounders, Acoustic Doppler Current Profilers (ADCP), water

[11] http://www.seebyte.com/wp-content/uploads/2014/09/NOC_019.jpg

samplers and passive acoustic data acquisition systems (PAM); Wynn et al., 2013). The sensors deployed determine the altitude (depth), speed and endurance of the vehicle. For example, higher power sensors (SSS and SBP) reduce endurance, high resolution seafloor imaging (HD camera) requires low altitudes (Wynn et al., 2013). Fernandes et al., (2003) investigated the application of AUV for fisheries acoustics. For marine animal monitoring; passive and active acoustic sensors (PAM and AAM) have been successfully integrated into AUV and ASV, as dumb (recording only) and smart (real-time processing) sensors, and reports published of their findings (Table 8). However, within the existing literature, no review has been found that evaluates field trials of AAM or PAM for marine mammals as installed in autonomous vehicles.

PAM systems have successfully been deployed on buoyancy gliders for the detection of baleen whale calls (Baumgartner et al., 2008; Baumgartner et al., 2013; Baumgartner et al., 2014b; Baumgartner, 2014; Baumgartner and Fratantoni, 2008)) and for beaked whales (Klinck et al., 2009; Klinck et al., 2012; Klinck et al., 2014). Baumgartner et al., (2014a) used a DMON detector mounted on a Slocum Electric Glider, programmed to detect the tonal vocalisations of several baleen whale species. Trials were conducted of a Decimus PAM system on an SV2 waveglider in the spring 2014 off the coast of Scotland, successfully detecting harbour porpoise clicks, dolphin whistles, sperm whales and seismic airgun noise (D. Gillespie, pers. Comm.). Harbour porpoises were also detected using a modified DMON system on a submarine glider off the SW of the UK (Suberg et al., 2014). The British based company MOST trialled their own wave-powered vehicle (Autonaut) in 2014, which was equipped with a short streamer array, although unfortunately this had insufficient bandwidth for the detection of cetaceans (D. Gillespie, pers. Comm.).

The level of real-time reporting from these installations varied considerably. Baumgartner et al., (2013) were able to send sufficient data to shore to detect the presence of baleen whales in near real time. Klinck et al., (2012) sent summary data for each dive to shore, but a high false alarm rate meant that it would have been difficult to use these data for real-time decision making. The system described in Suberg et al., (2014) had no real-time reporting capability. In most cases, only a single hydrophone was deployed on each device, so the vehicles were unable to provide localisation information. The exception to this is a study described by Fucile et al., (2006), who report on a deployment where three Slocum gliders were equipped with time synchronised hydrophones. The gliders were programmed to maintain station approximately 5 to 7 km apart and time of arrival differences were used to localise animals. PAM systems have also been successfully deployed from both profiling and surface floats. Wall et al., (2012; 2014) describe studies in which a recording device mounted on a Slocum glider was used to detect fish sounds off West-central Florida. Several species of soniferous fish were detected as well as some unknown sounds believed to be of biological origin. Matsumoto et al., (2013) describe a PAM system designed to detect beaked whales which uses the same acoustic hardware as described by Klinck et al., (2012) attached to an APEX profiling float[12]. Low cost surface drifters are also under development by

[12] http://www.webbresearch.com/apex.aspx

researchers at NOAA fisheries (Griffiths, 2015). Due to their relative low cost, profiling floats and drifters have the potential to be deployed in large numbers, however total lack of navigational control may limit their use to regions with specific current regimes. PAM systems have also been incorporated into a number of small surface vehicles including the Liquid Robotics Waveglider, the ASV C-Enduro and the MOST Autonaut, however no peer reviewed literature yet exists describing these deployments.

We are not aware of any studies which have collected PAM data from powered underwater vehicles. The expense, short mission duration and noise output from these vehicles which can both mask PAM detections and affect the behaviour of marine organisms has led the research community to show little interest in these platforms for PAM.

Acoustic receivers for the detection of acoustic tags have been integrated into both underwater gliders and AUV (Eiler et al., 2013; Haulsee et al., 2015). There are also a number of articles online that discuss the integration of acoustic tags for tracking fish and other marine life[13] [14] [15].

AAM have already been integrated into underwater gliders and ASV (Table 8) and have focused on using echosounders to detect zooplankton rather than fish and other larger organisms, although we have included them in this review as proof of concept. AAM is used frequently in fisheries research to provide fish biomass and distribution estimates (e.g. herring, blue whiting, mackerel, sardines and anchovy; Doray, 2012; Huse et al., 2015). For the purposes of this review, we have identified the following challenges for their integration into autonomous vehicles:

(1) Transducer size balanced with beamwidth balanced with required frequency. For example, only high frequency (120 kHz) wide beam angle (10 degrees) are used on small autonomous platforms such as Imagenex ES853 on Seaglider (Guihen et al., 2014),

(2) Power consumption (most hull mounted transducers transmit at 0.2 to 2 kWatt), and

(3) Data transmission for real-time decisions (even the simple single-beam echosounder raw data is too large to transmit back over Iridium). Currently acoustic processing is not undertaken on board, but this could be an area for future development.

AAM have also been used to detect several different species of marine mammal, however, these studies have not been conducted with AUV or ASV, but rather with AAM sensors deployed from vessels, fixed structures or in tanks. We include examples of this work here to demonstrate the potential of the AAM systems for marine mammal (and other large animal) detection: grey whales (Lucifredi and Stein, 2007), fin whales (Nøttestad et al., 2002), humpback whales (Love, 1973), bowhead whales (Pyc et al., 2015), right whales (Miller and Potter,

[13] http://www.futurity.org/glider-fleet-to-track-fish-in-real-time/
[14] http://news.uaf.edu/underwater-gliders-may-change-how-scientists-track-fish/
[15] http://www.gizmag.com/wave-glider-sharks-stanford/23758/

2001), bottlenose dolphins (Au, 1996), dusky dolphins (Bernasconi et al., 2011), spinner dolphins (Benoit-Bird and Au, 2003b; Benoit-Bird and Au, 2003a), killer whales (Knudsen et al., 2008), West Indian manatees (Gonzalez-Socoloske et al., 2009; Gonzalez-Socoloske and Olivera-Gomez, 2012), grey seals (Hastie et al., 2014), harbour porpoise (Hastie, 2012). A wide range of different AAM sensors have been used in these studies including: the Simrad SA950, EK60 and EK500, the Humminbird 987c SI, the Tournament Master Fishfinder NCC 5300, the Kongsberg SM2000, the CodaOctopus Echoscope 2 and the Tritech Gemini. AAM has also been used to detect shark species including bull sharks, great white sharks and tiger sharks (Parsons et al., 2014) and basking sharks (Lieber et al., 2014) using the Tritech Gemini and the Reson 7128 sensor systems. There are also a few examples where AAM devices have been used to detect and investigate the target strength of various turtle species (Mahfurdz et al., 2015; Perez-Arjona et al., 2013; Mahfurdz and Hamzah, 2014; Mahfurdz et al., 2013; Davy and Fenton, 2013).

9.2.1.2.1 Autonomous underwater vehicles

AUV have been primarily applied in seabed imaging for topographic characterisation and habitat assessment of benthic species (e.g. Williams et al., 2010), environmental monitoring, hydrographic surveys, and detection and density estimation of zooplankton (Brierley et al., 2002) and fish schools (Fernandes and Brierley, 1999). Fernandes and Brierley have also carried out studies on the avoidance response of krill and fish to vessels (Brierley et al., 2003; Fernandes et al., 2000).

In the commercial sector, site surveying and geo-hazard assessment have been the primary use of AUVs. Other typical commercial applications of AUV are pipeline monitoring, oceanographic surveys and water quality assessment, geophysical surveying and coastal mapping. Environmental and oceanographic applications are beginning to crossover into the commercial sector, in which ASV have primarily been utilised in bathymetric and environmental surveying (Caccia et al., 2009). Semi-submersible models have been used for bathymetric and hydrographic surveys in military, civil and commercial applications (Wolking, 2011). Self-powered craft have been used for meteorological and oceanographic data collection as well as some environmental monitoring in both the research and commercial sectors (Caccia et al., 2009).

For naval purposes, AUV have been utilised for mine sweeping, battle space preparation, harbour security, submarine detection and ISR (Intelligence, Surveillance and Reconnaissance). They have been deployed for harbour security, mine sweeping and also used as ordnance targets. These applications have frequently been based on remotely operated surface crafts (e.g. ASV's *C-Worker* and *Target* families). Military interest for self-powered craft is unknown, but there would appear to be scope for a surveillance application

For AUV, as GPS reception is lost due to the antenna being submerged, alternative solutions for navigation are required for positioning under water. AUV navigate using 1) arrays of acoustic beacons (transponders) on the seafloor for Long Baseline (LBL) communication, or 2) a combination of Ultra Short Baseline (USBL) communications, GPS positioning and inertial navigation, applying dead reckoning when below the surface using combined information from depth, inertial and Doppler velocity sensors (Wynn et al., 2013).

Propelled AUV originate from the modern torpedo, a self-propelled projectile driven by compressed air, invented by Robert Whitehead in 1866. Whitehead's torpedo travelled at a speed of 3 m/s, covering distances of up to 700 m. The first AUV was the Special Purpose Underwater Research Vehicle or SPURV, developed by the Applied Physics Laboratory at the University of Washington in 1957, used to study diffusion, acoustic transmission and submarine wakes. Work done in the 1960s comprised the initial investigations on possible AUV applications. In the 1970s there were important advances in the development of the technology, and the experimentation with prototypes noticeably increased over a couple of decades. In the 1990s, experimentation moved into a first generation of AUV aimed to perform defined tasks. The proliferation of AUV models led to the existence of around 75 AUV worldwide in 2001 (Fernandes et al., 2003), when the first truly commercial products became available (Blidberg, 2001).

Autonomous underwater buoyancy gliders are revolutionising the way the marine environment is investigated, monitored and assessed (Stommel, 1989; Davis et al., 2002; Griffiths et al., 2007). They enable observations to be made in regions previously inaccessible to vessel-based instruments e.g. beneath polar ice sheets (Sagen et al., 2008; Sagen et al., 2009; Jones et al., 2011a), or in hurricanes and tropical storms (Miles et al., 2015), and continue to operate in weather conditions (both visibility and sea state) that would limit vessel-based observations (Miles et al., 2013). They provide extremely high vertical and lateral resolution data that make observations of ocean mechanisms at scales that are not resolved using conventional measurements from vessels (Heywood et al., 2014; Kaufman et al., 2014). They are a relatively inexpensive technology, with the cost of the platform and its daily running typically orders of magnitude less than that of vessels (Davis et al., 2002). Frequently this enables multiple platforms to be deployed simultaneously, significantly widening the spatial and temporal resolution of the survey (Rudnick et al., 2004). Compared with many other vessels they are acoustically quiet (Wood and Mierzwa, 2013), making them an ideal platform to measure background noise (Baumgartner et al., 2014b). Finally, whilst frequently used for open ocean research, they are typically small, lightweight, and deployable by a small rigid hulled inflatable boat (RHIB or "RIB") with a crew of only two people making them highly versatile (Davis et al., 2002). In the last ten years gliders have moved from being experimental, developmental platforms, to forming key components of routine coastal observational networks (Schofield et al., 2007; Schofield et al., 2010). Their application in defence, industry and policy sectors is also being examined (Wynn et al., 2013).

The ability to receive instructions to adjust operational parameters and transmit datasets quickly is a key feature of underwater buoyancy gliders. Nearly all gliders use low-earth orbit satellite communications (and in particular the Iridium satellite phone system for bi-directional worldwide communication), several also have the capability to use radio frequency (RF) Local Area Network (line of sight RF modem), Circuit Switched Cellular and acoustic modem communication. ARGOS[16] is commonly used as an emergency back-up locator. ARGOS transceiver modules are mounted on near-polar low-orbitting satellites. At the poles, each satellite passes approximately twice a day (equal to 28 passes), at the equator there are 6 to 7 passes in total. Location estimates for an instrument require a minimum of two received messages during a single satellite pass. Due to the low number of satellite passes at low latitudes, gaps of a few hours can occur where position information is not possible. All systems, except acoustic modems, are subject to loss of performance in high sea-states (Davis et al., 2002). The amount of data and communication undertaken is a balance between the bandwidth of the communication method, the cost of data transfer and, with the exception of acoustic modems, the time taken. When at the surface a glider is not in control of its navigation and therefore both susceptible to ocean currents and collisions with other vessels.

Either waypoints or heading direction are used to direct the underwater glider mission and gliders are sent on transects (e.g. Piterbarg et al., 2014) or to act as a virtual mooring, profiling up and down at a single location (e.g. Smeed et al., 2013). When current speeds are less than the glider speed, a glider can perform repeated profiles while maintaining at a nearly constant horizontal position (Rudnick et al., 2004). The primary navigation system of underwater gliders uses an on-board GPS receiver coupled with an altitude sensor, a depth sensor and an altimeter to provide dead-reckoned navigation. A simple navigation algorithm is used to compute the heading and dive angle required to reach a desired location from the current position. The majority of gliders do not compensate for water currents; the Seaglider is unique in its ability to estimate water currents using a Kalman filter (Bender et al., 2008). In regions where surface access is challenging (as a result of ice or heavy ship traffic), alternative means of location are acoustic base-line or geophysical-aided navigation methods or a surface vessel shadowing the AUV (Claus and Bachmayer, 2015). The use of RAFOS (Ranging and Fixing of Sound), typically a network of sea-floor mounted baseline transponders as reference points for navigation (an acoustic base-line), has been successfully implemented into gliders (Jones et al., 2011b; DAMOCLES). The geophysical-aided navigation methods proposed by Claus and Bachmayer, (2015) involve terrain-aided navigation using the gliders dead-reckoning navigation solution, the on-board altimeter and a local Digital Elevation Model (DEM - 3D representation of a terrains surface created from bathymetric data).

The majority of buoyancy gliders are currently battery powered, and carry an increasing variety of sensors of interest to oceanographers (Rudnick et al., 2004). These include physical variables (e.g. pressure, temperature, salinity, currents), noise (e.g. background, ambient, ships, marine mammal calls, fish), chemical variables (e.g. dissolved oxygen, CDOM, nitrate, pH) and biological relevant variables such as abundance of phytoplankton and zooplankton (Rudnick et al., 2004; Davis et al., 2008; Guihen et al., 2014; Klinck et al., 2012). Three types of sensors can be fitted to gliders that have the potential to monitor marine mammals, turtles and fish: passive acoustic monitoring (PAM) sensors, active acoustic monitoring (AAM) sensors and animal tags.

[16] www.argos-system.org

9.2.1.2.2 Autonomous surface vehicles

Civilian applications of ASV consist basically in bathymetric and environmental survey and monitoring (Caccia et al., 2009). Military applications include harbour security, coastal surveillance, mine sweeping and submarine detection. ASV have undergone the most applied trialling in the defence sector. The development of ASV was in a pioneer stage by 2006 and there are now many options to choose from (Caccia, 2006; Caccia et al., 2009).

Powered ASV research focuses on meteorological and oceanographic data collection, with bathymetry imaging being the most common surveying activity (e.g. Vaneck et al., 1996). Other important environmentally oriented studies have been focused on automated fish tracking (Goudey et al., 1998) and acquisition of water samples in the sea surface top microlayer for the analysis of climatic changes (Caccia et al., 2005).

The automated navigation technology used in modern civilian ASV, both powered and self-powered, has its origin in three autonomous vessels created by MIT during the nineties (ARTEMIS, ACES and AutoCat) and the autonomous kayak SCOUT. These demonstrated the feasibility of automatic heading control, way-point navigation based on DGPS and fully automated collection of hydrographic data (Caccia et al., 2009). Power can be derived from a variety of sources, including diesel motors, fuel cells and battery packs. Electrical power supply is generally preferred in environmental sampling applications, which require no pollution of the operating area; diesel propulsion is preferred in long missions (e.g. coastal surveillance or Mine Counter Measure (MCM) operations). These vehicles can travel at high speeds and have the capacity to carry/tow significant payloads.

9.2.1.3 Mission Planning and Vehicle Control

For safety and legal reasons (see section 9.4) aircraft and large surface vehicles are generally not operated out of line of sight of a human "pilot", although there is no fundamental reason as to why they could not be given greater levels of autonomy if legal and safety constraints can be overcome. Advances in GPS technology, and now AIS, have been key to the rapid development of powered as well as self-powered ASV for many research, commercial and military applications. ASV navigation at the water surface allows them to relay high frequency transmissions in the air and acoustic transmissions in the water (ASV can be used to support AUV navigation). ASV are outfitted with GPS receivers and attitude and heading reference system (AHRS) sensors. AUV's on the other hand, can only gather accurate GPS positions when they come to the surface. Other ancillary sensors are Doppler velocity logs (DVL), which measure the fluid flow (currents) and allow for better control of trajectories. Typically, in an autonomous vehicle, lower level actions (like rudder control) are automated and overall behaviour (like waypoint selection) is managed by an operator. Full autonomy is desired in research and civil applications; in military applications remote-controlled vessels are preferred, and automation is regarded as a way to optimise system performance (Alves, 2002; Caccia, 2006). Various options of control include:

- **Control in the horizontal plane**: from simple heading control to more complex techniques.
- **Trajectory tracking:** Capability of the vessel to follow a time-parametrised reference curve in two-dimensions (control of the position of the vessel at specific instants), which is especially challenging in

presence of external disturbance (waves, wind, currents). Time constraints are more relaxed in practical applications.

- **Path following**: Capability of the vessel to follow a reference curve in two-dimensions, without temporal constraints. A desired temporal speed profile will still be applied.
- **Cooperative motion control**: Capability of the vessel to adapt its trajectory in the presence of automated marine vehicles. Interesting applications are the use of an ASV as a communication link between an AUV and a support vessel (leader-follower problem) or the coordination of multiple ASV for hydrographic surveying.
- **Mission control**: A Mission Control System (MCS) allows the end user to execute and supervise the progress of one or multiple vehicles. Mission planning and control is limited to the definition of the trajectory by multiple points and a few emergency actions (e.g. abort and stop).

Table 7: List of published studies involving UAS with application in the marine environment.

Reference	Objective	UAS Type	Sensor	Data type	Study conclusions	Country
Bevan et al., 2015	Evaluate the effectiveness of a low-cost commercially available UAS for identifying both adult and hatchling sea turtles in near-shore waters adjacent to nesting beaches.	DJI Phantom 1 quadcopter	GoPro and GPS enabler	Video	The results indicate that this UAS system provides a practical and effective method of conducting daytime surveys in near-shore waters for monitoring sea turtle abundance and movements. Even in turbid near-shore waters, they were able to monitor the surfacing of adult females as they left the nesting beach. While the UAS was controlled from shore in the current study, it could also be launched and controlled from a boat for monitoring turtles in offshore areas such as foraging grounds.	Mexico
Cameron et al., 2009	NOAA tests of a UAS to determine its effectiveness for surveying subarctic pack ice for ice seals.	ScanEagle aircrafts	Single Lens Reflex (SLR) Nikon D300 and video	Photo and video	The ScanEagle performed well in a variety of weather conditions, and the images collected have the necessary resolution to distinguish the different species, ages, and occasionally even the gender of ice seals.	Bering sea (USA and Russia)
Durban et al., 2015	UAS as an alternative method for successfully obtaining photogrammetry images of killer whales at sea.	APH-22 hexacopter (Aerial Imaging Solutions)	Olympus E-PM2, Olympus M-Zuiko 25mm f1.8 lens	Video and photo (triggered manually with 12.3 MP)	The APH-22 hexacopter has great utility for collecting photogrammetry images to fill scientific data gaps about free ranging whales. It is small and portable with VTOL capability that enables safe deployment and retrieval even from small boat platforms, and enables photogrammetry in remote locations where conventional aircrafts are impractical. Can be flown in low altitudes without disturbing the whales. Allows differentiation of individual whales using natural markings, with precise altitude to enable quantitative measurements.	Canada
Hodgson et al., 2010	Coastal UAS tests and manned vs UAS - different tests.	Powered Warrigul	Sony Digital Recorder	Video	The combination of the typical UAS imaging system we used and the altitudes tried did not provide images of high enough resolution to reliably detect dugongs or whales.	Australia

Reference	Objective	UAS Type	Sensor	Data type	Study conclusions	Country
Hodgson et al., 2013	Coastal monitoring of Dugongs using UAS	Powered - ScanEagle	SLR camera Nikon® D90 12 megapixel	Photo	The ScanEagle would need to fly 2.8 times as many transects to achieve the same area coverage that a standard manned survey could achieve. This limitation could be addressed by using a camera that captures images at a higher resolution so that one could use a wider lens or fly higher, or one could use multiple cameras.	Australia
Jones et al., 2006	Land and coastal assessment of an UAS for wildlife research.	MLB FoldBat	Canon Elura 2	Video	Although the FoldBat UAS system did not prove useful as an operational wildlife research tool, it had a number of characteristics that illuminated system requirements for succeeding generations of UAS design and more successful UAS missions. The Elura 2 produced satisfactory images for wildlife research applications targeting small and inconspicuous species such as small, white wading birds. However, the utility of the images was limited because they were not instantaneously georeferenced.	USA
Koski et al., 2009b	Comparison of traditional offshore survey with human surveyors vs aerial digital image monitoring.	Powered- Insight A-20	Alticam 400	Video	UAS has the potential to replace manned aircraft during surveys for large cetaceans or large groups of small cetaceans if the search area is small. However, higher video resolution is needed before the UAS would be effective for surveys of large areas or for detection of smaller cetaceans and pinnipeds.	USA
Koski et al., 2013	Comparison of traditional offshore survey with human surveyors vs aerial digital image monitoring.	Fixed-wing manned with cameras	Nikon D800 DSLR, video Canon HD XF100	HD video and Digital SLR photos	The analyses suggest that imagery from these cameras provides similar quality data to those collected by observers flying in an airplane, and that UAS surveys can be flown in some conditions when manned aircraft cannot, it appears that UAS could replace manned aerial surveys for marine mammals. However, the sample sizes for these analyses were low and did not cover all of the conditions that would be encountered during manned aerial surveys so additional tests with larger sample sizes and covering a wider array of conditions are recommended.	USA

Reference	Objective	UAS Type	Sensor	Data type	Study conclusions	Country
Thamm, 2011	Equipment evaluation.	Kite SUSI 62	Not specified		The SUSI 62 was designed as a robust and safe UAS with a large payload and long flight time for day to day applications. Its capability to operate different sensors (e.g. optical, multi spectral and thermal) at the same time and the ease of swapping sensors offers fascinating options for research and commercial applications. The auto pilot guarantees that the area of investigation is covered completely with the desired overlap and ground resolution.	Europe, Africa

Table 8. List of studies involving AUV and ASV with possible application in the marine environment

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
Ainley et al., 2015	Presence / absence	Seaglider	Imagenex ES853	AAM	An echosounder mounted on the Seaglider was used to determine the depth, distribution and abundance of prey (assumed to be krill and fish). The glider was deployed for 78 days making observations of the physical and biological environment. The paper applied the method of Guihen et al. 2014.	Antarctica
Armstrong et al., 2006	Characterise the coral reef habitat	Propeller twin-hull AUV *Seabed*	Pixelfly CCD camera	Image	The AUV *Seabed* equipped with a CCD camera captured images every 2.5 s of the benthic communities that inhabit the shelf coral reef of the Hind Bank marine conservation district. The data was used to provide information on benthic species composition and abundance.	St. Thomas (US Virgin Islands)
Baumgartner et al., 2008	Acoustic recordings from autonomous platforms.	Slocum coastal gliders	custom built	PAM	Obtained good quality acoustic recordings with no detectable flow noise while profiling up or down. Glider noise was detectable at the top and bottom of each dive preventing detection of whale vocalisations at the same time.	Great South Channel
Baumgartner et al., 2013	Presence / Absence of baleen whales	Slocum	DMON	PAM	A hardware and software system was developed to detect, classify, and report 14 call types produced by 4 species of baleen whales in real-time from ocean gliders. Two gliders reported over 25 000 acoustic detections and used LFDCS to attribute them to fin, humpback, sei, and right whales. The gliders made lots of noise at the surface (surface waves, internal pumps, radio transmissions), so DMON detections were turned off. Detection accuracy was high for fin and right whales, modest for humpback whales, and undetermined for sei whales. Whales were detected with the glider and used to direct the ship to locate them.	Atlantic
Baumgartner et al., 2014b	Presence / absence	Slocum	DMON	PAM	A Low Frequency Detection and Classification System (LFDCS) was used to autonomously detect and classify sounds, additionally raw data was saved on the	Arctic

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
					DMON. Bowhead whales, walrus, bearded seals, beluga whales, air guns and ships noise were detected. Real-time review of pitch tracks by analysts onshore allowed unambiguous identification of bowhead whale calls and air gun pulses. The on-board classification system was less successful; this was attributed to the immature state of the call library.	
Bingham et al., 2012	Performance of the Wave Glider for acoustic applications	Wave Glider	DMON	PAM	The noise generated by the wave glider is very low. The ambient noise at the submerged glider is significantly lower than the ambient noise at the surface float. The sea state does not have a strong influence on the wave glider's emitted noise.	South coast of Oahu
Bingham et al., 2012	Performance of the Wave Glider for acoustic applications	Wave Glider	ITC-3013	AAM	The wave glider modem was able to receive signals from the transmitter at depths of 500 and 2,500 m and at ranges in excess of 3 km. The reliability and the input SNR varied with the local noise field around the surface receiver.	South coast of Oahu
Bourgeois et al., 1997	Bathymetry mapping	Semi-submersible ASV	Simrad EM-1000	AAM	The semi-submersible ASV prototype *ORCA*, a diesel-powered unmanned vehicle with a tall mast for air take and communications, was used to acquire bathymetric data with a multi-beam echosounder. The bathymetric data is validated and corrected in real time, and used by a vessel-based operator to re-adjust navigation waypoints and optimise sensor operating parameters. This methodology offers high coverage and accuracy for the acquired data.	Florida
Brierley and Fernandes, 2001	Fish survey – the presence of diving birds changed the initial objective	Propeller AUV *Autosub-1*	Simrad EK500	AAM	The AUV *Autosub-1* was equipped with an upward-looking echosounder for fish surveys in the North Sea. The echograms from the AUV contained vertical traces starting from the sea surface caused by diving birds, identified as Northern Gannets by visual observations. The mean dive depth was 19.7 m, somewhat deeper than expected to other studied gannets. The diving depths have implications on foraging capabilities of gannets, so the effective vertical foraging range of the species should be reconsidered.	Shetland and Orkney

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
Brierley et al., 2002	Estimate krill densities under Antarctic ice	Propeller AUV *Autosub-2*	Simrad EK500	AAM	The AUV *Autosub-2* was deployed to estimate krill abundance under Antarctic ice, up to a distance of 27 km beyond the ice edge. Krill densities five times greater than in open water were registered.	Antarctic Ocean
Brierley et al., 2003	Assess avoidance response of krill to a survey vessel	Propeller AUV *Autosub-2*	Simrad EK500	AAM	The AUV *Autosub-2* was deployed ahead the research vessel *James Clark Ross* in the Antarctic Ocean to assess krill avoidance to the vessel. Both *James Clark* and *Autosub-2* were equipped with the same scientific echosounder to assess the response of krill to the vessel. The similarity of the density calculated with the data acquired by the AUV and the vessel suggested that the avoidance of krill to the *James Clark* was not important enough to bias the estimation of krill abundance.	Antarctic Ocean
Caccia et al., 2005	Samples from the sea surface micro-layer	ASV catamaran *SESAMO*	Multiuse microlayer sampler	samplers	The ASV catamaran *SESAMO* was used in the Terra Nova Bay area of the Ross Sea between January and February 2004 to collect data and samples of the sea-air interface in a completely automated manner. The composition of the sea-surface microlayer (~ 1 mm) provides valuable information about the physical and chemical interactions between the hydrosphere and atmosphere, and their relation with climatic and environmental changes.	Ross Sea Antarctic Sea
Correa et al., 2012	Nature of the waveform coral ridges of Miami Terrace	Propeller AUV *C-Surveyor-II*	Simrad EM2000 Edgetech 120 kHz	AAM	The AUV *C-Surveyor-II* was sent on a 24.5 h mission to acquire 27 km^2 of high resolution seabed maps (with multi-beam echosounder and side-scan sonar), sub-surface profiles and bottom current data (ADCP) to study the nature of the cold-water coral ridges, with waveform morphology, found at the base of the Miami Terrace in the Straits of Florida.	Miami Terrace, Straits of Florida
Davis et al., 2008	Presence / absence, quantity	Spray	Sontek 750 kHz ADP	AAM	Spray gliders were deployed across the Southern California Current system and collected concurrent measurements of temperature, salinity, ADCP shear, chlorophyll a fluorescence and 750 kHz acoustic backscatter. The long time series and high spatial resolution data (28 months, across three lines over two years) characterised close links between fronts in physical and biological variables. The ADP was calibrated with tungsten carbide spheres, so variability in quantitative	USA

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
					measurements is 2 dB between missions. The study observed diel vertical migration of zooplankton and micronekton, but the single frequency was not species specific and therefore not quantitative.	
D'Spain et al., 2004	Low signature AUV for passive ocean acoustic studies	Bluefin Propeller AUV	not specified	PAM	A mid-size AUV is retrofitted with a vector-thrust system manufactured by Bluefin Robotics, which decreases the radiated sound levels between 20 and 50 dB in the 20 to 10k Hz band. The low acoustic signature permits the use of a vehicle mounted hydrophone array for passive ocean acoustic studies.	Not specified
Fernandes and Brierley, 1999	Test the capability of AUV *Autosub-1* to detect fish	Propeller AUV *Autosub-1*	Simrad EK500	AAM	The AUV *Autosub-1* equipped with a scientific echosounder was sent into 13 missions to gather acoustic data for detection and density estimation of fish schools. The absence of an avoidance response by a fish school with the *Autosub-1* 7 m far from it suggested that fish is not sensitive to the presence of the vehicle beyond that distance.	North Sea
Fernandes et al., 2000	Assess the avoidance response of fish to a survey vessel	Propeller AUV *Autosub-1*	Simrad EK500	AAM	Research vessels are used for density and abundance estimation of fish, and there is a widespread concern that the noise generated by these vessels may cause an avoidance response on fish, which will bias the abundance results. The AUV *Autosub-1* was deployed ahead the research vessel *Scotia* during an acoustic survey of herring in the North Sea. The AUV was equipped with the same echosounder model as the *Scotia* to assess, by data comparison, the response of the school as the vessel goes past. The similarity of the data from the AUV and the vessel leads to conclude that fish do not avoid survey vessels.	North Sea
Fernandes et al., 2003	Fisheries & plankton acoustics research	Autosub	SIMRAD EK500	AAM	AUV can sample previously impenetrable environments such as the sea surface, the deep sea, and under-sea ice. However, advances in power-source technology are required to increase the range of operation before AUV are suitable for these applications.	

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
Fratantoni et al., 2011	Develop a fully-integrated autonomous system	APEX float, Slocum glider, Z-Ray glider	DMON	PAM	Trials have been a success. The system is low-noise, low-power, data-efficient and reliable. In the San Clemente Island trial, both the gliders and the floats were able to send numerous real-time beaked whale detections.	
Fucile et al., 2006	Time-stamped baleen whale vocalizations from a glider	Slocum Electric Glider	HTI-96-MIN hydrophone Persistor CF2 Data Logger	PAM	The quality of the acoustic data recorded was very good. The glider movement and flow noise did not affect the recordings. Multiple gliders deployed at once meant that the vocalising whales could be localised to within a few hundred meters.	Gulf of Maine
Goudey et al., 1998	Kaya-shaped ASV used to track a tagged wimming animal	Kayak ASV	Acoustic transducer in a tracking tag.	AAM	A small kayak-shaped ASV, 25 cm long and powered by an electric battery, was used to follow a tagged swimming animal (fish) during an entire day (24 hours). The small size and electric power were selected to minimise the noise output of the vehicle.	Not specified
Grasmueck, 2006	morphology & oceanographic conditions	C-Surveyor IITMAUV	KongsbergT MEM1002	AAM	The data obtained by the AUV was able to provide information to fill the gap between low-resolution surface-based mapping and visual observations on the seafloor.	Straits of Florida
Greene et al., 2014	Fisheries acoustic stock assessments.	Wave Glider	BioSonics DT-X-SUB	AAM	A fleet of wave gliders could survey the West Coast USA EEZ much faster and more frequently than a traditional fisheries survey vessel	West Coast USA EEZ
Guihen et al., 2014	Presence / absence, quantity	Seaglider	Imagenex ES853 120 kHz	AAM	Made acoustic backscatter measurements through the downcast and upcast of a Seaglider mission using a calibrated single frequency (120 kHz) echosounder. Antarctic krill swarms were identified in the acoustic data and krill abundance in the Weddell Sea was estimated during two short periods in January 2012. The study highlighted the complexity of animal target orientation and glider orientation and its effect on target strengths and therefore biomass estimates. It also	Antarctica

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
					highlighted the need for appropriate sampling strategies for gliders to be used for biological surveys.	
Haulsee et al., 2015	Presence / absence	Slocum	Vemco, acoustic receiver	AAM	Integrated VR2C acoustic receivers (VEMCO, frequency = 69 kHz) into a Slocum G2 glider. The hydrophones extended out of both the dorsal and ventral hull to increase listening capabilities. The sand tigers were caught and tagged (internally) with acoustic transmitters as part of previous projects. The AUV detected 97% of acoustic transmissions from test tags within a distance of 250 m. The percentage of tags detected decreased exponentially at distances greater than 250 m. The study was unable to determine the vertical position of any shark detected by the AUV.	North Atlantic
Johnson, 2012	Automatically detect and classify vocalisations.	Slocum glider, Apex profiling float, Drifting surface float	DMON	PAM	Beaked whale detections were examined to establish miss-classification rates to improve classification thresholds in the detector. Glider and profiler motors were noisy but had a low duty cycle and so are considered viable platforms. Profiles were preferred while the short shallow dives of the glider made it less effective.	Canary Islands
Kennish et al., 2004	Seabed patterns and benthic habitats	Propeller AUV *Remus*	600 kHz side-scan sonar	AAM	Study of the bedforms and related benthic habitat of invertebrate and demersal finfish populations in Great Bay (New Jersey), using an AUV (*REMUS*) outfitted with a side-scan sonar.	New Jersey
Klinck et al., 2012	Presence / absence	Seaglider	High Tech Inc HTI-99-HF	PAM	The Seaglider was instrumented with a hydrophone. Acoustic data were compressed using Free Lossless Audio Codec (FLAC) and stored on flash drives, in parallel acoustic data were screened for beaked whale vocalisations using an energy ratio mapping algorithm (ERMA) onboard the glider and detections were reported back to shore on surfacing. Beaked whales were detected on 7 of the 85 dives (one every 27.5 hours), similar densities to those recorded by visual survey. The data confirmed the glider is capable of detecting the presence of beaked whales within a few kilometers. The hydrophone was not recording throughout the whole dive, and they identified how vocalizations could be missed as a result of this.	Hawai'i

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
Lucieer et al., 2013	Classification of multibeam acoustic data	Propeller AUV *Sirius*	Stereo camera system	Image	The AUV *Sirius* was sent on five missions to map the benthic habitat of coastal reefs along the Fortescue coast using high resolution images obtained from a stereo camera system at 1 s intervals. The camera images where used to geo-reference available MBES images. The results allowed identification of attributes from the multibeam acoustic data which could be correlated with the presence of benthic species.	New Jersey
Manley and Vaneck, 1998	Bathymetry mapping	Catamaran ASV *ACES*	Basic recreational depth sounder	AAM	The ASV *ACES* is a small catamaran powered with a gasoline engine and equipped with a control system for automatic navigation. This study describes the initial tests of *ACES* as an instrument for hydrographic surveys (bathymetry mapping). The 72% of the collected data met Class 1 standards when compared to previous highly accurate bathymetry data collected by the USACE in the same area.	Massachusetts
Matsumoto et al., 2013	Compare acoustic float to Navy M3R system	QUEphone acoustic float	HTI92WB hydrophone ERMA detection algorithm	PAM	The QUEphone's detections were comparable to that of M3R's, concluding that the float is effective at detecting beaked whales.	AUTEC (Bahamas)
Ohman et al., 2013	Presence / absence, quantity	Spray	Sontek 750 kHz ADP	AAM	Observations of zooplankton diel vertical migration in the California Current system. The deeper daytime depths and larger amplitude of zooplankton diel vertical migration behaviour associated with the offshore waters at frontal transitions are attributable to a faunistic change across the front and associated spatial changes in light mediated predation risk.	California
Powell and Ohman, 2015a	Presence / absence, quantity, behaviour	Spray	Sontek 750 kHz ADP	AAM	Six years of Spray glider transects across the California current system are presented. Waters on the denser side of a front contained higher chlorophyll a and acoustic backscatter than waters on the less dense side. Diel vertical migration behaviour of zooplankton increased offshore and covaried with optical transparency of the water column. Differences in acoustic backscatter across the	California

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
					front were validated with net samples that showed differences in zooplankton composition and size classes across the front.	
Powell and Ohman, 2015b	Presence / absence, quantity, behaviour	Spray	Sontek 750 kHz ADP	AAM	Six years of Spray glider transects across the California current are presented. Mean Volume Backscatter Strength (MVBS) recorded from a 750 kHz acoustic Doppler profiler were used to observe changes in zooplankton coincident with density fronts. MVBS was significantly correlated with density gradients, and it was hypothesised that large mobile predators foraging in the vicinity of such features could locate habitat with higher zooplankton biomass concentrations up to 85% of the time by travelling up local density gradients (i.e., toward rather than away from denser surface waters).	California
Suberg et al., 2014	Presence / absence, quantity	Slocum	Imagenex ES853	AAM / PAM	Two slocum gliders equipped with CTD and fluorometers, one carried an echosounder for resolving zooplankton and fish, the other carried a modified d-tag sensor. Strong tidal currents deflected both gliders, which ultimately led to recovery and redeployment of the gliders. In 6 weeks, the gliders completed 5,474 dives and travelled 2,389 km. Fish marks were observed in the 120 kHz acoustic data, although no species identification was possible. Harbour porpoise clicks and dolphin clicks and whistles were detected during a limited subsection of the mission before the d-tag power cable was damaged. Noise attributable to the glider pump was also recorded.	Isles of Scilly
Vaneck et al., 1996	Bathymetry data acquisition in littoral region	ASV (surface craft) *ARTEMIS*	not specified	AAM	The prototype autonomous surface craft (ASC) *ARTEMIS* is used to collect bathymetric data in littoral regions, for potential future use in costal surveys and monitoring, mine countermeasures and oceanographic surveys. Accurate geolocation of bathymetric points is achieved through a guidance controller with differentially corrected GPS.	Not specified

Reference	Objective	AUV / ASV type	Sensor	Data type	Summary	Country
Wall et al., 2012	Presence / absence, quantity	Slocum	Digital Spectrogra m Recorder	PAM	A hydrophone was integrated into the cowling of a slocum glider to measure fish sounds. Red grouper and toadfish sounds were recorded, as well as 3 other biological sounds suspected to be fish. Sounds were recorded along glider transects to provide biogeography of these fishes. The Digital SpectroGram Recorder (DSG) recorded sound for 25s every 5 minutes at a sample rate of 70,000 Hz. Data were stored on a 16 GB SD card. The DSG clock was synchronised to the glider's computer to store embedded time stamps into the raw data file structure. Fish sounds were manually detected, as glider altimeter, pump and at-surface Iridium noise hampered automated detection methods.	Gulf of Mexico
Wall et al., 2014	Presence / absence, quantity	Slocum	Digital Spectrogra m Recorder	PAM	Three passive acoustic glider missions were conducted off west-central Florida, two in a red tide, in order to assess whether red tides influence soniferous fish. In addition to detections of red grouper and toadfish, a cusk eel sound was also identified and recorded. Different fish type noises were associated with different depth layers and with different diurnal frequency.	Gulf of Mexico
Williams et al., 2010	Study of drowned reef along the GRB	Propeller AUV *Sirius*	Imagenex DeltaT	AAM	A ship-based seafloor mapping supported by AUV surveying and dredging samples was carried out in Queensland, to study the drowned coral reefs along the shelf edge of the Great Barrier Reef. The AUV *Sirius* was used to gather high-resolution sea floor imagery at close range from the seabed to validate the interpretations of the sonar data from the ship.	Australia

9.2.1 Cooperative systems

Autonomous aerial, surface and underwater vehicles may track individual animals and obtain data from the robotic platforms in a coordinated effort or a network (see Figure 12 as example). This can improve our understanding of the individual technologies' limitations and acquire detailed information about the animal under study and its surrounding environment. Though this requires a lot of effort to coordinate all the systems, it is nevertheless highly valuable for improving the current knowledge of individual systems and how current innovation can be applied with a broader approach to the marine environment. At the same time, this coordination using global communication and data centralisation allows for a greater situational awareness by using satellite, radio, and internet communications. Initiatives such as the Ocean Observing systems (e.g., ONR Noise Observing System, NSF Ocean Observatories Initiative Coastal & Global Scale Nodes, Global Ocean Observing System, Ocean Networks Canada, NOAA Integrated Ocean System) provide multi-scale, multidisciplinary ocean observing systems using the interactive capability of advanced sensors and platforms, and real-time access to data and visualization tools (NSF, 2009). These networks are able to collect ocean and seafloor data, together with information about the effects of anthropogenic activities on marine species (e.g., Clark et al., 2008), at high sampling rates that can last years to decades.

Modern surveys and observing systems utilise, for example, multiple gliders to observe the oceans. Technology is being integrated to coordinate and control multiple platforms and to track dynamic features. For example: The Glider Monitoring, Piloting and Communication (GLMPC) system (Jones et al., 2011b), the Adaptive Sampling and Prediction (ASAP) research initiative (Leonard et al., 2010), and the Adaptive Autonomous Ocean Sampling Networks (AAOSN)[17] (see also Zhang et al., 2007; Alvarez, 2009). This includes tracking tagged organisms such as fish and sharks (e.g. MASSMO project[18]). These systems envisage interfacing autonomous decision making for multiple autonomous vehicles of different types, and are currently being tested in model and field scenarios[19].

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[17] http://noc.ac.uk/sbri
[18] http://projects.noc.ac.uk/exploring-ocean-fronts/robotic-vehicles-successfully-track-tagged-fish-plymouth
[19] http://noc.ac.uk/SBRI

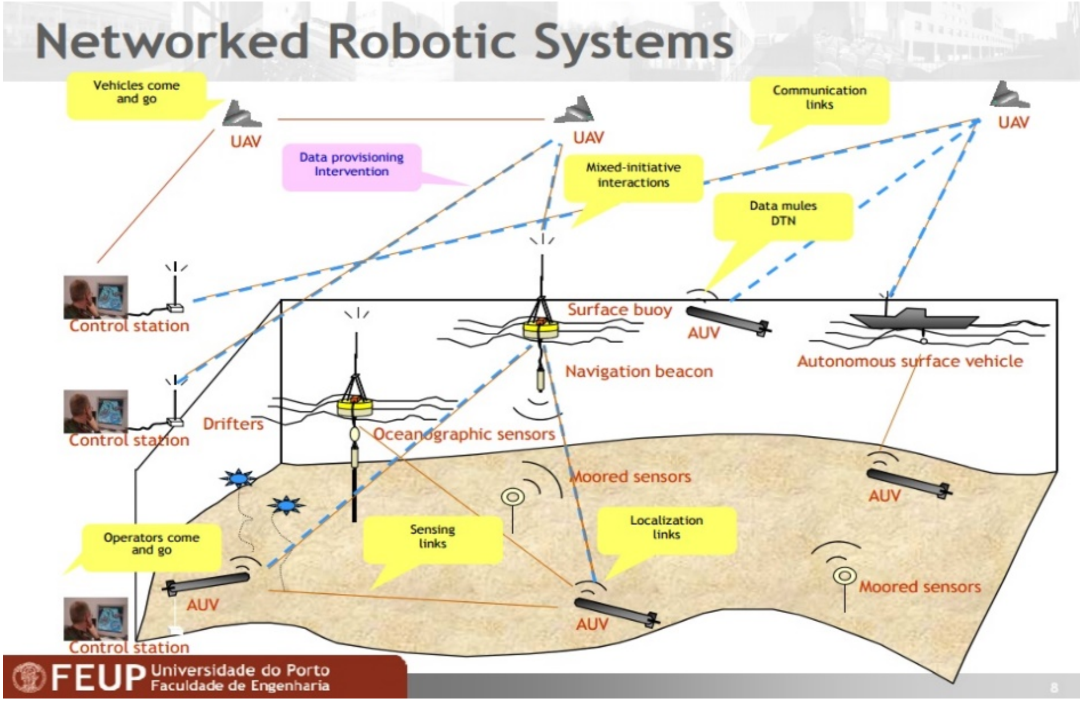

Figure 12. Sunfish Tracking project (Pinto, 2014)[20]

9.3 Operational aspects to consider

The operational aspects of the use of autonomous vehicles during E&P activities cover the practical implications of deploying autonomous vehicles as well as trade-offs that need to be considered based on the level of technology, abilities of systems and the capability to integrate with existing systems or monitoring efforts.

Enhanced data, survey quality, and mission versatility are cost-benefit advantages to using autonomous vehicles. The prime advantage of these vehicles however would be to reduce the deployment of conventional platforms and personnel in the field. Hypothetically, environmental monitoring could be completed by autonomous systems without the need for a conventional vessel leaving harbour or an aircraft taking off. The offshore environment is inherently hazardous and the implication that an autonomous vehicle could remove the need for a person to leave the safety of land is significant. Major concerns are raised with managing any vessel/aircraft offshore and considerable risk analysis would be required for unmanned craft in an area of industry operations. This potential reduction in health and safety risks is likely to be extremely appealing to industry.

However, the possible introduction of alternative health and safety risk into at-sea field of operations would delay the maturation of autonomous vehicles in an E&P operational setting. A high level of understanding and confidence will be required regarding operational health and safety risks. Procedures for managing unmanned devices would need significant development and detailed risk assessments and would need to be conducted on a case by case basis.

[20] https://bts.fer.hr/_download/repository/Jose_Pinto.pdf

Safety will be the overarching theme as we consider operational practicalities of utilising autonomous vehicles in an industrial setting. The vast range of possible contexts requires that we take a general approach in attempting to compare across platforms. The categories within which we will explore these issues are:

- Technical Reliability: Extensive trials and proven track record are likely to be required of any craft before usage in industrial field of operations.
- Mission Duration: Any autonomous vehicle that can maintain long mission duration with complete independence will offer a crucial advantage.
- Logistics: Logistical factors must be taken into account, albeit on a project by project basis, for safety concerns and also cost implications.
- Remote Operation: Technical and safety assurance will be required regarding the dependability of the link and responsive ability of remote operation.
- Interaction with other marine/airspace users: Clear code of practice is likely to be required and disseminated to potential interactors in the area in advance.

Additionally, practical realities of operations, such as deploying and retrieving the craft, tend to fall outside the scope of studies and very little published information was found exploring these issues. However, practical knowledge gained from first-hand experience of trials is included.

9.3.1 Technical Reliability

Confidence in reliability would be required in mechanical and manoeuvrability performance. Any risk of, for instance, ASV breakdown ahead of a seismic vessel and associated equipment, would have time, cost and safety implications. Support might be available via a chase vessel but this is not to be guaranteed. Close attention to accurate waypoint-marking and remote operation, including an over-ride facility in case of any malfunction is required. Of the highest importance is that any autonomous vehicle operating in the vicinity has sufficient power and manoeuvrability to be where it needs to be at the appropriate time (or at least not to be where it shouldn't be). Absolutely key to industry operations is that any additional hardware must not interfere with the industrial operations taking place. In the case of ASV, trials to date have invariably involved close support from an accompanying (conventional) vessel. The stage is set for an ASV model to prove its capability to independently complete extended duration missions. For underwater buoyancy gliders, Brito, (2014) calculated risk profiles for shallow and deep gliders (combining manufacturer's platforms). They found that the probability of a glider surviving its mission deployment without a premature mission end was 0.5 and 0.59 for deep and shallow gliders respectively. This identifies that currently other factors than battery power are limiting glider performance. Such analyses should be completed for all autonomous platforms (AUV / ASV / UAS) intended for surveys conducted for the O&G industry, as they identify the amount of redundancy required (in terms of number of vehicles to complete the mission), as well as inform on likelihood of technical failure. One current challenge is that many of these platforms are constantly evolving. Extensive trials and proven track record are likely to be required of any craft before usage in industrial field of operations.

9.3.2 Mission Duration – Power considerations

The means of power underpins much of the operational aspects discussed in this review. There are a range of power methods available (often as hybrid options on the same craft). Additionally, the power budget is frequently tailored to project specifics. However, in broad terms: conventional fuel requires refuelling, which limits mission duration. Renewable harvesting (e.g. solar energy) addresses this but requires a consistency in supply that cannot be guaranteed due to variability in environmental conditions. Power by wave motion offers the great advantage of almost limitless mission duration, albeit at low speeds and lower manoeuvrability. The means of refuelling / recharging also requires consideration. In the case of ASV / AUV, a support vessel would be required, incurring marine operation logistics, costs and risks that any ASV / AUV intends to reduce. In many instances, particularly for UAS, the mission duration will define the operation. Within this defined mission time limit there would have to be significant contingency. An autonomous vehicle that can genuinely maintain long mission duration, wholly independently of any support vessels, offers a crucial advantage by removing the need for in-field logistical support.

9.3.3 Logistics

The deployment and recovery of autonomous systems is an important consideration. Complete independence would be preferred, whereby a craft exits and arrives at a survey site at sea under its own power - a possibility for some ASV and AUV, and many underwater buoyancy gliders (albeit slowly in the latter cases). Short of this capability, mechanisms such as a supporting vessel fitted with lifting equipment and suitable landing areas will be required. These will bring further HSE concerns, especially in poor weather. Transportation of craft is also a consideration to be made. There is a huge range of sizes in autonomous vehicles (Table 13) but all would likely be required to be freighted to the operations area. This might well be overseas and issues including importation requirements and in particular transportation of lithium batteries may come into play. Logistical factors must be taken into account, albeit on a project by project basis, for safety concerns and also implications on cost.

9.3.4 Remote Operation

A large range of, often sophisticated, remote control mechanisms and options are covered through the unmanned vehicles reviewed here. How they would be implemented in practice in an operational area needs to be addressed. The operation of a vehicle from a remote location, such as by satellite link, opens the way for craft being manoeuvred in an E&P survey area with several other vessels or installations on-site by a specialist thousands of miles away. Communication protocols will be vital, to ensure that "ground-truthed" information, especially navigational and environmental, is supplied to assist the remote operator and full transparency of such remote operations, not least positioning information, is transmitted to the relevant personnel offshore. This issue additionally impacts interaction with other marine/airspace users.

The control, handling and maintenance of autonomous vehicles may require specialist knowledge. This would therefore entail the provision of specialists into the offshore working environment. A key implication of additional personnel is physical bunk space - invariably at a premium in oil and gas operations. Alternatively, specialist training could be rolled out for existing crew.

Technical and safety assurance will be required regarding the dependability of the communication links and responsive ability of remote operation.

9.3.5 Interaction with other marine/airspace users

Safety is paramount with the number and diversity of other assets in a field of operation. The operation of autonomous vehicles within an industrial field of operations means that it's highly likely that other platforms will be in the area. Also, the hardware (whether deployed from existing vessels or from autonomous platforms) must not interfere with the industrial operations taking place. Of the highest importance is, as mentioned previously, that any autonomous vehicle is technically reliable in its manoeuvrability. Smaller, low powered vehicles, which are easier to deploy, are likely to have problems in this area, in which case measures would need to be taken to rapidly recover any vehicle which is posing a hazard to other activities. Though governmental regulations for safe use may be in place, these are in early stage of development (especially in case of maritime activities). Consideration would need to be given to the spatial requirements of individual autonomous vehicles in any given setting, relative to other marine / airspace users. Sensors and mechanisms for collision avoidance will be of high priority, as will methods for positioning and reporting that position. Data transmission systems will have to comply with local regulations and restrictions and there should be minimised risk of cross-interference. Remote operation is a key component here with the question arising of whether a remote operator is required to communicate with, potentially, third party marine / airspace users. If so, the means by which to achieve such communication with third party users would need to be defined. In summary, a clear code of practice is likely to be required and disseminated to potential interactors in the area in advance.

9.4 Regulatory / political barriers

9.4.1 Regulations for the airspace

There are several regulatory and political considerations involved in the use of UAS in offshore operations. For instance, study sites near airports or populated areas and nocturnal surveys may be more restricted than remote sites and daylight surveys, and may demand special permits by local authorities. However, regulations governing the use of UAS are currently changing, and users should seek updated information in due time before the planned research operations (Watts et al., 2010). Without an on-board pilot, there is a significant reliance on the command and control link, and a greater emphasis on the loss of functionality associated with lost link communication with the ground station. Furthermore, for Air Traffic Control (ATC) operations requiring visual means of maintaining in-flight separation, the lack of an on-board pilot does not permit ATC to issue all of the standard clearances or instructions available under the current edition of FAA Order 7110.65, ATC (FAA, 2013). Consequently, to ensure an equivalent level of safety, UAS flight operations require an alternative method of compliance (AMOC) or risk control to address their "see-and-avoid" impediments to safety of flight, and any problems they may generate for ATC. Currently, the lack of technology to detect and avoid other vehicles in their vicinity, is one of the main limitations for the use of UAS, which, if implemented, would be highly valuable in preventing collisions with other aircraft particularly during operations beyond-Line-Of-Sight (BLOS). In future, permanent and consistent methods of compliance will be needed for UAS operations in the National Airspace (NAS) without the need for waivers or exemptions (FAA, 2013).

Depending on the type of operation and the air space regulations within the country of operation, certain requirements must be fulfilled (see Figure 13). In Norway, for instance, all approved Remotely Piloted Aircraft System (RPAS) operators can operate within VLOS and typically below 400 ft without applying for a permit from the civil aviation authority. For a VLOS operation, visual contact without any optical devices, other than prescription glasses, must be maintained at all time. The maximum VLOS (vertical) distance from the pilot depends on weather conditions, time of day and type of background. It can vary from 200 to 300 m for small multi-rotors and up to 3 to 4 km for fixed wing aircrafts fitted with high visibility paint or lighting[21]. It is possible to extend this range by utilising one or more remote observers so that the unmanned aircraft is within visual sight of an observer at all times. The operation is then referred to as an extended visible line of sight (EVLOS) operation. Critical flight information is relayed via radio for assisting the remote pilot in maintaining safe separation from other aircrafts. RPAS operations beyond visible line of sight (BLOS) is usually only approved in areas where safe separation to other aircrafts can be ensured, such as remote or segregated airspace. BLOS operations require an approval from the civil aviation authorities, which has to be applied for in advance (typically 3 to 4 months in Norway).

Currently, all UAS operators should ensure their operations meet all applicable National Civil Aviation Authority (NCAA), local, state and federal regulatory legal requirements. The IOGP launched a set of guidelines in early 2015, specifically designed for UAS operations. These guidelines include issues which are highly relevant to ensure safe aerial operations such as maintenance, communication, and training (FAA, 2013). These guidelines also specify that operations should be incorporated into a Safety Management System (SMS) consistent with the Oil and Gas Producer's Aircraft Management Guidelines (AMG) (Luftfartstilsynet, 2015).

The main limitation to the use of UAS is the acceptance of the technology by regulatory bodies, aviation-related restrictions on flying UAS and responsiveness by system manufacturers. It is yet to be assured that current monitoring and mitigation methods can be replaced by UAS, and this is one of the critical points that stimulate

[21] http://www.acuo.org.au/industry-information/terminology/how-do-we-see-them/

more research and data collection about different systems. At the same time, the need for further research is limited by the availability of permits and regulations that allows it. However, countries like Norway, Canada and Australia have invested in developing new systems and new methods of surveillance, which in turn can facilitate the acceptance by more restrictive jurisdictions. This has already started to change in countries such as USA, where the main aviation authority, the Federal Aviation Administration (FAA), has started to take measures for safe UAS integration in their regulations.

Country-specific regulations are under development, considering mainly commercial applications. The continuous focus on airspace regulations that are more integrative of UAS worldwide is a clear sign that this technology is here to stay.

Figure 13. Current commercial small UAS rules in countries with strong and growing markets for UAS systems (Bonggay, 2016)[22].

9.4.2 Regulations for the sea

The regulatory framework for marine autonomous vehicles is in a state of flux. There is a clear need for greater clarity around legal issues and diplomatic clearance as applied for the different users, e.g. military, marine scientific research or - increasingly - commercial surveys. Unmanned systems are becoming ubiquitous in the oceans. International law governing activities on, over and under the sea emerged well before the development

[22] http://media.precisionhawk.com/topic/commercial-drones-faa/ (accessed 2/10/2015)

of unmanned systems. As ASV and AUV become more advanced – already autonomous, expendable and "intelligent" robots are emerging, forming networked systems – legal and policy issues are becoming acute. Legitimate concerns over insurance and recoverable loss are also raised. Kraska (2010) points out that as "aircraft" and "vessels," unmanned naval systems fit within the existing legal architecture for peacetime maritime operations, including the 1944 Chicago Convention on Civil Aviation and the 1982 United Nations Convention on the Law of the Sea. These two treaties and their progeny provide guidance for the use of most of the global commons, and reflect a liberal legal architecture for unmanned air/sea vehicles and systems. Furthermore, the 1982 United Nations Convention on the Law of the Sea (UNCLOS) plays a key role in the legal framework for AUV / ASV deployment. However, the available State practice concerning the deployment and operation is not uniform or universal in scope with regard to customary international law (CORDIS_result_171941). Even the legal definition of an AUV / ASV remains unclear, i.e. whether or not a craft is classed as a "ship" (GROOM, 2013; Wynn et al., 2013).

As a result, the legal views relating to the operational use of autonomous marine vehicles are varied and tend to be driven by scenario (e.g. requirement for navigational safety) or by class of operator (defence/academic/commercial) (Rogers, 2012). As such, it is important to track current progress in forming a pragmatic Code of Practice for the use of AUV / ASV, also known as Maritime Autonomous Systems (MAS). At the present time, such craft are typically relatively small vessels, operating on both the surface and underwater (ASV and AUV). We note that research is well underway on much larger commercial vessels, led by companies such as Rolls Royce and the EU MUNIN project.

In the UK, the MAS Regulatory Working Group (MASRWG) is addressing this specific need. It was formed in 2014 with two main aims:

- To formulate a regulatory framework that could be adopted by the UK and other States, as well as the international bodies charged with the responsibility to regulate the marine and maritime world; and
- To develop a Code of Practice for the safe operation of MAS.

An initial Information Paper, prepared by the MASRWG, was presented by the UK to the International Maritime Organisation (IMO) in June 2015. This was accepted as a signpost for other nations to become aware of the work the UK is undertaking on the combined requirements for regulation, equivalence, training, standards and accreditation for ASV. Following a successful conference in October 2015, the next output of the MASRWG will be to present a full Code of Practice to IMO, through the UK Maritime and Coastguard Agency. This will be at the Maritime Safety Committee (MSC) 96 in June 2016.

A number of other nations and organisations are now liaising with the MASRWG to input to the UK Code of Practice; international consensus is a key component of this work. In practise, an increasing number of AUV and ASV are being operated in different parts of the world despite the lack of formal country specific regulations. Craft operate, essentially safely, by working within the existing conventions and regulations as far as possible.

These include the Collision Regulations, United Nations Convention on the Law of the Sea (UNCLOS), Safety of Life at Sea (SOLAS), International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL), Notice to Mariners, Navigational Telex (NAVTEX) and many more. Risk assessments and safety cases are a critical part of their safe operation. Understandably, ASV and AUV must earn the confidence of the wider maritime community to be accepted as safe marine-users. To provide such assurance, huge developmental effort has been invested into methods for navigational positioning and collision avoidance. Technology such as automatic obstacle avoidance is regarded as key to paving the way for establishing legal policies for unmanned vessels (Campbell et al., 2012). Various gaps in the existing documentation bring scope for confusion, particularly within the plethora of definitions that are emerging. A good example of this is with the various definitions and interpretations of the word 'Autonomy' itself. The Code of Practice will address this and many other issues. It may prove largely unnecessary for the emergence of ASV/AUV to spawn a suite of new regulations. Wherever feasible, they would find their place within the existing structure. The principle of equivalence is key here whereby mariners of every kind of vessel, manned or unmanned, have the freedom to operate as desired - under a common understanding of legality and safety.

The intention is that an Industry-led Code of Practice for AUV and ASV will help to make this transitional process as smooth as possible. In turn, this will follow on a worldwide scale with country-specific requirements.

9.5 Technical challenges of managing, storing and analysing large amount of data

Over the course of a day, autonomous sensors can acquire tens of Gigabytes of raw data. The management and science questions to answer with these data often require the reduction the data to one or two numbers or simple decisions, e.g. "Is there an animal in the exclusion zone?" or "Was an animal detected in the 20 minute period?", "Can we start the survey line?", "The density of animals in this area is …". The job of the data processing chain is to extract these relatively simple answers from the great volume of raw data. Data processing is often done in multiple stages and sensing systems often combine automatic processing of raw data with data displays viewed by a human operator as an aid to final decision making.

Sensor packages for autonomous platforms come in many formats. The simplest systems consist of little more than the sensor itself and some sort of data recorder (Figure 14A). These days, the recorder is often a low power computer that streams data from the sensor to a data storage drive. While simple, such systems can have the advantage of high reliability and low power and are often ideal if data are not needed immediately. Slightly more complex systems, often used with high bandwidth data where storage is a problem, might carry out some initial screening of the data in order to remove those data highly unlikely to contain anything of interest but keep processing to a bare minimum and do not provide data in real-time (Figure 14B). If data are required in real time, then those data must be transmitted to shore or a nearby manned platform (vessel or aircraft) so that they can be used in near real-time decision making (Figure 14C). This can create significant challenges, particularly when working with high frequency (and therefore high volume) data over low power or where it is expensive to send large volumes of data (e.g. satellite). When it is not possible to transmit raw data, then sufficient processing must take place on board the platform in order to reduce the amount of data to that which can practically be transmitted (Figure 14D).

The quantity of data that can be sent through the various communications devices varies enormously (section 8.1.4) but suffice to say that many communications options do not have the capability to transmit high bandwidth data, in which case it is necessary to process data on the platform itself in order to reduce the amount of data that is transmitted (Figure 14D).

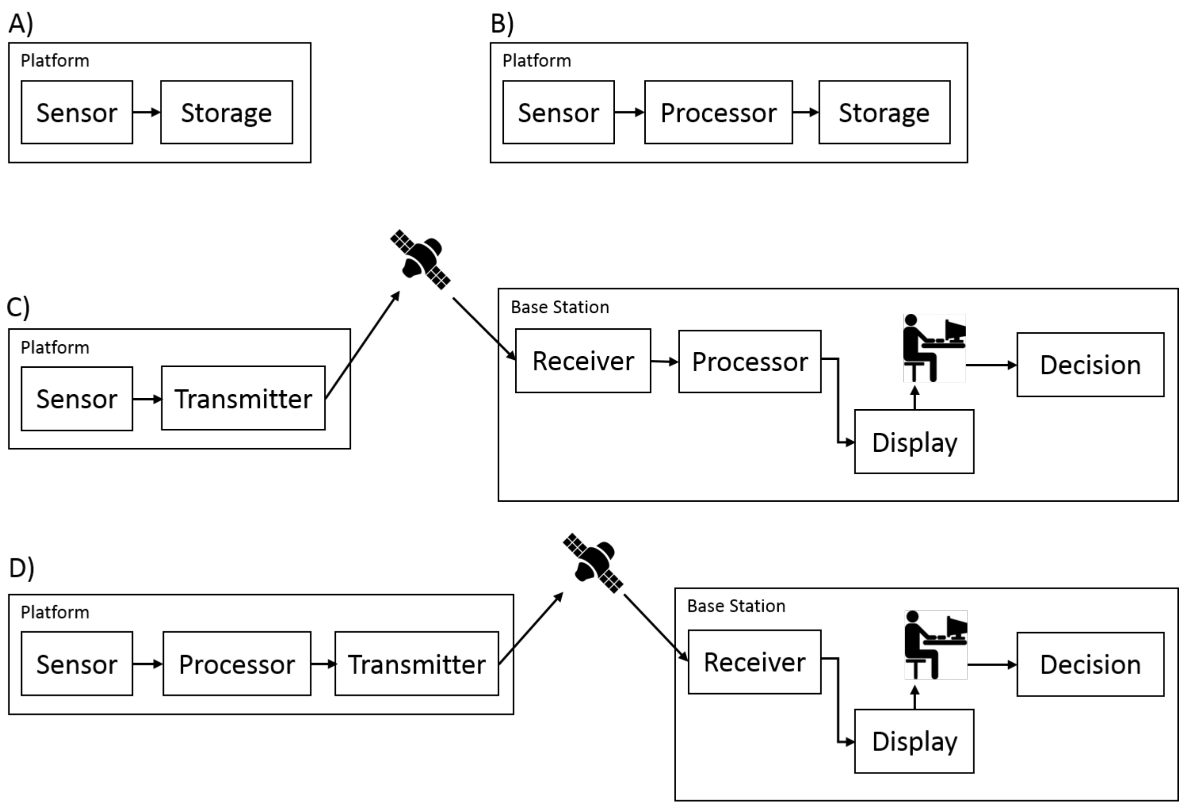

Figure 14. Schematic diagrams of four different sensor data handling combinations. These are intended primarily as examples and many more combinations exist. A) Simple sensing and data storage, B) Sensor, basic processing and data storage, C) Real-time transmission of raw data with processing on shore, D) On board processing to reduce data volume prior to transmission of a minimal amount of data.

Herein lie the fundamental problems and limitations of sensors on autonomous platforms: for situations where data are not required in near real time, the limitations are storage capacity and power; if data are required in real-time (or near real-time) then the amount of data that can be transmitted are governed by transmission distance, power availability and cost. Data must therefore be reduced by whatever factor is required to satisfy those limitations. However, processing algorithms must be sufficiently reliable and sufficient data must still be transmitted that an operator has enough information for accurate decision making. If insufficient data are presented to an operator and there is an over reliance on potentially unreliable automatic processing algorithms, then errors will occur: animals which are present may be missed, and false alarms will be received.

The amount of processing that can be carried out on the platform will depend on the sensor type, the strength and distinctiveness of the signals of interest and also the type and quantity of background noise which may vary widely between regions. For some sensors, species and situations, researchers have been able to reduce data sufficiently for reliable information to be sent to shore via relatively low bandwidth satellite communications links (e.g. Baumgartner et al., 2013). This does not, however, mean that such systems can be easily developed for other species and other situations. In many cases, it has proven necessary to use much higher power, short range communications systems which transmit high volumes of data over relatively short distances.

9.5.1 Electro-optical imaging sensors

Optical sensors (RGB, IR, and video) may differ in terms of data transfer and processing depending on the type of sensor in consideration. Still-photo and video data (either in RGB or IR) may be stored on-board an SD card for post processing or gathered during real-time transmission of a video and manually triggered to obtain a photo of a target. The resolution required here may play a key role in the type of sensor to be used, since it is possible to transmit HD images in real-time, but higher resolutions still appear to be unreliable for this type of application. Data transmission will therefore depend on the data type, with radio links affecting the range to which it is possible to fly. For higher ranges, it is then required to acquire a stronger radio link, such as Kongsberg Maritime Broadband Radio.

Automated detection of objects of interest is an advantage in circumstances where the amount of data to be acquired is very large. This is highly relevant particularly for transect-based surveys in population studies and monitoring of areas relevant to seismic operations. Zitterbart et al. (2013) have shown the potential of this technology in detecting large cetaceans using thermal IR systems in ship surveys by identifying whale blows based on their thermal signature. Additionally, work developed between LGL Alaska, Inc, and Brainlike, Inc. (Ireland et al., 2015) has progressed the availability of a real-time animal detection software. This type of software requires a degree of machine learning, since survey conditions may vary both in time, space, and in the type of species possible to encounter. On the other hand, algorithms that are operational for post-survey analysis are still unreliable due to the lack of animal movement that improves detectability. Mejias, (2013) developed two algorithms that seem to be promising in marine mammal detection, however, the amount of false detections remained high, highlighting the status of data processing for post-survey analysis.

Though UAS are an upcoming technology with many different applications, the amount of digital imagery that these systems collect can sometimes be overwhelming. Depending on the survey design, the time required to manually analyse the images from each survey can make this methodology costly, highlighting the need for automated analysis processes. There are many issues concerning the use of automated detection of marine organisms; sea state condition is one of the key issues affecting detectability, which in terms of automated detection could have a major effect, since the presence of surf wake can create false positives that may go unnoticed unless manually checked. Another issue is the presence of glare and other environmental factors that may affect the detection of animals based purely on body shape. Ireland et al. (2015) developed an automated process that can quickly process high resolution digital still images and identify potential marine mammal detections, with an overall successful detection rate of approximately 70%. The time required to manually review the automated processing output based on this work was less than 2% of the full manual analysis time, thus significantly reducing the amount of time and associated cost of image analysis. This work, done in collaboration with Brainlike Inc., has been incorporated into aerial survey work conducted by Shell Oil using PixMin™, a software designed for target recognition. However, most of the work developed in automated detection involves post survey analysis, although Koski et al. (2013) showed that real-time monitoring with UAS and video camera is feasible. The need for survey technology (platforms and sensors) has been pushing the development of aerial systems that can deliver accurate and unbiased data both to industry authorities and research. Therefore, imagery analysis remains a constraint that is quickly being overcome by the progress in the development of both sensors and aerial platforms, as the quality of the data improves and the availability of detection algorithms that can be tested increases.

9.5.2 PAM systems

Table 9 shows the volume of raw uncompressed data from a single hydrophone digitized with 16 bit accuracy. Note that these are raw data volumes and that it is possible to run compression on audio data which will reduce data volume by around a factor of four using algorithms such as FLAC or X3 (Johnson, 2013). If multi-hydrophone systems are considered (as would be required for animal localisation) then these values should be scaled up by the number of hydrophones. As can be seen, for baleen whales, which vocalise at low frequencies, a year's recording will generate only a modest amount of data and even sampling at the standard human audio sample rate of 48 kHz for a year will generate no more data than can be fitted on a single portable hard disk drive. However, for the majority of dolphin, beaked whale and porpoise echolocation clicks, higher bandwidths are required, which generate significant volumes of data.

Even in situations where large data volumes can be stored, transmitting those data to a remote platform may be impractical due to bandwidth and power limitations. If sufficient power is available, radio links can be used over ranges of a few kilometres; for larger distances in remote locations, it may be necessary to use satellite communications systems, in which case power, bandwidth and cost all become problematic. In this case the only option is to pre-process data on board the autonomous platform and transmit only a summary of the detection data, which is hopefully sufficient for accurate decision-making. In some cases (with low frequency data or highly distinctive species) this has been proven possible, however for species which are difficult to distinguish from background noise, or for which complex tracking is required, it is currently not possible to transmit sufficient data through low bandwidth systems for accurate real-time decision making.

Table 9. Data volume (Gigabytes) for different recording bandwidths and recording durations for a single hydrophone recorded at 16-bit accuracy.

Sample Rate (Hz)	Bandwidth (Hz)	Gigabytes per Day	Gigabytes per Week	Gigabytes per Month	Gigabytes per Year	Species Accessible
250	125	0.04	0.28	1.21	14.69	Blue and some other large baleen whales
2000	1000	0.32	2.25	9.66	117.48	Baleen whales
48000	24000	7.72	54.07	231.74	2,819.54	Sperm whales, most dolphin whistles and some clicks
500000	250000	80.47	563.26	2,413.99	29,370.19	Dolphin, beaked whale and porpoise clicks.

An increasing number of algorithms are now available for the automatic detection of marine mammal sounds with considerable momentum to the field being given by biennial workshops funded by the US Office for Naval Research and others and published as special issues of various journals[23]. However, many of the algorithms presented in the literature have been tuned to very specific data sets covering a limited range of species, and nearly all require human validation of their output, particularly when working in a variable noise environment. Research groups processing large data sets generally try to find a balance between automatic processing and human validation, putting considerable effort into the development of data visualisation tools which enable operators to home in on candidate detections or areas of interest in the data (e.g. Triton software developed by SCRIPPS Whale Acoustics Lab, the Raven and XBat packages from Cornell and PAMGuard from SMRU). For some sound types, detector output data, containing only very short snips of real data, are sufficient for data checking. For others, the contextual information that is only available from a spectrogram of a longer section of raw data can be more important. For example, Figure 15 shows false and real whistle detections from an automatic detector both without and with the full spectrogram information. From the detected whistle contours, it is impossible to say whether the detections are real or false. By viewing spectrograms of the raw data and also by listening to them, it was clear that the first sound is mechanical (in this case the hydraulic system lowering the outboard engine on a vessel deploying a PAM equipped Waveglider) and that the second example is a genuine animal sound. However, the full 5 seconds of raw audio data shown in this example would require around half a megabyte of data relay, whereas the detection data alone only requires a tiny fraction of this.

[23]For example: Canadian Acoustics, Vol 32, No 2 (2004), Canadian Acoustics, Vol 36. No. 1 (2008), Applied Acoustics, Volume 71, Issue 11, Pages 991-1112 (November 2010), J. Acoust. Soc. Am. Special issue on Methods for Marine Mammal Passive Acoustics , J. Acoust. Soc. Am. 134 (2013)

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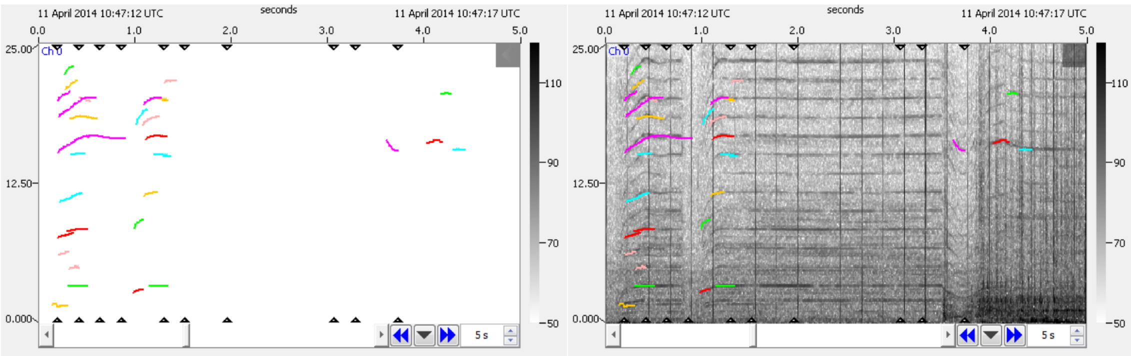
understand • assess • mitigate

A



B

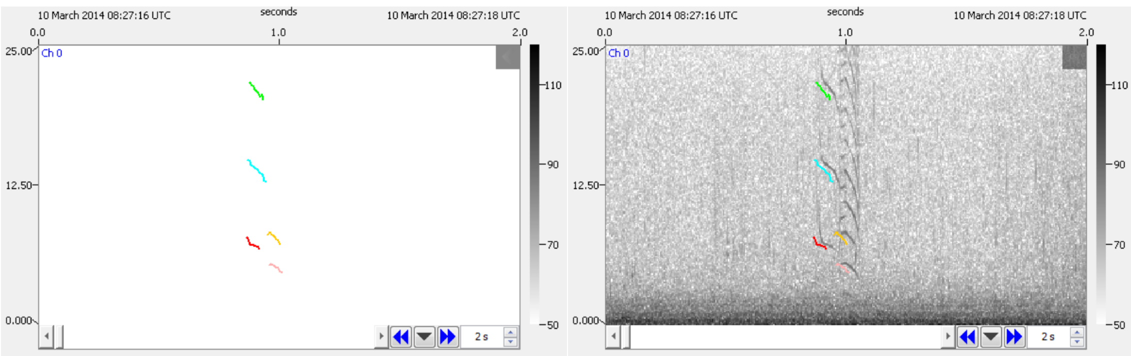


Figure 15. Examples of real and false whistle detections both without and with full spectrogram information. A) A false detection caused by the hydraulics of a nearby engine. B) A dolphin whistle.

9.5.3 AAM sensors

The amount of data collected by active acoustic methods (single beam, split beam, omni-directional, wide band and multibeam echosounders) is dependent on the resolution (e.g. ping rate, number of beams), the complexity of the data (e.g. single / multifrequency or wideband) and the range collected to. Data volume is controlled by varying any of these three criteria. For example, 10 pings of 120 kHz single frequency data (1.024 ms pulse length) to a range of 100 m with an EK80 generates a ~300 kB data file, whereas 10 pings of wideband data (95 – 160 kHz, central frequency of 120 kHz, 2.048 ms pulse length) to a range of 100 m generates a ~5 mB data file. As a result of this high data volume creation, the AAM sensors typically store data locally for retrieval and analysis once the platform is recovered, unless they are part of a cabled observatory[24]. The logical solution is to look for methods to reduce or compress the raw data or to pre-process data on-board the platform (although this has a payload and power cost to the platform) for transmission of summary statistics. We are not aware of any published examples of data compression, although there are examples where it is alluded to during the use of

[24] e.g. http://www.interactiveoceans.washington.edu/story/NSF_Ocean_Observatories_Initiative

an EK60 on a Hugin AUV (Patel, 2004) and for real-time transmission of tuna detection using the Zunibal Tunabel e7 buoy[25].

Methods for the detection and estimation of animal biomass, in particular fish, from active acoustics is well-developed (e.g. Korneliussen and Ona, 2003; Petitgas et al., 2003). However, like the PAM systems, these methods are typically tuned to specific features and species and frequently require human validation. Data processing and analysis is typically undertaken using either commercially available acoustic software[26] [27], in-house built (e.g. MOVIES 3D, cited in Trenkel et al., 2009) or toolboxes developed for Matlab[28]. The next step is to implement the processing of data (with a specific goal) on-board an AUV to send summary statistics back to the base station. We are unaware of any current activities that would enable this, but it is an area of active research interest.

Tritech International Ltd has developed the software Gemini SeaTec marine object tracking and target detection system[29] in close cooperation with SMRU Ltd (now SMRU Consulting) as a data reduction tool for behavioural monitoring and research. It also allows for early warning of the presence of marine mammals around renewable tidal devices (Hastie, 2012; Hastie, 2013). This system uses classification algorithms based on variables such as size, shape and swimming characteristics that provide a probabilistic indication of the identity of individual targets as valid marine mammal targets. Researchers at SMRU are currently developing improved algorithms for the automatic detection and tracking of marine mammal targets using the Tritech Gemini multibeam system (C. Sparling, pers. Comm). This system is also currently being adapted for shark detection to provide an alternative to current shark defence systems.

10 Acknowledgements

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[25] http://zunibal.com/en/product/tunabal-e7-buoy/
[26] Echoview, https://www.echoview.com/
[27] LSSS, http://www.marec.no/english/index.htm
[28] http://hydroacoustics.net/viewtopic.php?f=36&t=131
[29] http://www.tritech.co.uk/news-article/gemini-seatec-marine-object-tracking-and-target-detection

11 Appendix

11.1 List of criteria and metrics for platform, sensor and data relay

The evaluation criteria defined and explained in section Criteria and metrics were grouped into the following categories: general information, technical details, costs, survey capabilities, operational aspects and manning requirements for both the platforms and sensors. These general categories facilitated the organisation of the huge amount of information gathered for each system. Below, a bullet point list of the criteria as defined above as well as a link to the comparison matrix table is given for an easier navigation.

11.1.1 Platform

Criteria/Metric	Description
General Information	**Table 12 includes general information:**
General	Includes the type of platform, platform name and the manufacturer and/or the designers as well as technology readiness level as defined in Table 10.
Technical Details	**Table 13 and Table 14 include the following technical details:**
Mission Duration	Maximum mission duration
Duration Limitations	Factors limiting the mission duration
Speed	Minimum, maximum and typical speed
Vertical Range	Minimum and maximum vertical range (height above sea level for aerial vehicles and depth for underwater vehicles)
Environmental Factors	Environmental factors limiting the platform performance
Size & Weight	Operational and packaged size and weight
Hazard Class	Hazard class as defined in Table 11
Noise Level	Noise level emitted by the operating platform
Limiting Factors	Factors potentially interfering with the performance of the platform (other than environmental)
Interfaces	Types of interfaces
Additional Sensors	Presence or absence of additional sensors on the platform
CTD	Deployment type of CTD sensor: mounted, towed or winch deployment
Costs	**Table 15 contains the cost related criteria:**
Purchase	Purchase price
Rental	Rental price of the platform, requested as per 3 months for AUV / ASV and daily rate for UAS
Operational	Operational costs in terms of piloting manpower and piloting telemetry costs
Maintenance	Maintenance costs and the costs of batteries and/or fuel used to power the platform
Survey Capabilities	**Table 16 entails these survey specific criteria:**
Track Setting	Availability and kind of a track setting option such as programmed waypoints, manual piloting, both options or any other option
Environmental Limitations	Environmental limitations to track keeping such as current or weather (wind, rain)
Self-Correct	Availability of the instrument to self-correct its position when diverting from track

Criteria/Metric	Description
Station Keeping	Ability for station keeping (or at least perform turns to essentially stay in the same place)
Autonomous Decisions	Ability of autonomous decision making with multiple survey modes
Clock Sync	Ability for clock synchronisation
Operational Aspects	**Table 17 covers the following operational criteria:**
Fuel	Fuel type
Failsafe	Availability of a failsafe mode and kind of mode: bearing, location, end point, keep track or stop, including any other important information
Detect & Avoid	Transponder, detect and avoid capacity
Interface	Ground station interface such as Iridium, RF or Blue tooth
Autonomy	Level of autonomy: waypoints or continuous control
Payload Power	Payload power in Joules and Payload capacity dimensions and weight
Deploy & Recover	Deployment and recovery procedure
Manning Requirements	**Table 18 covers the manning requirements:**
Manning	Number of people/pilots required to operate the platform and the training requirements necessary.

11.1.2 Sensor

Criteria/Metric	Description
General Information	**Table 20 includes general information:**
General	for the sensors: the system class, such as AAM, PAM or Video, sensor name and the manufacturer as well as technology readiness level as defined in Table 10.
Technical details	**Table 21 includes details such as:**
Size & Weight	Operational and packaged size and weight of the platforms
Hazard Class	Hazard class as defined in Table 11, which is especially important for shipping and transport issues
Interfering Factors	Factors potentially interfering with the performance of the sensor (other than environmental)
Interface	Type of interface
Costs	**Table 22 covers the cost related criteria:**
Purchase	Purchase price
Rental	Rental price of the platform, requested as per 3 months for AUV / ASV sensors and daily rate for UAS sensors
Operational	Operational costs in terms of operator manpower
Maintenance	Maintenance costs per year
Integration	Integration of sensor into platform
Survey Capabilities	**Table 23 and Table 24 contain the criteria defining the sensor's survey capabilities:**
Environmental Limitations	Environmental factors limiting optimal sensor performance such as current or weather (wind, rain)
Type of Data	Type of collected data to understand if data are stored processed with an on-board processing procedure or as raw data
Species ID	Ability to for species identification from collected data to understand if the sensor has already been used to identify marine animal species and, if so, which kind
Bearing	Ability for estimating bearing to animal from a single vehicle with the data collected

Criteria/Metric	Description
Direct Range	Ability for direct range estimation from a single vehicle with the data collected, neglecting any possible bearing ambiguity or swimming depth of animal
Horizontal Range	Ability for horizontal range estimation from the animal to a track line / vehicle location from a single vehicle with the data collected
Real-Time	Ability for real-time data transmission of animal detections
PAM	Ability of PAM sensors for estimation of received levels of the detected animal vocalisation or ambient noise levels, or simultaneous CTD data collection (PAM sensors only)
Clock Sync	Ability for clock synchronisation to be synchronised with other sensors and its limitations to the accuracy
Operational Aspects	**Table 25 includes the following items:**
Autonomy	Level of autonomy: waypoints or continuous control
Deploy & Recover	Deployment and recovery procedure
Payload Power	Payload power in Watts as well as internal and external payload capacity dimensions and weight
Manning Requirements	**Table 26 covers manning criteria:**
Manning	Such as the number of people required to operate the sensor, the vessel as well as manning requirements for deploying and recovering the sensors, and the training requirements necessary.
Further information	**Table 27 gives information**
Further	Information on the raw data volume and the real-time data reduction capabilities of the sensor. Further information is given if sensors are recommended for future field trials for marine animal monitoring with regards to E&P activities, relevant references (not yet mentioned), links and further comments.

11.1.3 Data relay

Criteria/Metric	Description
General Information	**Table 28 includes general information:**
General	The general information requested in the data relay section including the system class such as Iridium, the system name and the manufacturer as well as technology readiness level as defined in Table 10.
Technical details	**Table 29 includes details such as:**
Environmental Limitations	Environmental limitations to optimal system performance such as current or weather (wind, rain)
Size & Weight	Operational and packaged size and weight of the system
Power	Power
Data	Data bandwidth in bits per second (bps)
Transmission	Transmission range
Costs	Purchase and operational costs
Power Consumption	Power consumption
Restrictions	Usage restrictions such as geographical or political restrictions
Delay	Data delay
Training	Training needs
Requirements	Platform requirements

Table 10 Technology Readiness Levels used in the evaluation matrices*

Technology Readiness Level	Description
TRL 1: Basic research	Principles postulated and observed but no experimental proof available.
TRL 2: Technology formulation	Concept and application have been formulated.
TRL 3: Applied research	First laboratory tests completed; proof of concept.
TRL 4: Small scale prototype	Built in a laboratory environment ("ugly" prototype).
TRL 5: Large scale prototype	Tested in intended environment.
TRL 6: Prototype system	Tested in intended environment close to expected performance
TRL 7: Demonstration system	Operating in operational environment at pre-commercial scale.
TRL 8: First of a kind commercial system	Manufacturing issues solved.
TRL 9: Full commercial application	Technology available for consumers.

* Adapted from the EU Framework Programme for Research and Innovation, Horizon 2020 definitions.

Table 11. Hazard class levels related to battery or fuel type of an evaluated system. Oils or other material used in manufacturing of systems that may have hazards are not considered.

Hazard Class	Description
1	Explosives
2	Gases
3	Flammable Liquids
4	Flammable Solids
5	Oxidizing Substances
6	Toxic & Infectious Substances
7	Radioactive Material
8	Corrosives
9	Miscellaneous Dangerous Goods

11.2 Shortlist of platforms and sensors

This section includes a short list of the current state of the art technologies of available UAS and AUV / ASV platforms and sensors technologies listed in the comparison matrices (appendix 11.1) that are most pertinent to O&G operations for monitoring marine mammal, sea turtles and fish.

The collected information and matrices were used to evaluate the systems with regards to their performance and suitability for operation during seismic surveys and other E&P activities and their potential use for assessing the effects of operations on marine species.

11.2.1 Powered aircrafts

11.2.1.1 UX5 [Trimble Navigation Ltd]

This UAS has been under focus mainly for mapping and surveillance solutions. It has been tested in various environmental conditions, such as wind, extensive heat, and snow. The UX5 has incorporated a reversed thrust, improving altitude measurement that will assist in accurate and predictable landings. This condition is ideal for professionals working in small areas. The aircraft is deployed using a catapult system, and recovered using belly landing. The maximum flight time recorded for this system is 50 minutes. The UX5 is delivered with a high-resolution still camera, which stores imagery on-board for post processing.

11.2.1.2 BRAMOR C4EYE [C-Astral]

The BRAMOR C4EYE UAS line is designed for operations where real-time or near real-time video observation and surveillance capability is the main focus. This system has an endurance of 3 hours and a standard datalink of 30 km. The deployment method is similar to the UX5 though the BRAMOR C4EYE has an automatic parachute landing, which allows for a smoother recovery of the equipment. This reduces the risk of damage of both the aircraft and sensors. It comes delivered with HD video or HD video + LWIR payload from manufacturer.

11.2.1.3 ScanEagle [Insitu]

This platform has been used in marine mammal studies in Australia (Hodgson, Kelly, and Peel, 2013), and demonstrated its ability to conduct flights at sea and of use for marine mammal monitoring. The aircraft is able to send live video feed to the ground station, which can be stored directly by the receiver for posterior analysis or used for timely decision-making. This system does not require nets or runway are required, reducing space constrictions in choosing launch and landing locations. Insitu can deliver a variety of payload turrets for the ScanEagle, where some are military only. For sea mammal studies the visible EO900 or the Visible+MVIR “Dual Imager” is recommended.

11.2.1.4 Penguin B [Uavfactory]

The Penguin B is a commercially available fixed-wing UAS capable of flights of over 20 hours and with similar launching procedures as for the previously mentioned powered UAS. What distinguishes this aircraft from the remaining is its modular composite structure, removable payload, and need for a wider area to land such as a runway. This may result in limited operations if vessel landing is required, though the flight capacity of this platform is able to overcome this obstacle due to its endurance and operational range. It can be delivered with a range of camera options, or without payload for integration of third party sensors.

11.2.1.5 Fulmar [Thales]

The Fulmar UAS is classified as a mini-UAS and is a highly versatile system, with capabilities for a variety of missions. It is launched using a catapult-based launcher system and landed using net landing. Thus, it can be operated and recovered at any time with few limitations concerning weather conditions and terrain characteristics. This system has a maximum flight time of 12 hours, and can be delivered with a range of sensor options, or without payload for integration of third party sensors.

11.2.1.6 Jump-20 [Arcturus UAV]

Jump-20 is a fixed wing UAS capable of vertical take-off and landing, with no need for launch system or runway. However, Jump aircraft can also be converted to catapult launch with a simple wing change. It is capable of conducting flights up to 16 hours under harsh weather conditions. The Jump-20 can be delivered with the TASE 400 gimbals (or the smaller versions) from CloudCap, or without payloads for integration of third party sensors.

11.2.2 Kites

11.2.2.1 Swan X1 Kite [Flying Robots SA]

The Swan X1 Kite (Flying Robots SA) consists of a delivery tricycle equipped with a soft wing following the concept of two-seater microlight. This system is composed by:

- An aerial platform FR SWAN XI;
- An autopilot that allows for take-off, flight, and landing autonomously;
- A ground station that allows communication between ground operators via UHF/VHF data in case manual control of the aircraft is needed.

This UAS is still a demonstration system and it is not yet available commercially. However, further testing will indicate the suitability of this equipment to be accessible for future scientific endeavours.

The Swan X1 is a versatile system that can be equipped with different sensors that are integrated in the hardware and software platform. It is capable of carrying a video kit and omnidirectional antenna (supplied by the manufacturer), which allows for real-time image transmission to the ground station.

11.2.3 Lighter-than-air aircraft systems

11.2.3.1 OceanEye [Maritime Robotics AS]

The OceanEye balloon, produced by Maritime Robotics AS, is a helium-filled balloon able to carry a sensor unit for persistent aerial surveillance. It is a tethered aerostat system that localizes the surveillance technology on-board a mission vessel. In other words, it is a vehicle with an aerostatic or buoyant lift that does not require movement through the surrounding air mass. It is dependent on the presence of a supporting vessel to which it is tethered and transmits its imagery and flight information. This system has not yet been tested for animal monitoring; though most of the applications of the OceanEye are conducted at sea for petroleum-industry related operations such as oil spill monitoring.

11.2.3.2 Desert Star 10 [Allsopp Helikites Ltd]

Helikite aerostats are a combination of a helium balloon and kite (also known as kitoons), which are able to overcome the shortfalls of normal tethered balloons and kites. The Helikites are tethered balloons with a wing that allows it to sustain harsh wind conditions. These platforms have been tested in several conditions and seem to be very versatile in terms of their adaptability to environmental conditions, are available in various sizes, and are ready to take on different challenges.

11.2.4 Propeller driven underwater craft and powered surface craft

11.2.4.1 REMUS Family [Hydroid, Konsberg Maritime}

The REMUS is a propeller-driven, torpedo-shaped AUV developed by Hydroid, a Konsberg Maritime company. The different REMUS models have been extensively tested in commercial and naval operations in a broad range of environments, from shallow and deep waters to arctic and tropical regions. REMUS 100 is a compact, man-portable AUV, the smallest of all models available; REMUS 600 is a mid-size, highly versatile and fully modular AUV; and REMUS 6000 is the largest model, designed for deep water operations.

All models are battery powered and use a DC motor attached to a 2-3 blade propeller. They can travel at an approximate maximum speed of 4 knots, with mission durations between 8 hours (for the REMUS 100) to 24 hours (for the REMUS 600). The vehicles are outfitted with a set of standard sensors, which include an acoustic Doppler current profiler (ADCP), a sidescan sonar (SSS), a CTD device, long baseline transponders (LBL), an inertial navigation system (INS) and data communication devices (acoustic modem, Iridium satellite and WiFi). The standard sensor configuration varies between models; additional sensors like cameras, environmental samplers or advanced sonar devices can be installed in the vehicle. The REMUS family uses a common software application (VIP or Vehicle Interface Program) for mission planning, visualization of survey progress and system status monitoring.

11.2.4.2 HUGIN Family [Konsberg Maritime]

The HUGIN is a propeller-driven AUV developed jointly by Konsberg Maritime and the Norwegian Defence Research Establishment (FFI). Currently, there are three models available commercially: HUGIN 1000, HUGIN 3000 and HUGIN 4500. All of them share the same technology base in terms of navigation, control, payload, communication, propulsion and emergency systems; the main differences are size, battery technology and endurance, and sensor configuration. The HUGIN has a long history of successful operations in commercial applications, with more than 150.000 km covered in a period of ten years. It was designed to satisfy the requirements of civilian and naval applications, for which robustness, data quality and operational efficiency were the main goals.

The three models use a large blade propeller for high electrical-to-hydrodynamic efficiency and low noise emission; the navigation speeds range between 2 and 4 kts (except the HUGIN 1000, which can reach 6 kts). The AUV can operate in three modes: autonomous, semi-autonomous and supervised. The navigation is controlled by an advanced real-time aided inertial navigation system (AINS), which utilises information from an inertial measurement unit (IMU), Doppler velocity log (DVL), depth sensor, ultra-short baseline transponders (USBL) and GPS. Data transmission and control from the mother ship can be set through an acoustic modem, radio or WLAN link, or Iridium satellite communications. The HUGIN 1000 is equipped with a Lithium polymer battery of 54 MJ, which provides an endurance of 24 h, less than half of what the AlHP semi-fuel cell batteries of the larger models can offer. The model number gives the maximum operational depth in meters. The standard sensors installed in the three AUV are essentially the same, but the larger models can be outfitted with a more capable sensor suite. The standard sensor configuration includes a multi-beam echosounder (MBE), a sidescan sonar (SSS) or synthetic aperture sonar (SAS), a sub-bottom profiler (SBP), an acoustic Doppler current profiler (ADCP), a CTD unit, a turbidity sensor and a camera.

11.2.4.3 MUNIN [Kongsberg Maritime]

The MUNIN is a compact propeller-driven AUV designed by Konsberg Maritime for high quality data and position accuracy. The MUNIN combines the most relevant technology of HUGIN and REMUS families, along with some new developments. The torpedo-shaped vehicle consists of five modular sections: 1) the nose, with conductivity-temperature (CT) and forward-looking sonar (FLS); 2) replaceable battery module; 3) navigation and payload module; 4) control and permanent battery; 5) tail with cNODE electronics and transponder. The vehicle uses the same operating software and user interface as HUGIN models.

The MUNIN includes two 18 MJ batteries, one of them removable, for an endurance of 12 to 24 hours. The AUV reaches a maximum speed of 4.5 kts. The information of an inertial measurement unit (IMU), a Doppler velocity log (DVL), GPS and single or multi-transponder acoustic communications (UTP, SSBL (Super Short Baseline), SBL (Short Baseline) and LBL (Long Baseline)) is assimilated by a real-time aided inertial navigation system (AINS) for accurate navigation. The communication is established through an acoustic link (cNODE), WiFi and Iridium satellite. The suite of sensors available for the MUNIN include a multibeam echosounder (MBE), a dual-frequency sidescan sonar (SSS), an interferometric synthetic aperture sonar (ISAS), a sub-bottom profiler (SBP), a conductivity-temperature unit (CT) and a still camera.

11.2.4.4 Bluefin Family [Bluefin Robotics]

The Bluefin is a propeller-driven AUV developed by Bluefin Robotics for civil, commercial and military applications. Five models form the Bluefin family: the compact, two-man portable AUV Bluefin 9 and 9M; the modular and versatile AUV Bluefin 12D and 12S; and the high payload capacity AUV Bluefin 21. Bluefin 9, 9M and 12S are better suited for inshore operations, due to their limited depth range of 200 to 300 m; the Bluefin 12D and Bluefin 21 can be operated in deep waters, up to 4500 m for the last model.

Each model is powered with a different number of Lithium-Polymer batteries, according their weight and required endurance. The 9 and 9M models can be sent on a 10 to 12 hour mission; the larger models offer an improved endurance of 25-30 hours. The Bluefin 9 and 12S are equipped with a simpler navigation system based on an inertial measurement unit (IMU), a Doppler velocity log (DVL), a sound velocity sensor (SVS), a compass and a GPS unit; the rest of the models use an inertial navigation system (INS) combined with IMU, DVL and SVS units. All models reach a maximum speed of 5 kts. The communications system is common to all models and includes an RF link, acoustic tracking and Iridium satellite communications. The sensor payload varies from one model to another, but typical available sensors are dual-frequency, interferometric and dynamically focused sidescan sonars (SSS), synthetic aperture sonar (SAS), multibeam echosounder, conductivity-temperature probe (CT), backscatter sensor and turbidity probe, among others. The software provided with the AUV provides an interface for all phases of a mission: planning, execution, monitoring and post-processing.

11.2.4.5 A Family [ECA Group]

A9-M and A18-D are propeller-driven AUV developed by the ECA group. Although the A family of AUV consists of several models, the two presented in this section cover the technology requirements for most applications. The A9-M is a compact, man-portable vehicle with low magnetic and acoustic signatures designed to cover depth-ranges of up to 200 m; the A18-D is a mid-size deep water AUV with an extended endurance and flexible sensor payload.

With 3 times more power capacity then the A9-M, the A18-D offers an endurance of 24 h, comparable to the maximum 20 h of the A9-M. The maximum speed in both models approximates 5 kts. The navigation system includes and inertial motion sensor (INS), a Doppler velocity log (DVL), GPS and, in the A18-D, an ultra-short baseline unit (USBL). Both models are equipped with RF link, WiFi, acoustic tracking and Iridium satellite communications. The payload capacity of A18-D is higher than in A9-D and supports a larger number of sensors, which are optional for the compact model. The suite of possible sensors, both standard and optional, includes a single or dual-frequency sidescan sonar (SSS), a sound velocity profiler (SVP), a forward-looking sonar (FLS), a multibeam echosounder (MBE), a CTD unit, environmental sensors, a sub-bottom profiler (SBP) and an interferometric sidescan sonar.

11.2.4.6 ARTEMI, ACES and AutoCat [MIT]

ARTEMIS, ACES and AutoCat were the first autonomous surface vehicles. Designed and developed at the MIT Sea Grant College Program between 1993 and 2000, these early designs inspired other ASV programs beyond MIT [Manley, 2008]. The goal was to develop a light autonomous surface vehicle to perform as a navigation and communication link to an AUV, capable of accurate surveying and suitable for educational purposes.

ARTEMIS is a 1.37 m long scale replica of a fishing trawler developed in 1993, originally designed to autonomously collect bathymetry data in the Charles River, in Boston (Manley, 2008; Vaneck et al, 1996). Its small size limited its endurance and seakeeping, but made it easy to be transported, deployed and recovered. The vehicle was equipped with an electric motor and servo actuated rudder and included automatic heading control and DGPS way point navigation. The installation of a radio modem allowed for human supervisory control.

ACES (Autonomous Coastal Exploration System) is a small catamaran 1.4 m long and 0.4 m wide developed between 1996 and 1997. The vehicle was outfitted with hydrographic survey sensors. More versatile and stable than the ARTEMIS, the ACES was equipped with two commercial hulls linked by a steel structure, navigation and control systems, a 3.3 hp gasoline engine for propulsion, batteries to provide power to the computers, and a generator to recharge the batteries. The vehicle was characterised by cruising and maximum speeds of 2 and 2.25 kts, a 30 kg payload and 4 hours endurance (Manley, 1997).

Autocat is the upgraded version of the ACES catamaran and was first time tested in the summer of 2000 (Manley, 2000; 2008). AutoCat is 1.8 m long and can travel at speeds of 8 m/s thanks to an electric trolling motor, which replaced the original gasoline propulsion system of the ACES. Payload sensors include DGPS and oceanographic equipment, but can be optionally outfitted with a sub-bottom profiler, communications link and SONAR. Last trials were carried out in 2000 and despite their historical value, it is unlikely that these models are still available for operation.

11.2.4.7 Measuring Dolphin [MESSIN]

The Measuring Dolphin is catamaran-shaped ASV with fiberglass hulls developed under the MESSIN project in Rostock (Germany) and sponsored by the German BMBF (Caccia et al., 2009; Caccia, 2006). Designed for track guidance and carrying measuring devices in shallow water, this vehicle was equipped with highly accurate DGPS positioning, compass and automatic course control. The Measuring Dolphin was equipped with one propeller on each hull and a hybrid energy supply system – batteries and internal combustion for electric power generation.

11.2.4.8 Delfim [DSOR Lab]

The Delfim is a small catamaran-shaped ASV designed and developed by the DSOR lab of Lisbon IST-ISR, under the EU funded project ASIMOV (Advanced System Integration for Managing the coordinated operation of robotic Ocean Vehicles) (Alves, 2002; Caccia et al., 2009; Caccia, 2006; Pascoal, 2000) This vehicle was designed to perform automatic marine data acquisition and to serve as an acoustic communication relay between an AUV and a support vessel. The Delphim was equipped with an 80 km range RF link for communication with the support vessel, a fixed GPS station and the on-shore control center.

11.2.4.9 Springer [University of Plymouth]

The Springer is a catamaran-shaped ASV developed by the University of Plymouth (UK) for tracing pollutants. The vehicle is 3 m long and 1.5 m high. Springer was developed by Marine and Industrial Dynamic Analysis Research Group (MIDAS) at Plymouth University as a cost effective and environmentally friendly ASV. It was designed primarily for undertaking pollutant tracking, and environmental and hydrographic surveys in rivers, reservoirs, inland waterways and coastal waters, particularly shallow waters. Springer also serves as a test bed platform for research in intelligent navigation systems and sensor and instrumentation technology.

11.2.4.10 ROAZ and ROAZ II [LSA]

ROAZ I and *ROAZ II* are two catamaran-shaped ASV developed by LSA (Laboratório de Sistemas Autónomos) at ISEP (Instituto Superior de Engenharia do Porto). ROAZ I is a small fiberglass ASV designed to perform environment monitoring, bathymetry mapping and support integrated operations with multiple autonomous vehicles in riverine and estuarine areas; ROAZ II is a medium-size HDPE ASV designed for ocean operations, namely hydrographic and bathymetry surveying, and support to security, search and rescue operations. Both vehicles were used as a test beds for the development of navigation, control and collaborative operations algorithms (Sonnenburg, 2013; LSA[30]).

11.2.4.11 C-Enduro [ASV]

Developed by ASV, the C-Enduro is a high endurance carbon fibre, self-righting catamaran. It is designed to operate in all marine environments with an endurance of up to 3 months and has great versatility for a range of applications. Its sensor payload includes passive acoustic monitoring (PAM) and a communication link between underwater vehicle and monitoring station. For power generation, the C-Enduro incorporates diesel, solar, wind and wave powered options. ASView system offers three modes of operation: direct, semi-autonomous and autonomous control (ASV[31]).

11.2.4.12 Viknes [NTNU & Marine Robotics]

The *Viknes* is an ASV boat designed and developed by the Norwegian University of Science and Technology (NTNU) in conjunction with Marine Robotics. The vehicle is equipped with inboard Yanmar 184 HP motor, boasting a top speed of up to 20 kts (Sonnenburg, 2013; Loe, 2008; Viknes[32]].

11.2.4.13 Mariner [NTNU & Marine Robotics]

The *Mariner* is an automated inflatable-hull craft designed and developed by the Norwegian University of Science and Technology (NTNU) in conjunction with Marine Robotics. The *Mariner* is equipped with a diesel engine with waterjet propulsion, with a top speed of more than 30 knots. Vehicle Control Station (VCS) is the interface used for mission control and monitoring on-board. The vehicle includes a VHF/UHF radio link with a range of up to 15 km (Maritime Robotics[33]).

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[30] http://www.lsa.isep.ipp.pt/roaz_home.html
[31] http://asvglobal.com/product/c-enduro/
[32] http://www.viknes.no/
[33] http://www.maritimerobotics.com/systems/mariner/

11.2.4.14 C-Worker 6 [ASV Unmanned Marine Systems]

The *C-Worker* is an unmanned rigid-hull craft developed by ASV Unmanned Marine Systems for security and surveillance as primary applications, and is the most versatile model of the *C-Worker* family. This vehicle is highly survivable, light and robust and is characterised by a modular payload bay for easy integration of standard or custom payloads. The *C-Worker 6* has been deployed with a Seiche PAM array and remote monitoring system, making several real-time detections.

11.2.4.15 C-Stat [ASV Unmanned Marine Systems]

The *C-Stat* is a small single hull automated vehicle developed by ASV Unmanned Marine Systems, with the capability to remain on station for extended periods. Among the possible applications are the positioning of subsea equipment, surface to underwater communications, oceanographic data collection and security support. The *C-Stat* is powered by diesel generator to charge the battery, offering an endurance of up to 4 days.

11.2.4.16 ASV-300 [C & C Technologies & ASV]

The *ASV-3000* high-endurance unmanned semi-submersible vehicle, akin to a small single-hull platform, designed by C & C Technologies and ASV. Previous designs of this type were the *ORCA* (Oceanographic Remotely Controlled Vehicle) from NRL and the *RMS* (Remote Minehunting System) from Lockheed Martin (Wolking, 2011).

11.2.5 Autonomous underwater buoyancy gliders

11.2.5.1 Slocum G2 electric [Teledyne Webb]

The Slocum G2 electric glider is manufactured by Teledyne Webb Research (TWR). It has a 1000 m depth rating with either deep water or littoral buoyancy engines to optimise efficiency, a modular payload capacity with a large variety of sensors already available on the market and a proven track record in delivery and operation. It has a high endurance of 25 to over 365 days, using either alkaline or lithium batteries. Communication is via Iridium/freewave or acoustic modem. A number of passive and active acoustic sensors have already been integrated into the Slocum glider and used to detect marine mammals and fish (Table 8). A hybrid version of this glider exists which utilises a thruster with a collapsible propeller to provide momentum in sub-optimal conditions. All new vehicles are shipped with this capability as a standard feature and existing G2 gliders can be upgraded. Finally, although not yet available as commercial off the shelf (COTS) technology, a thermal glider has been developed, where propulsion is fuelled by changes in the ocean temperature rather than battery power that allows greater longevity to any one mission (3 to 5 years).

11.2.5.2 Seaglider [Kongsberg]

Designed at the University of Washington (Eriksen et al., 2001), and manufactured by Kongsberg Maritime, the Seaglider has a flooded aft section used to carry self-contained instruments. Steering of the vehicles is undertaken by movement of the internal masses (e.g. batteries) both fore and aft and for rotation around the axis. The Seaglider is powered by lithium batteries with deployments of up to 10 months, and communication may either be using Iridium or through acoustic modem. A number of passive and active acoustic sensors have already been integrated into the Seaglider and used to detect marine mammals and fish (Table 8).

11.2.5.3 Spray [Scripps Institution of Oceanography]

Designed at Scripps Institution of Oceanography (Sherman et al., 2001), the Spray glider was commercially manufactured but is not currently. The Spray glider is similar to the Slocum, but with a more hydrodynamic shape and has been optimised for long-range and a depth rating of 1,500 m. Turning is initiated by rolling, like the Seaglider. The Spray uses lithium batteries and maximum mission duration is ~330 days.

11.2.5.4 SeaExplorer [ACSA-ALCEN]

The SeaExplorer, manufactured by ACSA-ALCEN, has been designed to be powered by rechargeable lithium ion batteries, and to be faster (1 knot) than the other buoyancy gliders. It has a modular design including an independent payload section located at the front of the vehicle. The SeaExplorer does not have wings and communication is by Iridium, radio or acoustic modem. The rechargeable batteries enable a maximum mission duration of ~2 months (1,200 km) on one battery charge, refuelling time is 20 hours and battery replacement every 10 years. Similar to the Slocum hybrid, a thruster option is available to enable the glider to operate in powered AUV mode. A number of sensors including an acoustic recorder are already integrated into the SeaExplorer.

11.2.5.5 eFòlaga [Graal-tech]

The eFòlaga is a hybrid glider conceptually designed at the Interuniversity Centre of Integrated Systems of the Marine Environment (ISME), and engineered by Graal-tech (Caffaz, 2009). It is a light-weight, low maintenance vehicle optimised for high manoeuvrability to undertake coastal oceanography. The eFòlaga has been designed to transit between stations using jet propulsion (in powered AUV mode) and then undertakes vertical profiles through changing its ballast (like a buoyancy glider). It uses a NiMh battery, and has an endurance of 6 hours (at max power), can travel at speeds up to 4 knots and has a maximum depth of 80 m. Communication is through either a radio link or acoustic modem. The eFòlaga has a payload bay that can host COTS sensors, typically CTDs have been tested so far. However, trials of the eFòlaga to tow a passive acoustic array have been undertaken for maritime surveillance[34].

11.2.5.6 Coastal glider [Exocetus Development LLC]

The Coastal glider was developed by Alaska Native Technologies, as a militarized glider product (Imlach and Mahr, 2012). These gliders, often termed Exocetus, were designed to operate in coastal waters with high density gradients and fast current speeds. They have a buoyancy engine 7 times larger than the Slocum and Seaglider, enabling them to operate over a large range of water densities. Alkaline or lithium batteries enable 14-60 days mission duration, and the buoyancy glider can accommodate current speeds up to 2 knots. Communication is implemented through Iridium, freewave (line of sight), wifi or acoustic modem. A number of different sensors have already been integrated into the Coastal glider, including omni-directional active acoustic sensors (Imlach and Mahr, 2012). Ocean Sonics smart hydrophones have also been integrated into the Coastal glider and used to provide a proof-of-concept vessel and fishing gear collision avoidance technique using the measured radiated noise from the fishing vessels (Wood, 2016).

11.2.6 Self-powered surface vehicles and drifting sensor packages

11.2.6.1 WaveGliders SV2 and SV3 [Liquid Robotics]

One of the most established vehicles currently available are the Liquid Robotics SV2 and SV3 Wavegliders. These consist of a surface float, about the size of a surf board, and a rack of fins suspended several metres below the surface. As the glider lifts on a wave, the fins tilt upwards slightly and surge forward through the water. When the wave relaxes, the fins tilt back to the horizontal and the weight of the structure supporting the fins again causes it to surge forwards. Payloads can be mounted in the floating hull, attached to the sub-surface unit or towed astern of the sub-unit. The SV3 is a slightly larger version of the SV2 and also has a small electrically driven propeller on the sub-unit which can be used in calm conditions when no wave power is available (solar power for this is generally more available on calm days). Wavegliders have been successfully trialled with a number of PAM sensors for marine mammal detection.

11.2.6.2 AutoNaut [MOST]

Developed by MOST (Autonomous Vessels) Ltd[35], AutoNaut is another self-powered, wave-energy propelled vehicle. Available in different sizes: larger boats show higher speeds, greater carrying capacity and more power for payload. These vehicles are genuinely self-powered with primary propulsion by direct wave propulsion (pitch and roll) using Wave Foil Technology. Solar panels harvest energy to power the sensor package with back up

[34] http://www.sea-technology.com/features/2014/0214/8.php
[35] http://www.autonautusv.com/

provided by battery and methanol fuel cells. The AutoNat displays minimal noise, is simple to deploy/retrieve and has a mission endurance of several months. The Autonaut has performed well in sea trials, e.g. with PAM sensors.

11.2.6.3 DASBR Drifting Buoy [NOAA]

The DASBR buoy has been developed by Emily Griffiths and Jay Barlow of NOAA South West Fisheries as a low cost alternative to autonomous surface vehicles. Components, including an autonomous recorder and two satellite trackers, can be purchased for around $5,000. Once deployed the buoys drift with the current. Considerable costs can therefore be incurred in tracking down and recovering the buoys.

11.2.7 PAM

11.2.7.1 Decimus [SA Instrumentation Ltd]

This is at the high power end of the spectrum in terms of power consumption but also contains a sophisticated array of processing algorithms which can work on up to four channels at a 500 kHz sample rate. It has successfully been integrated into buoys and Wavegliders. Data can be relayed in near real-time using wireless modems or uploaded daily through cell phone networks.

11.2.7.2 DMON [WHOI]

Developed by Mark Johnson using technologies from the DTAG (Johnson, 2003), this ultra-low power device has successfully been programmed and integrated into a Slocum underwater glider to automatically detect baleen whales (Baumgartner et al., 2008; Baumgartner et al., 2013; Baumgartner et al., 2014b; Baumgartner, 2014; Baumgartner and Fratantoni, 2008). The DMON is subject to export control restrictions from the US.

11.2.7.3 SoundTrap HF and Sound Trap 4 Channel [Mark Johnson]

Also developed by Mark Johnson, using similar technology to the DMON, this is another ultra-low power recording device which is commercially available through Ocean Instruments New Zealand. The latest software allows simultaneous recording at low frequencies combined with high frequency click detection, which can extend recording duration to several months. A four-channel version is currently under development.

11.2.7.4 Seiche Real-time System [Seiche]

The Seiche wireless PAM system is a highly configurable system which can be utilised for true real-time data transmission, with a wireless transmission range of up to 10 kms, typically using 2.4 GHz/5 GHz bands. It has two modes to enable real-time monitoring; In the first mode, an analogue to digital sampling device is installed within the unit on the transmitting platform (e.g. an ASV) and the full dataset is transferred to a PC at the receiver station (e.g. a support vessel) for processing in PAMGuard. The operator can then view and utilise the full required frequency range for monitoring in true real-time. This configuration requires higher bandwidth to allow receipt of full dataset at the receiver station. In the second mode, an electronic processing unit is installed on the transmitting platform within the unit where the audio signal is processed through PAMGuard. The operator at the receiving station has full control and viewing access of incoming LF and HF data within PAMGuard user interface via a remote software link. This configuration runs on lower bandwidth and offers a longer range. Additionally, no data loss is suffered should the link be lost as it is possible to record data at the base unit. Both configurations have been successfully trialled on the ASV C-Worker and C-Enduro, resulting in a number of live detections of a range of species.

11.2.7.5 WISPR Board [Oregon State University / Kongsberg]

The WISPR (Wideband Intelligent Sound Processor & Recorder) board was developed and is manufactured by Embedded Ocean Systems. The WISPR system is a mixed signal motherboard that processes and logs acoustic signals. It was specifically created for applications where both space and power are limited such as floats, gliders and moorings.

11.2.7.6 C-POD and C-POD-F [Chelonia Ltd]

The C-POD is a well-established click logging technology widely used to study harbour porpoise and other small odontocete species around the world. A simple processor logs key descriptors of each transient sound and offline analysis software classifies these into click trains. The C-POD was to be trialled on the C-Enduro vehicle, but the vehicle failed. The C-POD-F, which incorporates better processing and collects more accurate data on each logged event, will soon be available.

11.2.7.7 Auto Detection Buoys [Cornell]

Developed for the detection of North Atlantic Right Whales from buoys in the approaches to Boston harbour, software searches for specific sound types and sends a sample of candidate detections to shore for human verification in near real time. To date, this has only been used on moored buoys, but may be suitable for deployment on autonomous surface vehicles.

11.2.7.8 A-tag [Japanese Science and Technology Agency]

The A-tag is developed by Tomomari Akamatsu of the Japanese Science and Technology Agency, and is, similar to the C-POD, a click event logger. Two channels are used which enables it to calculate bearings to detected sounds. It operates fully autonomously and is small enough that it could potentially be incorporated into submarine gliders.

11.2.7.9 SM2M/SM3M [Wildlife Acoustics]

This is a well-established recording only unit which can sample at up to 384 kHz. They are usually used in moored systems but have also been used in drifting buoy systems.

11.2.7.10 AUSOMS-mini [Aqua Sound]

This is another recording only system, sampling at 44.1 kHz. It has relatively short recording lifetime but has been deployed on gliders. Little information is available out this product since the website is only in Japanese.

11.2.7.11 SDA14 and SDA416 [RTSYS]

Developed by RTSYS, these devices can sample at up to 1 MHz. Four channels are available per board and boards can be connected for more channels. The systems can measure noise in 1/3 octave bands and perform click event detection. They have been deployed on small size AUV, Profilers, Surface gliders, and Buoys.

11.2.8 AAM

11.2.8.1 ES853 [Imagenex]

This is a fully commercially available system that has already been successfully integrated into the Slocum G2 glider and Seaglider (ogive). It has a frequency of 120 kHz, its maximum operation depth is 1,000 m and it has a maximum detectable range of 100 m. It is programmable to have either a fixed 0.25 Hz ping rate (in glider mode for working on a Seaglider), or to be polled by the glider (Slocum scenario). Its operational weight is 1 kg in air and it is categorised as having no hazard class. The only interfering factor to the operation of this sensor is the presence of other active acoustic instruments in the vicinity.

11.2.8.2 WBAT and WBAT mini [Kongsberg/Simrad]

These are both fully commercially available systems but have not yet been integrated into any AUV platforms. The WBAT is a fully autonomous WideBand Autonomous Transceiver that stores data internally, operates autonomously, and has an internal battery. It is a stand-alone unit that could be deployed on a mooring, or attached to any ROV or larger AUV. The WBAT operates at the standard Simrad frequencies of 38, 70, 120, 200 and 333 kHz. The WBAT mini is being specifically designed to be integrated into very small vehicles such as a Seaglider or small AUV. The WBAT operates using both nickel rechargeable batteries and lithium batteries which affects its hazard class, whilst the WBT mini does not have a listed hazard class. The only interfering factor to the operation of these sensors is the presence of other acoustic instruments in the vicinity.

11.2.8.3 Sontek ADP [Sontek]

The Sontek ADP (Acoustic Doppler Profiler) is a fully commercially available system that has already been successfully integrated into the SCRIPPS Spray AUV glider (Powell and Ohman, 2015). It has a maximum profiling range of 180 m and operates at 250 kHz.

11.2.8.4 Nortek ADCP [Nortek]

The Nortek ADCP (Acoustic Doppler Current Profiler) is a fully commercially available system designed to measure water column currents using acoustic Doppler technology. A 1 Mhz Aquadopp profiler has already been successfully integrated into the Slocum G2 glider (Baumgartner and Fratantoni, 2008). The Aquadopp profiler weighs less than 3.5 kg, has a maximum profiling range of 100 m and can be programmed to either record data internally or to transmit data by phone or radio modem.

11.2.8.5 DT-X-SUB [BioSonics]

This is a fully commercially available system and a version of it has been integrated into the Waveglider (Greene et al. 2015). The BioSonics DT-X-SUB is a self-contained unit, designed for autonomous deployments, with a programmable duty cycle which enables it to be deployed for long term studies. The unit controls a fully function split-beam echosounder and works with transducers operating at 38, 70, 120, 200 and 420 kHz. Environmental performance limits include wind and wave conditions as this can impact the stabilisation of the towed instruments. The only other interfering factor to the operation of this sensor is the presence of other acoustic instruments in the vicinity.

11.2.8.6 AZFP [ASL]

The Acoustic Zooplankton Fish Profiler (AZFP) is currently commercially available as a moored system. It is available with 38, 67.5, 125, 200, 455, 769 and 2,000 kHz transducers, has a depth rating up to 1,000 m. The AZFP can operate in an internally recording mode or it can make data available in real time. The company offers compact AZFP packages for integration into AUV and towed bodies, but we are not aware of this having been tested yet.

11.2.8.7 Modular VR2C and VMT [Vemco]

The VEMCO VR2C acoustic receivers (frequency = 69 kHz) have been integrated into a Slocum G2 glider (Haulsee et al. 2015). The environmental performance limits of these systems is the maximum depth at which they can operate, which is 500 m for the modular VR2C or 1,000 m for the VMT. They both work by detecting the pings from deployed acoustic tags which can be attached to any animal large enough to be tagged.

11.2.8.8 Gemini 720i [Tritech]

This is a fully commercially available multibeam imaging sonar system which is suitable for deployment on a very small ROV or AUV. The standard unit has environmental performance limits of 300 m depth and operating temperatures between -10 and 35°C, however, a 4,000 m depth rated model is available for deeper water operations. Object detection and tracking is available with the Gemini SeaTech software which allows targets to be classified. This system has been previously used to detect and classify marine mammal targets in real-time to allow for mitigation actions to be taken in a timely manner.

11.3 Comparison matrices

11.3.1 List of platforms

Table 12. Autonomous platforms included in this review, their system class (powered and unpowered ASV, propeller and glider AUV, lighter-than-air aircrafts (l-t-a) UASs, kites and powered fixed wing UASs), system name, manufacturer and/or designer/originating university as well as their technology readiness level as defined in Table 10. Note that cells with the same kind of information for systems of the same manufacturer may be merged.

System class	System name	Manufacturer	Designer/ Originating University	Technology readiness level
ASV - powered	ASV-6300	ASV		Prototype system
	C-Cat 2			First of a kind commercial system
	C-Enduro			Full commercial application
	C-Stat			
	C-Target 3			
	C-Worker 4			First of a kind commercial system
	C-Worker 6			Full commercial application
	C-Worker 7			First of a kind commercial system
	C-Worker Hydro			
	Delfim	Institute for Systems and Robotics (Lisboa)		Applied Research
	Mariner	NTNU and Maritime Robotics		Full commercial application
	Measuring Dolphin	University of Rostock (Germany)	University of Rostock (MESSIN)	First of a kind commercial system
	ROAZ I	Laboratório de Sistemas Autónomos		Prototype system

System class	System name	Manufacturer	Designer/ Originating University	Technology readiness level
	ROAZ II			
	RTSYS USV	RTSYS		Demonstration system
ASV - unpowered	AutoNaut 2	MOST (Autonomous Vessels) Ltd		First of a kind commercial system
	AutoNaut 3			
	AutoNaut 5			
	AutoNaut 7			
	Waveglider SV2	Liquid Robotics		Full commercial application
	Waveglider SV3			
AUV - glider	ALBAC	Tokai University		Small scale prototype
	Coastal glider	Exocetus	Alaska Native Technologies	Full commercial application
	Deepglider		University of Washington	Demonstration system
	eFòlaga III	Graal-Tech	IMEDEA Institute	First of a kind commercial system
	Liberdade Xwing/Zray	ONR		Prototype system
	Petrel	Tianjin University, China		n. p.
	SeaBird		Kyushu Institute of Technology	Prototype system
	SeaExplorer	ACSA		Full commercial application
	Seaglider (ogive)	Kongsberg	University of Washington	Full commercial application
	Slcoum G2 hybrid	Teledyne Webb	Webb/WHOI	Full commercial application
	Slocum G2 glider			
	Slocum G2 thermal			Demonstration system
	Spray		SCRIPPS	Full commercial application

System class	System name	Manufacturer	Designer/ Originating University	Technology readiness level
	Sterne glider		Ecole Nationale Superiore D'Ingenieurs Brest	n. p.
	TONAI: Twilight Ocean-Zonal Natural Resources and Animal Investigator		Osaka Prefecture University, Taiji Whale Museum, Cetus	Basic research
AUV - propeller	A18-D	ECA Group		Full commercial application
	A9-M			
	Bluefin-12D	Bluefin Robotics		Full commercial application
	Bluefin-12S			
	Bluefin-21			
	Bluefin-9			
	Bluefin-9M			
	HUGIN 1000 (1000 m version)	Kongsberg Maritime		Full commercial application
	HUGIN 1000 (3000 m version)			
	HUGIN 3000			
	HUGIN 4500			
	MUNIN			n. p.
	REMUS 100	Hydroid (Kongsberg Maritime) + OSL (WHOI)		Full commercial application
	REMUS 3000			
	REMUS 600			
	REMUS 6000			
	RTSYS AUV	RTSYS		Demonstration system
UAS kite	Swan X1	Flying Robots SA		Demonstration system

System class	System name	Manufacturer	Designer/ Originating University	Technology readiness level
UAS l-t-a	Desert Star 10.	Allsopp Helikites Ltd.		Full commercial application
	Ocean Eye	Maritime Robotics AS		Full commercial application
UAS - powered-fixed	BRAMOR C4EYE	C-Astral		Full commercial application
	Bramor gEO			
	Bramor rTK			
	Fulmar	Thales		Full commercial application
	Jump 20	Arcturus UAV		Full commercial application
	Penguin B	Uavfactory		Full commercial application
	ScanEagle	Insitu		Full commercial application
	UX5	Trimble Navigation Limited		Full commercial application

11.3.2 Platform technical dimensions

Table 13. Technical dimensions of the autonomous platforms listed in Table 12. Given are their mission duration and factors limiting the mission duration, their minimum, maximum and typical speed, their vertical operational range, their environmental performance limits. Their operational size and weight as well as packing/freight weight and size are given and the range they can be controlled within. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: l-t-a: lighter-than-air aircrafts, NA: not applicable, n. p.: not provided, LWH: length, width, height. *unless otherwise specified

		Mission duration		Speed (knots)*			Vertical range (m)			Operational		Packing/freight		
System class	Platforms	Max	Limiting factors	Min	Max	Typical	Min	Max	Env performance limits	Size (m)*	Weight (kg)	Size (m)*	Weight (kg)	Control range (km):
ASV - powered	ASV-6300	2 - 4 days	Fuel capacity	n. p.	6	n. p.	NA	NA	n. p.	? x ? x 6.3	n. p.	n. p.	n. p.	n. p.
	C-Cat 2	3 - 9 hours dependent on battery option	Diesel capacity	Station keeping (0)	5	3	NA	NA	-10 to 45 C (application specific range available)	2.4 x 1.2 x 0.8 LWH (0.2 draft)	100	2.4 x 1.2 x 0.8 LWH	n. p.	~2 utilising RF comms
	C-Enduro	90 days	Energy capacity, sunlight and diesel		7	3	NA	NA		4.2 x 2.4 x 2.8 LWH (0.4 draft)	500	5 x 2.6 x 2	n. p.	Unlimited via Iridium or other satellite comms/ 2-20+ utilising RF comms
	C-Stat	4 days	Fuel capacity	n. p.	3.7	n. p.	NA	NA	n. p.	? x 1.2 x 2.4	450	n. p.	n. p.	n. p.
	C-Target 3	Up to 12 hours dependent on application	Diesel capacity	3	25	6	NA	NA	-10 to 45 C (application specific range available)	3.5 x 1.4 x 1.2 LWH	325	3.5 x 1.4 x 1.2 LWH	n. p.	2-20+ utilising RF comms
	C-Worker 4	48 hours	Diesel capacity	Station keeping (0)	9	6	NA	NA		4.1 x 1.6 x 1.7 LWH (0.4 draft)	700	4.1 x 1.6 x 1.7 LWH	n. p.	Unlimited via Iridium or other satellite comms / 2 - 20+ utilising RF comms
	C-Worker 6	30 days, Station keeping	Diesel capacity		6	4	NA	NA		5.8 x 2.2 x 4.75 LWH (0.9 draft)	4,000	6.3 x 2.2 x 2.2 LWH	n. p.	
	C-Worker 7	Dependent on application	Diesel capacity		6	4	NA	NA		7.2 x 2.3 x 4.2 LWH (0.9 draft)	5,300	7.5 x 2.3 x 2.5 LWH	n. p.	

		Mission duration		Speed (knots)*			Vertical range (m)			Operational		Packing/freight		
System class	Platforms	Max	Limiting factors	Min	Max	Typical	Min	Max	Env performance limits	Size (m)*	Weight (kg)	Size (m)*	Weight (kg)	Control range (km):
	C-Worker Hydro	6 days	Diesel capacity	3	10	8	NA	NA		5.5 x 1.8 x 1.8 LWH (0.9 draft)	1,900	5.5 x 1.8 x 1.8 LWH	n. p.	
	Delfim	n. p.	Battery life	n. p.	5	n. p.	NA	NA	n. p.	? x 2 x 3.5	320	n. p.	n. p.	80
	Mariner	50 hours @ 5 kts	Fuel capacity	n. p.	>30	5	NA	NA	n. p.	2.05 x 2.05 x 5.85	1,700	n. p.	n. p.	15
	Measuring Dolphin	3 hours (battery powered) or 10 hours (hybrid power)	Battery life	0.5	4	n. p.	NA	NA	n. p.	3.3 x 1.8 x 1.5	250	n. p.	n. p.	n. p.
	ROAZ I	n. p.	Battery life	n. p.	n. p.	n. p.	NA	NA	n. p.	1.5 x 1 x 0.52	n. p.	n. p.	n. p.	3
	ROAZ II	n. p.	n. p.	n. p.	n. p.	n. p.	NA	NA	n. p.	4.5 x 2.2 x 0.5	200	n. p.	n. p.	3
	RTSYS USV	6 hours	Battery life	1	6	3	0	0	Sea state	2 x 1 x 0.5	60	2.5 x 1.03 x 0.85	80	1
ASV - unpowered	AutoNaut 2	2 weeks	75Wp PV panel	0.25	2	1	surface sensors; 0.1	Towed sensors ; 20	Fully ocean capable; storm proven	1 x 0.5 x 0.3	60	Euro Pallet	n. p.	5
	AutoNaut 3	3+ months	Fuel for methanol fuel cell; anti-fouling system	0.5	3	2		Towed sensors ; 50		2 x 0.4 x 0 5	120	1.5 x 0.75 x 1.5	n. p.	oceanic; satellite comms
	AutoNaut 5				4.5	3		Towed sensors ; 100		3 x 0.8 x 1	250	2.0 x 1.0 x 2.5	n. p.	
	AutoNaut 7				6	4		Towed sensors ; 200		4 x 1.1 x 1.5	400	2.0 x 2.5 x 2.5	n. p.	
	Waveglider SV2	1 year+	Biofouling, Sun light availablity	0	2	1.25	NA	NA	Survived Sea State 8-9. No power in flat calm	~0.5 x 1 x 2 x 6 depth	~100	Multiple Crates, Air Freight OK	n. p.	unlimited

		Mission duration		Speed (knots)*			Vertical range (m)			Operational		Packing/freight		
System class	Platforms	Max	Limiting factors	Min	Max	Typical	Min	Max	Env performance limits	Size (m)*	Weight (kg)	Size (m)*	Weight (kg)	Control range (km):
	Waveglider SV3			0.3	2.5	1.75	NA	NA	Survived Sea State 8-9. Electrical propellers in flat calm if sufficient sunlight.	~0.5 x 1 x 3 x 5 depth	~150		n. p.	
AUV - glider	ALBAC	1 dive (30 minutes)	Release of dive weight	n. p.	n. p.	0.5 - 1 m/s	n. p.	300	Currents, vertical density gradients	1.4 (length) x 0.24 (diameter) x 1.2 (wing span)	45	n. p.	n. p.	n. p.
	Coastal glider	14 days (alkaline), 60 days (lithium)	Battery life	n. p.	1 m/s	1 m/s	Surface	200	Currents	2.87 (length) x 0.33 (diameter)	109	2.44 x 0.85 x 0.72 shipping carton	n. p.	unlimited
	Deepglider	380 days	Battery life	n. p.	0.45 m/s	0.25 m/s	Surface	6,000	Currents, vertical density gradients	1.8 (length) x 0.3 (diameter) x 1.0 (wing span)	62	n. p.	n. p.	unlimited
	eFòlaga III	6-8 hours	Battery life	n. p.	n. p.	1-2 m/s	Surface	50-100	Currents, vertical density gradients	2.0 (length) x 0.16 (diameter)	31	n. p.	n. p.	n. p.
	Liberdade Xwing/Zray	6 months	Battery life	n. p.	n. p.	0.5 - 1.5 m/s	n. p.	300	Currents, vertical density gradients	6.1 (wing span)	680	n. p.	n. p.	n. p.
	Petrel	n. p.	n. p.	n. p.	n. p.	0.5 m/s (2.0 m/s thrust)	n. p.	500	n. p.	3.2 (length) x 0.25 (diameter) x 1.8 (wing span)	130	n. p.	n. p.	n. p.
	SeaBird	n. p.	Battery life	n. p.	n. p.	n. p.	n. p.	10	Currents, vertical	0.45 (length) x 0.71	5	n. p.	n. p.	n. p.

		Mission duration		Speed (knots)*			Vertical range (m)			Operational		Packing/freight		
System class	Platforms	Max	Limiting factors	Min	Max	Typical	Min	Max	Env performance limits	Size (m)*	Weight (kg)	Size (m)*	Weight (kg)	Control range (km):
									density gradients	(width) x 0.14 (height)				
	SeaExplorer	2 months	Battery life	n. p.	1	1	Surface	700	Currents, vertical density gradients	2.0 (length) x 0.25 m (diameter) x 0.56 (wingspan) x 0.7 (antenna)	59	n. p.	n. p.	unlimited
	Seaglider (ogive)	10 months	Battery life	n. p.	n. p.	0.25 m/s	Surface	1000	Currents, vertical density gradients	1.8-2.0 (length) x 0.3 (diameter) x 1.0 (wing span)	52	n. p.	n. p.	unlimited
	Slcoum G2 hybrid	360/50 days (lithium/alkaline)	Battery life	n. p.	1 m/s	0.25 m/s	Surface	200 / 1,000	Currents, vertical density gradients	1.5 - 2.15 (length) x 0.22 (diameter) x 1.2 (wing span)	54	n. p.	n. p.	unlimited
	Slocum G2 glider	360/50 days (lithium/alkaline)		n. p.	0.38 m/s		Surface	200 / 1,000			54	n. p.	n. p.	unlimited
	Slocum G2 thermal	3 - 5 years		n. p.	0.38 m/s		Surface	1,200			60	n. p.	n. p.	unlimited
	Spray	330 days	Battery life	n. p.	n. p.	0.25 m/s	n. p.	1,200	Currents, vertical density gradients	2.0 (length) x 0.20 (diameter) x 1.2 (wing span)	51	Box dimensions 1.6 x 0.6 x 0.6	92	unlimited
	Sterne glider	n. p.	n. p.	n. p.	n. p.	1.3 m/s	n. p.	n. p.	n. p.	4.5 (length) x 0.6 (diameter	900	n. p.	n. p.	n. p.
	TONAI	n. p.	n. p.	n. p.	n. p.	0.2-0.5 m/s	n. p.	60	n. p.	1.65 (length) x 0.2 (diameter) x	92	n. p.	n. p.	n. p.

		Mission duration		Speed (knots)*			Vertical range (m)			Operational		Packing/freight		
System class	Platforms	Max	Limiting factors	Min	Max	Typical	Min	Max	Env performance limits	Size (m)*	Weight (kg)	Size (m)*	Weight (kg)	Control range (km):
										1.03 (wing span)				
AUV - propeller	A18-D	24 hours	Battery life	n. p.	6	3	5	3,000	n. p.	0.5 x 0.5 x 5.2	550-650	n. p.	n. p.	n. p.
	A9-M	20 hours with two energy sections		n. p.	5	3	3	200	n. p.	0.23 x 0.23 x 1.98	70	n. p.	n. p.	n. p.
	Bluefin-12D	30 hours @ 3 kts with standard payload		n. p.	5	n. p.		1,500	n. p.	0.32 x 0.32 x 4.32	260	n. p.	n. p.	n. p.
	Bluefin-12S	26 hours @ 3 kts with standard payload		n. p.	5	n. p.		200	n. p.	0.32 x 0.32 x 3.77	213	n. p.	n. p.	n. p.
	Bluefin-21	25 hours @ 3 kts with standard payload		n. p.	4.5	n. p.		4,500	n. p.	0.53 x 0.53 x 4.93	750	n. p.	n. p.	n. p.
	Bluefin-9	12 hours @ 3 kts with standard payload (SSS, camera and probes)	Battery life	n. p.	5	n. p.	Surface navigation (~ 0)	200	n. p.	0.24 x 0.24 x 1.75	60.5	n. p.	n. p.	n. p.
	Bluefin-9M	10 hours @ 3 kts with standard payload (SSS, camera and backscatter sensor)		n. p.	5	n. p.		300	n. p.	0.24 x 0.24 x 2.5	70	n. p.	n. p.	n. p.

		Mission duration		Speed (knots)*			Vertical range (m)			Operational		Packing/freight		
System class	Platforms	Max	Limiting factors	Min	Max	Typical	Min	Max	Env performance limits	Size (m)*	Weight (kg)	Size (m)*	Weight (kg)	Control range (km):
	HUGIN 1000 (1000 m version)	24 hours @ 4 kts (with MBE, SSS, SBP and CTD)	Battery life (depends on speed, sensor configuration, environment and mission program)	2	6	n. p.	Surface navigation (~ 0)	1,000	n. p.	0.75 x 0.75 x 4.5	850	n. p.	n. p.	n. p.
	HUGIN 1000 (3000 m version)	24 hours @ 4 kts (with MBE, SSS, SBP and CTD)		2	6	n. p.		3,000	n. p.	0.75 x 0.75 x 4.7	850	n. p.	n. p.	n. p.
	HUGIN 3000	60 hours @ 4 kts (with MBE, SSS, SBP and CTD)	Supply of fuel used in the semi-fuel cell	2	4	n. p.		3,000	n. p.	1 x 1 x 5.5	1,400	n. p.	n. p.	n. p.
	HUGIN 4500	60 hours @ 4 kts (with MBE, SSS, SBP and CTD)		2	4	n. p.		4500	n. p.	1 x 1 x 5.5	1,900	n. p.	n. p.	n. p.
	MUNIN	12-24 hours	Battery life (depends on speed, sensor configuration, environment and mission program)	n. p.	4.5	n. p.		1,500 (available 600 version)	n. p.	0.34 x 0.34 x 4	~ 300	n. p.	n. p.	n. p.
	REMUS 100	8 hours @ 5 kts; 22 hours @ 3 kts	Battery life (depends on speed, sensor configuration, environment and mission program)	n. p.	4.5	3	Surface navigation (~ 0)	100	Can be deployed in rough weather conditions	0.19 x 0.19 x 1.6	37	n. p.	n. p.	n. p.
	REMUS 3000	44 hours @ 4 kts (all sensors off) 33 hours @ 4 kts (sonar		n. p.	4	3		3,000	n. p.	0.36 x 0.36 x 3.7	335	n. p.	n. p.	n. p.

		Mission duration		Speed (knots)*			Vertical range (m)			Operational		Packing/freight		
System class	**Platforms**	**Max**	**Limiting factors**	**Min**	**Max**	**Typical**	**Min**	**Max**	**Env performance limits**	**Size (m)***	**Weight (kg)**	**Size (m)***	**Weight (kg)**	**Control range (km):**
		+ camera on)												
	REMUS 600	45 hours @ 4 kts (all sensors on)		n. p.	5	4		600 (available 1,500 configuration)	n. p.	0.32 x 0.32 x 3.25	240	n. p.	n. p.	n. p.
	REMUS 6000	22 hours @ 4 kts		n. p.	5	n. p.		6,000 (available 4,000 configuration)	n. p.	0.71 x 0.71 x 3.84	862	n. p.	n. p.	n. p.
	RTSYS AUV	20 hours	Battery life	3	15	4 to 10	2	250	Sea state for recovery	150 mm (diameter) x 2 m (long)	30	Pelicase 2.3	50	5
UAS - kite	Swan X1	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	3.5 x 2.3 x 2.3	n. p.	n. p.	n. p.	n. p.
UAS - l-t-a	Desert Star 10.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	Wind <72 km/h	12 x 9	n. p.	n. p.	n. p.	n. p.
	Ocean Eye	days	n. p.	n. p.	n. p.	0	n. p.	n. p.	n. p.	n. p.	n. p.	1.2 x 0.8 x 1.6	425	n. p.
UAS - powered-fixed	BRAMOR C4EYE	3 hours	Wind, air temperature, sensor temperature, humidity, visibility, cloud, fog, rain, snow	32	58.32	58	30,000	5,000	Wind < 15 m/s	0.02 x 2.30 x 0.96	4.5	Two flight boxes. Catapult box: 125 x 45 x 30; Bramor box: 115 x 55 x 45	Catapult box: 28; Bramor box: 35	30
	Bramor gEO	2.5 hours												
	Bramor rTK	2.5 hours												
	Fulmar	6 - 12 hours	n. p.	n. p.	n. p.	54	n. p.	800,000	Wind < 70 km/h	n. p.	20	n. p.	n. p.	70 - 90
	Jump 20	9 - 15 hours	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Penguin B	20+ hours	n. p.	n. p.	69.98	43	n. p.	n. p.	n. p.	? x 3.3 x 2.27	21.5	n. p.	10	n. p.

		Mission duration		Speed (knots)*			Vertical range (m)			Operational		Packing/freight		
System class	Platforms	Max	Limiting factors	Min	Max	Typical	Min	Max	Env performance limits	Size (m)*	Weight (kg)	Size (m)*	Weight (kg)	Control range (km):
	ScanEagle	24+ hours	n. p.	n. p.	80	50-60	n. p.	5,944	n. p.	? x 3.11 x 1.55	22	n. p.	14-18	101.86
	UX5	50 minutes	Rain (only tolerates light rain), wind	n. p.	n. p.	43	60,000	5,000	Wind < 18 m/s	1.05 x 1.00 x 0.65	2.5	n. p.	n. p.	< 5

11.3.3 Platform other technical details

Table 14. Other technical details of the autonomous platforms listed in Table 12. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: l-t-a: lighter-than-air aircrafts, NA: not applicable, n. p.: not provided, SSS: side scan sonar, CTD: conductivity, temperature, depth, IR: infrared, SVTP: sound, velocity, temperature and temperature, SUNA: Submersible Ultraviolet Nitrate Analyzer, LND, COTS: Commercial Off-The-Shelf, PAR: Photosynthetically Active Radiation, RiNKO: phosphorescent DO sensor.

System class	Platforms	Hazard class	Noise level	Interfering factors	Type of interface	Additional sensors	CTD sensor deployment
ASV - powered	ASV-6300	n. p.	n. p.	n. p.	n. p.	MBE, SSS, SBE, SAS, CT, video	n. p.
	C-Cat 2	Class 9: Miscellaneous Dangerous Goods	Noise from electric propellers	Propulsion drives (Jet)	Ethernet, Serial, ROS, proprietary	Sensor packages user definable	Surface, winch in development
	C-Enduro			Generator, propulsion drives			Winch and surface
	C-Stat	n. p.	Very low	n. p.	n. p.	Fully customizable	n. p.
	C-Target 3	None	Low	Engine	Ethernet, Serial, ROS, proprietary	Sensor packages user definable	NA
	C-Worker 4			Propulsion drive (Jet)			Surface, winch in development
	C-Worker 6			Generator, propulsion drives			
	C-Worker 7			Generator, propulsion drives			
	C-Worker Hydro			Propulsion drive			
	Delfim	n. p.	n. p.	n. p.	n. p.	Single-beam imaging sonar (SBS), sidescan sonar (SSS)	n. p.
	Mariner	n. p.	n. p.	n. p.	n. p.	EO/IR camera, radar, oceanographic instruments, SBES, MBES, sonar	n. p.
	Measuring Dolphin	n. p.	n. p.	n. p.	n. p.	Ultrasonic depth finder, ADCP	n. p.
	ROAZ I	n. p.	n. p.	n. p.	n. p.	SSS, Sonar Altimeter, CTD, Camera	Winch
	ROAZ II	n. p.	n. p.	n. p.	n. p.	SSS, Sonar Altimeter, CTD, Camera, IR Camera	
	RTSYS USV	None	n. p.	n. p.	Ethernet / serial	n. p.	Winch deployed
ASV - unpowered	AutoNaut 2	None	Silent	None	Ethernet or Serial	Very wide range of sensors; customer integration possible	Hull/strut mounted; towed
	AutoNaut 3						
	AutoNaut 5						Hull/strut mounted; towed; winched
	AutoNaut 7						
	Waveglider SV2	n. p.	Very Quiet	n. p.	Serial	50+	Mounted

System class	Platforms	Hazard class	Noise level	Interfering factors	Type of interface	Additional sensors	CTD sensor deployment
	Waveglider SV3	n. p.		n. p.	Ethernet, Serial		Mounted, Winch coming soon
AUV - glider	ALBAC	n. p.	n. p.	n. p.	n. p.	Temperature, velocity	Mounted
	Coastal glider	n. p.	n. p.	n. p.	n. p.	CTD/SVTP, acoustic altimeter, omnidirectional smart hydrophones, Wetlabs water quality sensors, RINKO dissolved oxygen, Seabird pumped CTD, SUNA nitrate, LND gamma ray	n. p.
	Deepglider	Class 9: Miscellaneous Dangerous Goods	n. p.	n. p.	n. p.	Seabird CTD, dissolved oxygen, Wet labs fluorometer optical backscatter	Mounted
	eFòlaga III	Class 8: Corrosives	n. p.	n. p.	n. p.	Any custom or COTS device	Mounted
	Liberdade Xwing/Zray	n. p.	n. p.	n. p.	n. p.	SPAWAR's 32 element Glider Towed Array System (GTAS), on-board passive acoustic monitoring system, DMON	n. p.
	Petrel	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SeaBird	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SeaExplorer	Class 9: Miscellaneous Dangerous Goods	n. p.	n. p.	n. p.	CTD, dissolved oxygen, turbidity, chlorophyll, CDOM, Phycobilins, Hydrocarbon Minifluo-UVc, Methane, Metals traces, Nitrate, acoustic recorder, altimeter …	Mounted
	Seaglider (ogive)	Class 9: Miscellaneous Dangerous Goods	n. p.	n. p.	n. p.	Biospherical Instruments PAR, Aanderra dissolved oxygen, Seabird electronics dissolved oxygen, Turner Instruments fluorometer/turbidimeter, Rockland turbulence sensor, passive acoustic monitoring, seabird CTD, Nortek acoustic Doppler current profiler, Wet labs backscatter meter/fluorometer, Control dissolved oxygen, Imagenex ES853	Mounted
	Slocum G2 hybrid	Class 9: Miscellaneous Dangerous Goods (if lithium battery used. Also uses alkaline batteries)	n. p.	n. p.	n. p.	Seabird pumped CTD, Wet labs fluorometer (chlorophyll a), CDOM, turbidity and volume scattering, Rinko optical oxygen, Vemco fish tracker hydrophone, Satlantic micro 4 channel irradiance and radiance sensors, Biospherical Instruments PAR, Satlantic Par, Aanderaa oxygen optode, Imagenex ES853, Teledyne RDI ADCP, SUNA	Mounted
	Slocum G2 glider		n. p.	n. p.	n. p.		

System class	Platforms	Hazard class	Noise level	Interfering factors	Type of interface	Additional sensors	CTD sensor deployment
						nutrient analyser, Rockland scientific MicroRider	
	Slocum G2 thermal		n. p.	n. p.	n. p.	Seabird pumped CTD, Wet labs fluorometer, chlorophyll a, turbidity and volume scattering, Rinko optical oxygen, Vemco fish tracker hydrophone, Satlantic micro 4 channel irradiance, and radiance sensors, Biospherical Instruments PAR, Satlantic Par, Aanderaa oxygen optode, Imagenex ES853, Teledyne RDI ADCP, SUNA nutrient analyser, Rockland scientific MicroRider	
	Spray	Class 9: Miscellaneous Dangerous Goods	n. p.	n. p.	n. p.	CTD, Seabird CTD, Sea point Optical Backscatter sensor, Sea point chlorophyll fluorometer, Tritech PA200 acoustic altimeter, Sontek Argonaut Acoustic Doppler Current Profiler, zooplankton camera	Mounted
	Sterne glider	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	TONAI	n. p.	n. p.	n. p.	n. p.	RINKO-Profiler include depth, water temperature, conductivity, salinity, dissolved oxygen, chlorophyll-a, turbidity. A-Tag, camera	n. p.
AUV - propeller	A18-D	n. p.	n. p.	n. p.	n. p.	Standard payload: SSS, MBE, video, FLS (Forward Looking Sonar), CTD and environmental sensors.	n. p.
	A9-M	n. p.	Low magnetic and acoustic signature (STANAG 1364 compliant)	n. p.	n. p.	Standard payload: SSS, video, SVP (CTD and environmental sensors on request)	n. p.
	Bluefin-12D	n. p.	n. p.	n. p.	n. p.	Various available payloads. Customizable	n. p.
	Bluefin-12S	n. p.	n. p.	n. p.	n. p.		n. p.
	Bluefin-21	n. p.	n. p.	n. p.	n. p.	Standard payload: SSS, SBP and MBE. Customizable	n. p.
	Bluefin-9	n. p.	n. p.	n. p.	n. p.	Standard payload: dual-freq. SSS, camera, CT probe, turbidity probe. Customizable.	n. p.
	Bluefin-9M	n. p.	n. p.	n. p.	n. p.	Standard payload: dual-freq. SSS, camera and backscatter sensor. Customizable	n. p.

System class	Platforms	Hazard class	Noise level	Interfering factors	Type of interface	Additional sensors	CTD sensor deployment
	HUGIN 1000 (1000 m version)	n. p.	n. p.	n. p.	n. p.	Broad range of sensors, customizable	Body mounted
	HUGIN 1000 (3000 m version)	n. p.	n. p.	n. p.	n. p.		
	HUGIN 3000	n. p.	n. p.	n. p.	n. p.		
	HUGIN 4500	n. p.	n. p.	n. p.	n. p.		
	MUNIN	n. p.	n. p.	n. p.	n. p.		Nose mounted
	REMUS 100	n. p.	silent	n. p.	n. p.	Broad range of sensors, customizable	Nose mounted
	REMUS 3000	n. p.	n. p.	n. p.	n. p.		
	REMUS 600	n. p.	n. p.	n. p.	n. p.	Broad range of sensors, customizable (fully modular)	
	REMUS 6000	n. p.	n. p.	n. p.	n. p.	Broad range of sensors, customizable	
	RTSYS AUV	Class 9: Miscellaneous Dangerous Goods	Less than 100dBµPa	Speed and payload	Ethernet - WiFi	Depth, Temperature	n. p.
UAS kite	Swan X1	Class 3: Flammable Liquids	n. p.	n. p.	n. p.	n. p.	NA
UAS l-t-a	Desert Star 10.	Class 2: Gases	n. p.	n. p.	n. p.	n. p.	NA
	Ocean Eye	None	n. p.	n. p.	n. p.	n. p.	NA
UAS - powered-fixed	BRAMOR C4EYE	n. p.	Noise level for the Bramor platform is 61.6 dB (A), as measured in September 2014. This is well below the EU noise thresholds, which is 82 dB in Austria for example.	Data communications	Radio frequency, if in the same band as the selected data transmission frequency	Navigation lights, strobe, AN/PVS--7 B/D, AN/PVS--14 and AN/AVS--9 compatible IR beacons, heated pitot, multiple air vehicle control from single GCS, air pollution, radiation, hazardous and non-hazardous gas sensor ADS--B transponder	NA
	Bramor gEO	n. p.				Include (but not limited to): 23.5 MP RGB camera, CIR, NDVI, 4 band, 5 band or 7 band Multispectral sensors, Rikola Hyperspectral sensor, air pollution, radiation,hazardous and non-hazardous gas sensor (laser mass spectrometer), transponder, locator beacon.	NA
	Bramor rTK	n. p.				Include (but not limited to): 23.5 MP RGB camera, CIR, NDVI, 4 band or 5 band Multispectral sensors, locator beacon.	NA
	Fulmar	None	n. p.	n. p.	n. p.	n. p.	NA
	Jump 20	None	n. p.	n. p.	n. p.	n. p.	NA
	Penguin B	None	n. p.	n. p.	n. p.	n. p.	NA

System class	Platforms	Hazard class	Noise level	Interfering factors	Type of interface	Additional sensors	CTD sensor deployment
	ScanEagle	None	n. p.	n. p.	n. p.	n. p.	NA
	UX5	None	n. p.	n. p.	n. p.	n. p.	NA

11.3.4 Platform costs

Table 15. Cost details of the autonomous platforms listed in Table 12. Given is the platform price for purchase or rental, the costs for operation, maintenance, battery/fuel costs and costs for piloting telemetry. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Prices are for vehicles only without sensors. Addition of sensor packages can significantly increase the price. Abbreviations: l-t-a: lighter-than-air aircrafts, NA: not applicable, n. p.: not provided.

		Price		Costs			
System class	Platforms	Purchase	Rental	Operation	Maintenance	Battery/ Fuel	Piloting telemetry
ASV - powered	ASV-6300	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	C-Cat 2	n. p.	n. p.	2 people for launch and recovery, 1 person on continuous watch (usually 4 - 6 hour watches)	Dependent on application	Rechargeable batteries	Dependent on application
	C-Enduro	n. p.	n. p.			90 L for full tanks	
	C-Target 3	n. p.	n. p.			40 L	
	C-Stat	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	C-Worker 4	n. p.	n. p.	2 people for launch and recovery, 1 person on continuous watch (usually 4 - 6 hour watches)	Dependent on application	100 L	Dependent on application
	C-Worker 6	n. p.	n. p.			1100 L full tanks	
	C-Worker 7	n. p.	n. p.			1200 L	
	C-Worker Hydro	n. p.	n. p.			780 L tank	
	Delfim	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Mariner	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Measuring Dolphin	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	ROAZ I	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	ROAZ II	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	RTSYS USV	$20,000 - $50,000	$2,000 - $5,000	$1,000 - $2,000	$1,000 - $2,000	$1,000 - $2,000	$1,000 - $2,000
ASV - unpowered	AutoNaut 2	$50,000 - $100,000	$20,000 - $50,000	Depends on operational area/requirement	$2000	$1000	UHF/Wifi
	AutoNaut 3	$100,000 +	$50,000 - $100,000		$10,000	$2000	Satellite comms account
	AutoNaut 5					$3000	
	AutoNaut 7				$15,000	$5000	

		Price		Costs			
System class	Platforms	Purchase	Rental	Operation	Maintenance	Battery/ Fuel	Piloting telemetry
	Waveglider SV2	n. p.	n. p.	n. p.	n. p.	NA	n. p.
	Waveglider SV3	n. p.	n. p.	n. p.	n. p.	NA	n. p.
AUV - glider	ALBAC	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	Coastal glider	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	Deepglider	Not yet a commercial product	Not yet a commercial product	Not yet a commercial product	Not yet a commercial product	Not yet a commercial product	Not yet a commercial product
AUV - glider	eFòlaga III	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	Liberdade Xwing/Zray	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	Petrel	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	SeaBird	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	SeaExplorer	$100,000 - $150,000	n. p.	n. p.	n. p.	$0 (rechargeable batteries)	n. p.
AUV - glider	Seaglider (ogive)	$100,000+	$50,000 - $100,000	n. p.	~$20,000 (including batteries)	~$9,000/set	~$2,000 - $3,000 per month
AUV - glider	Slocum G2 hybrid	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	Slocum G2 glider	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	Slocum G2 thermal	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	Spray	Spray with CTD: $50,000 - $100,000, with ZooCamera $100,000 - $150,000	Do not rent	Piloting is ~$10/day/glider	~$10,000/year/glider	Battery and refurbishment ~ $12,000 per 4 - 5 month mission	Piloting telemetry ~$2/day data transmission costs can be significant but we usually bring home large data sets on recorded media.
AUV - glider	Sterne glider	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - glider	TONAI	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - propeller	A18-D	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - propeller	A9-M	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - propeller	Bluefin-12D	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - propeller	Bluefin-12S	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.

		Price		Costs			
System class	Platforms	Purchase	Rental	Operation	Maintenance	Battery/ Fuel	Piloting telemetry
	Bluefin-21	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Bluefin-9	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Bluefin-9M	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	HUGIN 1000 (1000 m version)	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	HUGIN 1000 (3000 m version)	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	HUGIN 3000	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	HUGIN 4500	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	MUNIN	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	REMUS 100	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	REMUS 3000	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	REMUS 600	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	REMUS 6000	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	RTSYS AUV	$100,000 +	n. p.	$2,000 - $5,000	$2,000 - $5,000	$1,000 - $2,000	$1,000 - $2,000
UAS kite	Swan X1	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
UAS l-t-a	Desert Star 10.	$50,000 - $100,000	n. p.	n. p.	n. p.	n. p.	n. p.
	Ocean Eye	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
UAS - powered-fixed	BRAMOR C4EYE; Bramor gEO; Bramor rTK	$100,000+ starting price (depending on options)	TBD depending on location and duration. System lease is possible via different service providers, not via the manufacturer.	TBD depending on location and duration	Complete spares parts package is ~$22,000 for ~1000 flight hours	Included in mantainance costs. One battery pack (with 2 units) ~$1,500	Included in Operation costs
	Fulmar	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Jump 20	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Penguin B	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	ScanEagle	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.

		Price		Costs			
System class	Platforms	Purchase	Rental	Operation	Maintenance	Battery/ Fuel	Piloting telemetry
	UX5	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.

11.3.5 Platform survey capabilities

Table 16. Survey capabilities of the autonomous platforms listed in Table 12. Given is the capability of the platforms for track setting, including its implementation details and limitations, their ability for station keeping, autonomous decision making and clock synchronisation incl. their limitations. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: l-t-a: lighter-than-air aircrafts, NA: not applicable, n. p.: not provided.

System class	Platforms	Track setting	Implementation details	Track keeping limitations	Self correction	Explanation	Station keeping	Limitations to station keeping	Autonomous decision making	Decision limitations	Clock synchro-nisation	Synch limitations
ASV - powered	ASV-6300	Yes	Set waypoint	n. p.	n. p.	n. p.	n. p.	n. p.	Yes	n. p.	n. p.	n. p.
	C-Cat 2			Tracking limited by max speed and endurance requirements	Yes	System uses control system and GPS position to provide precise track correction	Location	Tracking limited by max speed and endurance requirements		This is available through tested and implemented 3rd party software	Yes	Requires satellite visibility
	C-Enduro											
	C-Target 3											
	C-Stat	No (station keeping buoy)	None	n. p.	No	NA	Yes	Sea state		n. p.	n. p.	n. p.
	C-Worker 4	Yes	Set waypoint	Tracking limited by max speed and endurance requirements	Yes	System uses control system and GPS position to provide precise track correction	Location	Tracking limited by max speed and endurance requirements		This is available through tested and implemented 3rd party software	Yes	Requires satellite visibility
	C-Worker 6											
	C-Worker 7											
	C-Worker Hydro											
	Delfim	Yes	Set waypoint	n. p.	Yes	Uses path following techniques, to make the vehicle follow a specific track at specified speed.	n. p.	n. p.	Yes	n. p.	n. p.	n. p.
	Mariner	Yes	Set waypoint	n. p.	n. p.	n. p.	No	n. p.	Yes	n. p.	n. p.	n. p.

System class	Platforms	Track setting	Implementation details	Track keeping limitations	Self correction	Explanation	Station keeping	Limitations to station keeping	Autono-mous decision making	Decision limitations	Clock synchro-nisation	Synch limitations
	Measuring Dolphin	Yes	Set waypoint	n. p.	n. p.	n. p.	n. p.	n. p.	Yes	n. p.	n. p.	n. p.
	ROAZ I	Yes	Set waypoint	n. p.	n. p.	n. p.	n. p.	n. p.	Yes	n. p.	n. p.	n. p.
	ROAZ II			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	RTSYS USV	Yes	Set waypoint	Wave	No	n. p.	Yes	n. p.	Yes	n. p.	Yes	GPS signal
ASV - unpowered	AutoNaut 2	Yes	Set waypoint	0.5 kt current	Yes	Set waypoint	Waypoints	< 25 m radius from waypoint	Yes	Level of autonomy programmed before mission commences	Yes	GPS time stamp; pre-mission synchronisation
	AutoNaut 3			< 2 kt current								
	AutoNaut 5			< 3 kt current			Yes	< 35 m radius from waypoint				
	AutoNaut 7			< 4 kt current			Waypoints	< 45 m radius from waypoint				
	Waveglider SV2	Yes	Set waypoint	Currents, Cloud, Vessel Traffic	Yes	Set waypoint	Yes	< 50 m CEP	Yes	n. p.	Yes	n. p.
	Waveglider SV3							< 30 m CEP		NA		n. p.
AUV - glider	ALBAC	No	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Coastal glider	Yes	Set waypoint	Current	n. p.	n. p.	Yes	Turn radius	n. p.	n. p.	n. p.	n. p.
	Deepglider	Yes	Set waypoint	Currents	Yes	Other	Yes	Turn radius, current	Yes	n. p.	n. p.	n. p.
	eFòlaga III	n. p.	n. p.	n. p.	No underwater navigation/ track correction	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Liberdade Xwing/Zray	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Petrel	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SeaBird	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SeaExplorer	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.

System class	Platforms	Track setting	Implementation details	Track keeping limitations	Self correction	Explanation	Station keeping	Limitations to station keeping	Autonomous decision making	Decision limitations	Clock synchronisation	Synch limitations
	Seaglider (ogive)	Yes	Set waypoint	Currents	Yes	Other	Yes	Turn radius, current	Yes	n. p.	n. p.	n. p.
	Slocum G2 hybrid	Yes	Set waypoint	Currents	Yes	Other	Yes	Turn radius, current	Yes	n. p.	n. p.	n. p.
	Slocum G2 glider							Turn radius (7 m, Davis et al 2002), current		n. p.	n. p.	n. p.
	Slocum G2 thermal							Turn radius, current		n. p.	n. p.	n. p.
	Spray	Yes	Set waypoint	Currents	Yes	Other	Yes	Turn radius, current	Yes	n. p.	See footnote[36]	n. p.
	Sterne glider	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	TONAI	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
AUV - propeller	A18-D	Yes	Set waypoint	n. p.	n. p.	n. p.	n. p.	n. p.	Yes	n. p.	n. p.	n. p.
	A9-M			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	Bluefin-12D	Yes	Set waypoint	n. p.	n. p.	n. p.	n. p.	n. p.	Yes	n. p.	n. p.	n. p.
	Bluefin-12S			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	Bluefin-21			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	Bluefin-9			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	Bluefin-9M			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	HUGIN 1000 (1000 m version)	Yes	Set waypoint	n. p.	n. p.	n. p.	n. p.	n. p.	Yes	n. p.	n. p.	n. p.
	HUGIN 1000 (3000 m version)			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	HUGIN 3000			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.

[36] Spray communicates with Iridium and GPS. While it is not programmed to do it, it could certainly "calibrate" its clock to milliseconds or better every 3-5 hours when it surfaces and share the calibration with a central site. We don't know much about its clock's stability.

System class	Platforms	Track setting	Implementation details	Track keeping limitations	Self correction	Explanation	Station keeping	Limitations to station keeping	Autonomous decision making	Decision limitations	Clock synchronisation	Synch limitations
	HUGIN 4500			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	MUNIN			n. p.	n. p.	n. p.	n. p.	n. p.		n. p.	n. p.	n. p.
	REMUS 100	Yes	Set waypoint	n. p.	n. p.	n. p.	Yes	Can hold station even in strong currents (no limitations specified)	Yes	Fully autonomous based on predefined mission plan	n. p.	n. p.
	REMUS 3000			n. p.	n. p.	n. p.	Yes		Yes		n. p.	n. p.
	REMUS 600			n. p.	n. p.	n. p.	Yes		Yes		n. p.	n. p.
	REMUS 6000			n. p.	n. p.	n. p.	Yes		Yes		n. p.	n. p.
	RTSYS AUV	Yes	Set waypoint	Drift of subsea navigation	No	n. p.	No	NA	Yes	Remote control and monitoring	Yes	GPS or PTP/NTP
UAS kite	Swan X1	Yes	Manual piloting	Wind	Yes	Manual piloting	n. p.	n. p.	No	n. p.	n. p.	n. p.
UAS l-t-a	Desert Star 10.	no	Other	n. p.	n. p.	Other	Not integrated	n. p.	No	n. p.	n. p.	n. p.
	Ocean Eye	no	Other	Wind	No	Other	n. p.	n. p.	No	n. p.	n. p.	n. p.
UAS - powered-fixed	BRAMOR C4EYE	Yes	Programmed waypoints. Or automatic target following from operator selection on video screen.	Wind, air temperature, sensor temperature, humidity, visibility, cloud, fog, rain, snow	Yes	When a failsafe is activated, the system will respond accordingly and then return to its last mission position to continue its planned flight mission after failsafe alert is inactive	n. p.	Time of loitering above station is limited only to battery lifetime	No	NA	Yes	Recorded time of the IR and RGB sensors video can be synchronized with the GPS data
	Bramor gEO						n. p.			NA		
	Bramor rTK						n. p.			NA		
	Fulmar	Yes	Set waypoint	n. p.	Yes	Set waypoint	n. p.	n. p.	No	n. p.	Yes	Control capacity for up to 3 UAVs, control transfer

System class	Platforms	Track setting	Implementati on details	Track keeping limitations	Self correction	Explanation	Station keeping	Limitations to station keeping	Autono-mous decision making	Decision limitations	Clock synchro-nisation	Synch limitations
												between stations
	Jump 20	Yes	Set waypoint	n. p.	Yes	Set waypoint	n. p.	n. p.	No	n. p.	n. p.	n. p.
	Penguin B	Yes	Set waypoint	n. p.	Yes	Set waypoint	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	ScanEagle	Yes	Set waypoint	n. p.	Yes	Set waypoint	Location	n. p.	No	NA	n. p.	n. p.
	UX5	Yes	Set waypoint	Wind, rain	Yes	Set waypoint	No	NA	No	NA	n. p.	n. p.

11.3.6 Platform operational information

Table 17. Operational information on the autonomous platforms listed in Table 12. Given is the fuel type, fail safe mode type, transponder, detect and avoid capacity, ground station interface, its level of autonomy, the payload capacity in terms of power, space and weight as well as the deployment and recovery procedure. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: l-t-a: lighter-than-air aircrafts, NA: not applicable, n. p.: not provided.

			Fail safe mode					Payload capacity			Procedure	
System class	Platforms	Fuel type	Type	More info	Transponder, detect and avoid capacity	Ground station interface	Level of autono-my	Power	Spac e	Weight (kg)	Deployment	Recovery
ASV - powered	ASV-6300	Diesel	n. p.	n. p.	n. p.	RF link	Waypoints	n. p.	n. p.	n. p.	ASV-6300 Sled L&R system. Crane	ASV-6300 Sled L&R system. Crane
	C-Cat 2	Battery	User settabl e	Fail safe mode is user settable, depending on requirements the system can return to waypoint, orbit in place or stop	None	IP radio, UHF	Waypoints	Up to 250 W dependent on endurance requirements	n. p.	50	Slipway, Crane or hand launched	Slipway, Crane or hand recovered
	C-Enduro	Diesel Electric hybrid	n. p.		Using AIS system detect and avoid available. radar and camera detect and avoid in development.	IP radio, Iridium, UHF		100 W continuous, 250 W peak	n. p.	~50	Slipway or crane launch	Slipway or crane recovery
	C-Stat	Diesel	n. p.	n. p.	Optional (customizable payload)	RF, satellite	Full (automated station keeping)	n. p.	n. p.	20	n. p.	n. p.
	C-Target 3	Petrol	User settabl e	Fail safe mode is user settable, depending on requirements the system can return to waypoint, orbit in place or stop	None	IP radio, UHF	Waypoints	Dependant on endurance requirements	n. p.	Dependent on application	Slipway or crane launch	Slipway or crane recovery
	C-Worker 4	Diesel	n. p.		Using AIS system detect and avoid available. radar and camera detect and avoid in development.	IP radio, Iridium, UHF		1000 W	n. p.	80		
	C-Worker 6	Diesel Electric Hybrid	n. p.						n. p.	500	Crane Launch	Crane Recovery
	C-Worker 7		n. p.						n. p.	500		
	C-Worker Hydro	Diesel	n. p.					800 W	n. p.	120		
	Delfim	None	n. p.	n. p.	No	RF link, 80 km range	Waypoints	n. p.	n. p.	n. p.	On-shore deployment or undocking	On-shore recovery or docking

			Fail safe mode					Payload capacity			Procedure	
System class	**Platforms**	**Fuel type**	**Type**	**More info**	**Transponder, detect and avoid capacity**	**Ground station interface**	**Level of autonomy**	**Power**	**Space**	**Weight (kg)**	**Deployment**	**Recovery**
	Mariner	Diesel	n. p.	n. p.	n. p.	RF, Iridium	Waypoints	n. p.	> 1 m^3	n. p.	On-shore deployment or undocking	On-shore recovery or docking
	Measuring Dolphin	None (2 x 400 W batteries for propulsion, 1 x 300 W battery for electronics and sensors)	n. p.	n. p.	Collision avoidance through forward looking echosounder	RDS (UHF/VHF radio link)	Waypoints	n. p.	n. p.	100	On-shore deployment or undocking	On-shore recovery or docking
	ROAZ I	None (variable number of 12 V / 3700 Ah battery packs)	n. p.	n. p.	Collision avoidance through video	RF (WiFi 802.11 a/b/g)	Waypoints, target tracking	n. p.	n. p.	50	On-shore deployment or undocking	On-shore recovery or docking
	ROAZ II	None (4 x AMG 12 V / 56 Ah battery packs)	n. p.	n. p.		RF (WiFi 802.11 a/b/g)		n. p.	n. p.	n. p.		
	RTSYS USV	Location	n. p.	Transponder, no avoidance	RF - Wifi	Continuous control	n. p.	n. p.	50 x 40 x 30	5	Manual	Manual
ASV - unpowered	AutoNaut 2	None	End point	Home waypoint can be set pre-mission if required.	Radar transponder; AIS Class B or C; autonomous collision avoidance based on AIS target information	UHF; Wifi	Waypoints	5 MJ	n. p.	20	Launch from slipway/beach by one person; launch from support vessel with davit/crane	reverse of launch
	AutoNaut 3	Methanol, if required				Acoustic modem, Iridium; UHF; wifi		50 MJ		40		LARS (Launch and Recovery System); operations van
	AutoNaut 5					Acoustic modem, Iridium; Inmarsat; UHF; wifi		175 MJ		130	Launch from slipway/beach by two people; launch from support vessel	

			Fail safe mode					Payload capacity			Procedure	
System class	**Platforms**	**Fuel type**	**Type**	**More info**	**Transponder, detect and avoid capacity**	**Ground station interface**	**Level of autono-my**	**Power**	**Space**	**Weight (kg)**	**Deployment**	**Recovery**
											with davit/crane	
	AutoNaut 7					Iridium; Inmarsat; UHF; wifi		300 MJ		200	Launch from slipway; launch from support vessel with davit/crane	Reverse of launch
	Waveglider SV2	NA	Keep track	Will continue on last programmed course or heading until comms are restored	AIS Receiver	Xbee, Acoustic communications, iridium, WiFi, Gateway Buoy	Waypoints	Up to 130 W	n. p.	45 + ~2 towed (neutrally buoyant)	One-man deployment	n. p.
	Waveglider SV3				AIS Receiver, fully autonomous vehicle avoidance, optional acoustic receiver	Acoustic modem, iridium, Wifi, Cell		Up to 400 W		60 + ~2 towed (neutrally buoyant)	LARS (Launch and Recovery System); operations van	LARS (Launch and Recovery System); operations van
AUV - glider	ALBAC	Ni-Zn battery	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	3 l	n. p.	n. p.	n. p.
	Coastal glider	Alkaline or lithium battery	n. p.	Emergency rise manoeuvre, emergency dive (heading)	altimeter, use hydrophone for vessel avoidance	Iridium, ARGOS, Freewave UHF, Wifi, acoustic modems	Waypoints	14 MJ (alkaline), 67 MJ (lithium) or 29.5 MJ (rechargeable)	8 L	5	Crane/davit	Crane/davit
	Deepglider	Lithium sulfuryl chloride batteries	Location	Argos, bearing, location	Altitude sensor for bottom detection. Ice coping algorithm/behaviour control	Iridium, acoustic modem	Waypoints	17 MJ (2 * 24 V), 4.4 MJ (10 VDC)	n. p.	25	Rib/crane	Lasso
	eFòlaga III	Lead acid or NiMh batteries	n. p.	n. p.	n. p.	GPRS (cellular), wifi, GSM, 24 GHz radio link	Waypoints and continuous	3.1 MJ	n. p.	n. p.	n. p.	n. p.

			Fail safe mode					Payload capacity			Procedure	
System class	Platforms	Fuel type	Type	More info	Transponder, detect and avoid capacity	Ground station interface	Level of autono-my	Power	Spac e	Weight (kg)	Deployment	Recovery
	Liberdade Xwing/Zray	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Petrel	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	Crane/davit	Crane/davit
	SeaBird	Ni-MH	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SeaExplorer	Rechargeabl e lithium ion	n. p.	Autonomous drop weight, location pinger, argos	n. p.	Iridium, Radiofrequ ency, GPS	n. p.	n. p.	9 l	8	2 people - rubber boat	2 people - rubber boat
	Seaglider (ogive)	Lithium sulfuryl chloride batteries (optional rechargeable)	Locatio n	Argos, bearing, location	Altitude sensor for bottom detection. Ice coping algorithm/behaviou r control	Iridium, acoustic modem	Waypoints	18 MJ	n. p.	4 (Davis et al 2002), 25 (Wood 2009)	Rib/crane	Lasso
	Slocum G2 hybrid	Alkaline batteries, lithium batteries	Locatio n	Drop weight, last gasp mode, ARGOS	Altitude sensor for bottom detection. Ice coping algorithm/behaviou r control	Iridium, Freewave 900 MHz (line of sight), Benthos ATM-900 Modem	Waypoints	8 MJ (Alkaline)	n. p.	5 per payload bay (2 payloads possible)	Rib/crane	Nose cone recovery
	Slocum G2 glider					Iridium, Freewave 900 MHz (line of sight), Benthos ATM-900 Modem, ARGOS		8 MJ (Alkaline), 28 MJ (needs checking see UNM2014_w hite)	n. p.			
	Slocum G2 thermal					Iridium, Freewave 900 MHz (line of sight), Benthos		6 MJ	n. p.	2		

			Fail safe mode					Payload capacity			Procedure	
System class	**Platforms**	**Fuel type**	**Type**	**More info**	**Transponder, detect and avoid capacity**	**Ground station interface**	**Level of autono-my**	**Power**	**Spac e**	**Weight (kg)**	**Deployment**	**Recovery**
						ATM-900 Modem						
	Spray	Lithium sulfuryl chloride batteries	Locatio n	Drop weight, surfacing, RF beacon, acoustic pinger	Altitude sensor for bottom detection (Sherman et al 2001)	Orbcomm, Iridium satellite	Waypoints	13 MJ	n. p.	3.5 to 51.8	Rib/crane	n. p.
	Sterne glider	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	TONAI	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	2	n. p.	n. p.
AUV - propeller	A18-D	None	n. p.	n. p.	Obstacle Avoidance System	Iridium, RF, WiFi and acoustic. Ethernet (onshore)	Waypoints	51.9 MJ	n. p.	n. p.	LARS or RHIB	LARS or RHIB
	A9-M		n. p.	Emergency pinger	Obstacle Avoidance System (optional)	Iridium (optional), RF, WiFi and acoustic. Ethernet (onshore)		7.6 MJ per energy section	n. p.	n. p.	Manual	Manual. Local Remote Control for surface recovery
	Bluefin-12D	None	n. p.	n. p.	Acoustic tracking transponder	RF, Iridium and acoustic (remote). Ethernet (onshore)	Waypoints	27 MJ (5 x 5.4 MJ LiPo battery packs)	n. p.	n. p.	By A-frame or crane	By A-frame or crane
	Bluefin-12S		n. p.	n. p.				16.2 MJ (3 x 5.4 MJ LiPo battery packs)	n. p.	n. p.		
	Bluefin-21		n. p.	n. p.				48.6 MJ (9 x 5.4 MJ LiPo battery packs)	n. p.	n. p.		
	Bluefin-9		n. p.	n. p.		RF and acoustic (remote).		5.4 MJ (1 x LiPo battery pack)	n. p.	n. p.	Manual	Manual

			Fail safe mode					Payload capacity			Procedure	
System class	**Platforms**	**Fuel type**	**Type**	**More info**	**Transponder, detect and avoid capacity**	**Ground station interface**	**Level of autono-my**	**Power**	**Spac e**	**Weight (kg)**	**Deployment**	**Recovery**
						Ethernet (onshore)						
	Bluefin-9M		n. p.	n. p.		RF, Iridium and acoustic (remote). Ethernet (onshore)		5.4 MJ (1 x LiPo battery pack)	n. p.	n. p.	Manual or by crane	Manual or by crane
	HUGIN 1000 (1000 m version)	None	End point	Homing and docking	Collision avoidance with Forward Looking Sonar (FLS)	Acoustic modem, iridium, WiFi	Waypoints	54 MJ	n. p.	n. p.	LARS (safe up to sea state 5)	LARS (safe up to sea state 5)
	HUGIN 1000 (3000 m version)							54 MJ	n. p.	n. p.		
	HUGIN 3000	Type used in semi-fuel cell (e.g. hydrogen)						162 MJ	n. p.	n. p.		
	HUGIN 4500							216 MJ	n. p.	n. p.		
	MUNIN	None		n. p.				18 MJ	n. p.	n. p.	Mini stinger or MUNIN adapter for LARS	Mini stinger or MUNIN adapter for LARS
	REMUS 100	None	End point	Mission abort, homing and docking	Ability to detect, locate and identify objects.	Acoustic communica tions, iridium, WiFi, Gateway Buoy	Waypoints	3.6 MJ	n. p.	n. p.	One-man deployment	n. p.
	REMUS 3000					Acoustic modem, iridium, WiFi		n. p.	n. p.	n. p.	LARS (Launch and Recovery System); operations van	LARS
	REMUS 600							18.7 MJ	n. p.	n. p.		
	REMUS 6000							39.6 MJ	n. p.	n. p.		
	RTSYS AUV	Li-Ion battery 110	End point	Built in Failure tree	n. p.	WiFi - Iridium	Waypoints	3000 Kj	250 mm long	4	Launching ramp	Handle or cradle

			Fail safe mode					Payload capacity			Procedure	
System class	Platforms	Fuel type	Type	More info	Transponder, detect and avoid capacity	Ground station interface	Level of autono-my	Power	Spac e	Weight (kg)	Deployment	Recovery
		220 V charger							- Diameter 140 mm			
UAS - kite	Swan X1	Gasoline	None	n. p.	n. p.	n. p.	Continuous control	n. p.	0.84 x 1.23 x 0.88	n. p.	Runway	n. p.
UAS - l-t-a	Desert Star 10.	NA	None	n. p.	n. p.	n. p.	Continuous control	n. p.	n. p.	30	Boat tow	Tethered line
UAS - l-t-a	Ocean Eye	NA	None	n. p.	n. p.	n. p.	Continuous control	n. p.	n. p.	n. p.	Boat tow	Tethered line
UAS - powered-fixed	BRAMOR C4EYE	Electric	n. p.	Multiple flight modes and fail safes available, user-configurable. Loss of communications and GPS indicators and aural warning. Low battery indication and aural warning, critical battery indication and aural warning. Terrain data support with terrain notification and minimum terrain obstacle failsafe operation. Return to home features,	S-mode transponder is available as an option	Surrounding RF can cause interference, if the same as the selected transmitter /receiver frequency. Radio comms are usually between 800-920 MHz or 902-928 MHz radio for military applications (can be adapted according	Waypoints	7 J	8 cm high, 83 cm diameter	0.3	Automatic catapult launch (elastic or pneumatic catapult options)	Parachute automatic landing
	Bramor gEO		n. p.						89.8 x 172.8 x 77 cm HLW	0.8		
	Bramor rTK		n. p.						89.8 x 172.8 x 77 cm HLW	0.74		

			Fail safe mode					Payload capacity			Procedure	
System class	Platforms	Fuel type	Type	More info	Transponder, detect and avoid capacity	Ground station interface	Level of autono-my	Power	Spac e	Weight (kg)	Deployment	Recovery
				emergency landing features.		to country TRA)						
	Fulmar	Gasoline and heavy fuel	Locatio n	n. p.	n. p.	RF	Waypoints	n. p.	n. p.	8	Catapult	Net landing
	Jump 20	Gasoline	Locatio n	n. p.	n. p.	RF	Waypoints	n. p.	n. p.	30 (incl fuel)	Vertical takeoff	Vertical landing
	Penguin B	Gasoline	n. p.	n. p.	n. p.	RF	Waypoints	n. p.	n. p.	10	Catapult, runway or car stop launch	n. p.
	ScanEagle	Gasoline	n. p.	n. p.	n. p.	RF	Waypoints	n. p.	n. p.	3.4	Automatic catapult launch	Automatic with SkyHook® cable
	UX5	Electric	n. p.	n. p.	n. p.	RF	Waypoints	n. p.	n. p.	n. p.	Automatic catapult launch	Belly landing

11.3.7 Platform manning requirements

Table 18. Manning requirements for the autonomous platforms listed in Table 12. Given is xx. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: l-t-a: lighter-than-air aircrafts, NA: not applicable, n. p.: not provided.

					Manning requirements		
System class	**Platforms**	**Piloting**	**Min number of people for operation**	**Vessel requirements**	**Deployment**	**Recovery**	**Training needs**
ASV - powered	ASV-6300	Autonmous, supervised navigation or remote control	1	n. p.	n. p.	n. p.	n. p.
	C-Cat 2	1 continuously on shift	1	Dependent on application	1-2 people	1-2 people	4 day course
	C-Target 3		1 - 2		2 people	2 people	
	C-Enduro		2 - 3				
	C-Stat	Autonomous	1	n. p.	n. p.	n. p.	n. p.
	C-Worker 4	1 continuously on shift	2 -3	Dependent on application	2 people	2 people	4 Day course
	C-Worker 6		3		3 people	3 people	Dependent on application
	C-Worker 7						
	C-Worker Hydro						
	Delfim	Autnomous (based on mission plan)	1	None	2 people	2 people	n. p.
	Mariner	Autonomous (based on mission plan)	1	n. p.	n. p.	n. p.	n. p.
	Measuring Dolphin	Autonomous (mission plan). Autopilot or Remote Control (docking)	1	n. p.	2 people	2 people	n. p.
	ROAZ I	Autonmous, supervised navigation or remote control	1	n. p.	2 people	2 people	n. p.
	ROAZ II			n. p.			n. p.
	RTSYS USV	n. p.	2	0	Trail	Trail	No
ASV - unpowered	AutoNaut 2	Depends on operational mission/location; eg 24/7 monitoring in busy coastal waters, regular monitoring with auto warnings in quiet offshore waters	1	Trained technician for maintenance between missions	1	1	Pilot & maintainer training, 3 days ashore with 1 day at sea.
	AutoNaut 3		2		Possible with 1, but usually 2	Same as launch	
	AutoNaut 5				2		
	AutoNaut 7						
	Waveglider SV2	Supervision and mission control through Vehicle Inteface Program (VIP), 24 hour passive (alert based)	1 per 20 Wave Gliders	16 m minimum, 1 tonne lifting capability	2 people + captain	2 people + captain	L&R Training, 3-day class
	Waveglider SV3		1 per 60 Wave Gliders		3 people + captain	3 people + captain	
AUV - glide	ALBAC	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.

					Manning requirements		
System class	Platforms	Piloting	Min number of people for operation	Vessel requirements	Deployment	Recovery	Training needs
	Coastal glider	n. p.	2	Rib/vessel to get to water depth	2	2	n. p.
	Deepglider	1-2 people, occasional tweaking	n. p.	Rib/vessel to get to water > 50 m	1-2 people	1-2 people	Deployment/recovery minimal training, piloting requires training and computer skills
	eFòlaga III	1-2 people, occasional tweaking	n. p.	n. p.	1-2 people	1-2 people	Deployment/recovery minimal training, piloting requires training and computer skills
	Liberdade Xwing/Zray	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Petrel	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SeaBird	n. p.	1	n. p.	n. p.	n. p.	n. p.
	SeaExplorer	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	Seaglider (ogive)	1 - 2 people, occasional tweaking	n. p.	Rib/vessel to get to water > 50 m	1 - 2 people	1 - 2 people	Deployment/recovery minimal training, piloting requires training and computer skills
	Slocum G2 hybrid	1 - 2 people, occasional tweaking	n. p.	Shore/Rib/vessel to get to water	1 - 2 people	1 - 2 people	Deployment/recovery minimal training, piloting requires training and computer skills
	Slocum G2 glider		n. p.	Rib/vessel to get to water > 20 m			
	Slocum G2 thermal		n. p.				
	Spray	1 - 2 people, occasional tweaking	n. p.	Rib/vessel to get to water > 20 m	1 - 2 people	1 - 2 people	Deployment/recovery minimal training, piloting requires training and computer skills
	Sterne glider	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	TONAI	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.

					Manning requirements		
System class	Platforms	Piloting	Min number of people for operation	Vessel requirements	Deployment	Recovery	Training needs
AUV - propeller	A18-D	Autonomous	1	n. p.	Whatever LARS or RHIB may require	Whatever LARS or RHIB may require	n. p.
	A9-M			n. p.	2 people (2 lift points located fore and aft)	2 people (2 lift points located fore and aft)	n. p.
	Bluefin-12D	Autonomous. Monitoring through Operator Tool Suite	1	n. p.	1 lift point in the middle for crane recovery	1 lift point in the middle for crane recovery	n. p.
	Bluefin-12S			n. p.			n. p.
	Bluefin-21			n. p.			n. p.
	Bluefin-9			None	2 people (2 lift points located fore and aft)	2 people (2 lift points located fore and aft)	n. p.
	Bluefin-9M				2 people (2 lift points located fore and aft). 1 extra reinforced lift point for crane recovery	2 people (2 lift points located fore and aft). 1 extra reinforced lift point for crane recovery	n. p.
	HUGIN 1000 (1000 m version)	Supervision and mission control through HUGIN Operator System (HOS)	1	Trained technician for maintenance between missions	1	1	Pilot & maintainer training
	HUGIN 1000 (3000 m version)						
	HUGIN 3000						
	HUGIN 4500						
	MUNIN						
	REMUS 100	Supervision and mission control through Vehicle Inteface Program (VIP)	1	Trained technician for maintenance between missions	1	1	Pilot & maintainer training
	REMUS 3000						
	REMUS 600						
	REMUS 6000						
	RTSYS AUV	Autonomous during misssion	2	No specific requirements	1 person	Rigid-hulled inflatable boat	Yes
UAS - kite	Swan X1	1	1	NA	n. p.	n. p.	UAS pilot certification
UAS l-t-a	Desert Star 10.	n. p.	n. p.	NA	n. p.	n. p.	n. p.
	Ocean Eye	1	1	NA	n. p.	n. p.	UAS pilot certification

					Manning requirements		
System class	Platforms	Piloting	Min number of people for operation	Vessel requirements	Deployment	Recovery	Training needs
UAS - powered-fixed	BRAMOR C4EYE Bramor gEO Bramor rTK	1	1 pilot and 1 payload operator (ideally)	NA	1 person	1 person	5 days
	Fulmar	n. p.	2	NA	n. p.	n. p.	UAS pilot certification
	Jump 20	n. p.	n. p.	NA	n. p.	n. p.	UAS pilot certification
	Penguin B	n. p.	2	NA	n. p.	n. p.	UAS pilot certification
	ScanEagle	n. p.	2	NA	n. p.	n. p.	UAS pilot certification
	UX5	n. p.	2	NA	n. p.	n. p.	UAS pilot certification

11.3.8 List of sensor

Table 19. Sensors that may be integrated into autonomous vehicles and included in this review, their system class (AAM, PAM, Video), system name, manufacturer as well as their technology readiness level as defined in Table 10). Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: AAM: active acoustic monitoring, PAM: passive acoustic monitoring.

System class	System name	Manufacturer	Technology readiness level
AAM	Aquadopp	Nortek	Full commercial application
	ADP	Sontek	Full commercial application
	AZFP	ASL	Basic research Full commercially application as moored system (for AUVs)
	DT-X SUB	BioSonics	Full commercial application
	ES853	Imagenex	Full commercial application
	Gemini 720i	Tritech	Full commercial application
	Gemini 720is		
	modular VR2C	Vemco	Full commercial application
	VMT		
	WBAT	Kongsberg/Simrad	Full commercial application
	WBT mini		Prototype system
PAM	A-Tag	Marine Micro Technology	Full commercial application
	AUSOMS-mini Black	Aquasound Inc.	Full commercial application
	C-POD-F	Chelonia	Small scale prototype
	C-POD		Demonstration system
	Cornell / AutoBuoys	Cornell (PAM) / EOS (buoy)	Ready
	Decimus	SA Instrumentation Ltd	Full commercial application
	DMON	WHOI	Available from WHOI n. p.

System class	System name	Manufacturer	Technology readiness level
	SDA14	RTSYS	Demonstration system
	SDA416		Prototype system
	Seiche real time transmission system	Seiche Measurements Ltd	n. p.
	SM2/SM3	Wildlife Acoustics	Full commercial application
	SoundTrap 4 channel	Ocean Instruments	Prototype system
	SoundTrap HF		Full commercial application
	WISPR	Embedded Ocean System	n. p.
VIDEO	CM100	UAV vision	Full commercial application
	CM202		
	Dual Imager	Insitu	Full commercial application
	EO900		
	OTUS U135 HIGH DEF	DST	Full commercial application
	OTUS-L205 HIGH DEF		
	TASE 310	Cloudcap technology	Full commercial application
	TASE 400HD		

11.3.9 Sensor technical details

Table 20. Technical details of the sensors listed in Table 19. Given are the environmental performance limits of the sensors, their operational as well as packing/freight size and weight, hazard class as defined in Table 11, any factors interfering with the operation of the sensor, and the sensor's type of interface. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: AAM: active acoustic monitoring, PAM: passive acoustic monitoring, NA: not applicable, n. p.: not provided.

			Operational		Packing/freight				
System class	System name	Env performance limits	Size (cm)*	Weight (kg)*	Size (cm)*	Weight (kg)*	Hazard class	Interfering factors	Type of interface
AAM	Aquadopp	n. p.	47-71 (height), 7.5 (diameter)	2,200	n. p.	n. p.	n. p.	n. p.	RS232, RS422
	ADP	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	AZFP	n. p.	100 (length), 17 (diameter) + transducer size	n. p.	n. p.	50	n. p.	n. p.	RS422
	DT-X SUB	A stable platform is necessary for data collection. The towed body is isolated from the mechanical surge of the Wave Glider engine via a specifically-engineered, compliant tow cable. However, extreme wind/wave conditions may result in destabilization of the towed body. The system is powered via solar generated electricity, thus prolonged darkness will result in temporary shutdown until batteries can be recharged.	56 (length), 25 (diameter) + transducers either 19 or 26 (diameter)	In water weight 20 lbs. (10,000 g)	80 x 30 x 30	45	None	Other acoustic instruments	USB and ethernet ports
	ES853	n. p.	94 (height), 83 (diameter)	1000	n. p.	n. p.	None	Other acoustic instruments	R232
	Gemini 720i	Standard is 300 m. available in a 4,000 m depth rated model for deep-water operations. Temperature ranges -10 to 35°C (operating)	n. p.	1.2 (300m), 7.5 (4000m) in water	48 x 28 x 46 (300 m), 53 x 50 x 50 (4000 m)	14 (300 m), 20 (4000 m)	None	None	Ethernet, VDSL, RS232, Isolated TTL

			Operational		Packing/freight				
System class	**System name**	**Env performance limits**	**Size (cm)***	**Weight (kg)***	**Size (cm)***	**Weight (kg)***	**Hazard class**	**Interfering factors**	**Type of interface**
	Gemini 720is	Standard is 1,000 m (aluminium). available in a 4,000 m (titanium) depth rated model for deep-water operations. Temperature ranges -10 to 35°C (operating)	11 x 14 x 28	1.5 (1000 m), 3.0 (4000 m) in water	48 x 28 x 46 (1000 m), 48 x 28 x 46 (4000 m)	14 (1000 m), 17 (4000 m)			
	modular VR2C	500 m depth limit	pcb 21 (length), 2 (width)	99 g air	n. p.	n. p.	n. p.	n. p.	Serial
	VMT	1000 m depth limit	18 by 3.5 diameter	280 g air	n. p.	n. p.	n. p.	n. p.	Optical - has a dedicated reader or can be Bluetooth
	WBAT	n. p.	n. p.	n. p.	n. p.	n. p.	Class 9: Miscellaneous Dangerous Goods	Other acoustic instruments	Self-contained/ USB download interface
	WBT mini	n. p.	10 x 10 x 15 + wrapping	n. p.	n. p.	n. p.	None	n. p.	n. p.
PAM	A-Tag	0-40 Celcius, 200 m	NA	NA	NA	NA	NA	NA	A-tag is a stand-alone system without any interface to the outside.
	AUSOMS-mini Black	0-40 Celcius, 1000 m	NA	NA	NA	NA	NA	NA	AUSOMS-mini is a stand-alone system without any interface to the outside.
	C-POD-F	All marine water temps; 0 -100 m. Or 0-2000 m (Deep C-POD)	NA	NA	NA	NA	NA	NA	None yet
	C-POD		NA	NA	NA	NA	NA	NA	None, except via third party

			Operational		Packing/freight				
System class	**System name**	**Env performance limits**	**Size (cm)***	**Weight (kg)***	**Size (cm)***	**Weight (kg)***	**Hazard class**	**Interfering factors**	**Type of interface**
	Cornell / AutoBuoys	NA	NA	NA	NA	NA	NA	NA	Ethernet, serial
	Decimus	-10-60 deg c	NA	NA	NA	NA	NA	NA	Serial, Ethernet, WiFi
	DMON	n. p.	NA	NA	NA	NA	NA	NA	n. p.
	SDA14	0°C - 80°C	NA	NA	NA	NA	NA	NA	Serial, ethernet, wifi, uhf
	SDA416		NA	NA	NA	NA	NA	NA	
	Seiche real time tranmission system	n. p.	NA	NA	NA	NA	NA	NA	n. p.
	SM2/SM3	Maximum depth is 150 m for the shallow version, 800 m for the deep-water version	NA	NA	NA	NA	NA	NA	None
	SoundTrap 4 channel	Temp: -10 to >50 deg C, depth: < 1,000 m	NA	NA	NA	NA	NA	NA	RS232, RS485
	SoundTrap HF		NA	NA	NA	NA	NA	NA	
	WISPR	NA	NA	NA	NA	NA	NA	NA	Ethernet, serial
VIDEO	CM100	n. p.	190 x 100	800 g	n. p.	n. p.	None	n. p.	n. p.
	CM202	n. p.	295 x 190	3.5	n. p.	n. p.	None	n. p.	n. p.
	Dual Imager	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	EO900	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	OTUS U135 HIGH DEF	n. p.	185 x 135	1.5	n. p.	n. p.	n. p.	n. p.	n. p.
	OTUS-L205 HIGH DEF	n. p.	256 x 205	2.6	n. p.	n. p.	n. p.	n. p.	n. p.

			Operational		Packing/freight				
System class	**System name**	**Env performance limits**	**Size (cm)***	**Weight (kg)***	**Size (cm)***	**Weight (kg)***	**Hazard class**	**Interfering factors**	**Type of interface**
	TASE 310	Operating Temperature Range: -20°C to +60°C	Size: 178 x 178 x 267 mm Turret Diameter: 178 mm	3	n. p.	n. p.	None	n. p.	Control Interface: RS-232, CAN, Ethernet (with adaptor)
	TASE 400HD			3.5	n. p.	n. p.		n. p.	

11.3.10 Sensor costs

Table 21. Costs sensors listed in Table 19. Given are the purchase and rental price, as well as operational, maintenance, battery/fuel as well as integration costs. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: AAM: active acoustic monitoring, PAM: passive acoustic monitoring, NA: not applicable, n. p.: not provided.

		Price		Costs			
System class	**System name**	**Purchase**	**Rental**	**Operation**	**Maintenance**	**Battery/ Fuel**	**Integration**
AAM	Aquadopp	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	ADP	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	AZFP	CAD $35,000 - $80,000	3-month rental cost is in the $10,000 - $20,000 range	Battery costs are in the $1,000 - $2,000 range	n. p.	n.p.	n. p.
	DT-X SUB	$50,000 - $100,000	$5,000 - $10,000	$1,000 - $2,000	$1,000 - $2,000	$1,000 - $2,000	Both possible
	ES853	$5,000 - $10,000	NA	Integration Cost	No moving parts	Requires 24 vdc	Integration Cost
	Gemini 720i	$30,000 - $50,000	$1,000 - $2,000 per week	None; setup and run/log data on PC	None	35 W power requirement	Software Development Kit available
	Gemini 720is					25 W power requirement	
	modular VR2C	$2,000 - $5,000	NA	n. p.	n. p.	Minimal - powered off glider less than 1 milliamp	n. p.
	VMT		NA	n. p.	n. p.	$350 for annual rebat at factory	n. p.
	WBAT	$30,000 - $50,000	n. p.	n. p.	n. p.	Battery is either lithium or NiMh. Cost is 18,000 NOK for lithium	n. p.
	WBT mini		n. p.	n. p.	n. p.	n. p.	n. p.
PAM	A-Tag	$5,000 - $10,000	n. p.	NA	NA	NA	NA
	AUSOMS-mini Black	$2,000 - $5,000	n. p.	NA	NA	NA	NA

		Price		Costs			
System class	**System name**	**Purchase**	**Rental**	**Operation**	**Maintenance**	**Battery/ Fuel**	**Integration**
	C-POD	$2,000 - $5,000	$1,000 - $2,000	NA	NA	NA	NA
	C-POD-F			NA	NA	NA	NA
	Cornell / AutoBuoys	TBD	TBD	NA	NA	NA	NA
	Decimus	n. p.	n. p.	NA	NA	NA	NA
	DMON	n. p.	n. p.	NA	NA	NA	NA
	SDA14	$2,000 - $5,000	n. p.	NA	NA	NA	NA
	SDA416	$5,000 - $10,000	n. p.	NA	NA	NA	NA
	Seiche real time tranmission system	n. p.	n. p.	NA	NA	NA	NA
	SM2/SM3	$5,000 - $10,000	n. p.	NA	NA	NA	NA
	SoundTrap 4 channel	$2,000 - $5,000	n. p.	NA	NA	NA	NA
	SoundTrap HF		n. p.	NA	NA	NA	NA
	WISPR	n. p.	n. p.	NA	NA	NA	NA
VIDEO	CM100	n. p.	n. p.	n. p.	n. p.	n. p.	Integrated
	CM202	n. p.	n. p.	n. p.	n. p.	n. p.	Integrated
	Dual Imager	n. p.	n. p.	n. p.	n. p.	n. p.	Integrated
	EO900	n. p.	n. p.	n. p.	n. p.	n. p.	Integrated
	OTUS U135 HIGH DEF	n. p.	n. p.	n. p.	n. p.	n. p.	Integrated
	OTUS-L205 HIGH DEF	n. p.	n. p.	n. p.	n. p.	n. p.	Integrated
	TASE 310	n. p.	n. p.	n. p.	n. p.	n. p.	Integrated
	TASE 400HD	n. p.	n. p.	n. p.	n. p.	n. p.	Both possible

11.3.11 Sensor survey capabilities I

Table 22. First set of survey capability criteria for sensors listed in Table 19. Given is the data type collected, data processing details, if species identification is possible and if so, which type, and if the bearing, direct and/or horizontal range to the animal is estimable with the sensor data. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: AAM: active acoustic monitoring, PAM: passive acoustic monitoring, NA: not applicable, n. p.: not provided.

						Estimable to animal		
System class	System name	Collected data type	Processes	Species identification	Species type	Bearing	Direct range	Horizontal range
AAM	Aquadopp	Raw	n. p.	Not proven	Fish/zooplankton	Yes	Yes	No
AAM	ADP	Raw	n. p.	Not proven	Fish/zooplankton	Yes	Yes	No
AAM	AZFP	Raw	n. p.	If multifrequency, possible	Fish/zooplankton	Yes	Yes	No
AAM	DT-X SUB	Raw	On-board processing generates data summaries which can be transmitted and viewed as simplified echograms. It is also possible to generate alerts triggered by acoustic events (detection of target(s) having TS exceeding a specific threshold)	If multifrequency, possible	Fish/zooplankton	Yes	Yes	No
AAM	ES853	Raw	n. p.	Not proven	Fish/zooplankton	Yes	Yes	No
AAM	Gemini 720i Gemini 720is	Raw Gemini format image data logged	Sonar data is collected in a proprietary Tritech format, which can be replayed at the same quality it was recorded. Third party software would need a Tritech ECD file converter to access the data in the files. The Gemini SeaTec System utilises the industry standard Gemini hardware, combined with Gemini SeaTec software (an adaption of Tritech's standalone Gemini software). SeaTec software provides intuitive object detection and target tracking capabilities. Targets are classified based on the probability of them being a specific, predetermined type. For example, marine mammals, pipes or debris.	Yes	Marine mammal automatic detection, rudimentary fish detection	Yes	Yes	Yes
AAM	modular VR2C VMT	Tag detections	Acoustic pings are decoded into tag IDs	Yes	Any aquatic species - large enough to hold an acoustic tag	No	No	No
AAM	WBAT	Raw	n. p.	If wideband, probable	Fish/zooplankton	Yes	Yes	No
AAM	WBT mini	Raw	n. p.	If wideband, probable	Fish/zooplankton	Yes	Yes	No
PAM	A-Tag	Summary click information	Akamatsu et al (2005), Marine Technology Society Journal 39(2), 3-9.	Small odontocetes, snapping shrimps	Identification of Delphinidad and Phocoenidae family	Yes	No	No

						Estimable to animal		
System class	System name	Collected data type	Processes	Species identification	Species type	Bearing	Direct range	Horizontal range
	AUSOMS-mini Black	Raw recording of Linear PCM, MP3 and WMA formats	Commonly used compression formats	Cetaceans, fish, shrimps	Depends on off-line analysis	No	No	No
	C-POD	Descriptors of ultrasonic tones and clicks as detection data and as input to train detection process.	Selection of ultrasonic clicks and tones; estimation of key descriptors of these for storage.	All odontocete clicks > 20 kHz	Some species groups	Yes	Yes	No
	C-POD-F	Descriptors of ultrasonic tones and clicks as detection data and as input to train detection process. Waveforms of selected clicks in trains to aid species identification.	Selection of ultrasonic clicks and tones; estimation of key parameters of these for storage. Train detection to identify 'specimen' cetacean clicks for storage of full waveform.	All odontocete clicks > 17 kHz				
	Cornell / AutoBuoys	Compressed raw data (FLAC), detections	n. p.	NRW, BHW, any species for which a trusted algorithm exists	NRW, BHW, any species for which a trusted algorithm exists	Yes, with an array of units	Yes, with an array of units	Yes, with an array of units
	Decimus	Raw recordings & binary data	Various detectors / noise monitors available	Harbour porpoise, Bottlenose dolphins, Sperm whales, Baleen whales, Beluga whales, Right whales	Harbour porpoise, Bottlenose dolphins, Sperm whales, Baleen whales, Beluga whales, Right whales	Yes	No	No
	DMON	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SDA14	Raw (24bits. Wav), .txt log files; pre-computed information, event detection	Third octave bands, click like event detection, advanced specific processing on request	Porpoise, dolphins (requires post visual identification), whales	Porpoise, whales	Yes	Yes	Yes
	SDA416							
	Seiche real time tranmission system	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.

						Estimable to animal		
System class	System name	Collected data type	Processes	Species identification	Species type	Bearing	Direct range	Horizontal range
	SM2/SM3	Raw recordings are stored either in uncompressed .wav file format or with WAC0 lossless compression which saves approximately 50% on card space.	n. p.	Data has been used to record all marine mammal types including whales, dolphins, porpoises, manatees, etc	n. p.	No	No	No
	SoundTrap 4 channel	Raw and/or detections	click detector - energy in band	Toothed whales	n. p.	Yes	Yes	Yes
	SoundTrap HF				n. p.	No	No	No
	WISPR	Compressed raw data (FLAC), detections	n. p.	Any species for which a trusted algorithm exists	Any species for which a trusted algorithm exists	Yes, with an array of units	Yes, with an array of units	Yes, with an array of units
VIDEO	CM100	Raw	n. p.	n. p.	n. p.	Yes	Yes	Yes
	CM202	Raw	n. p.	n. p.	n. p.			
	Dual Imager	Raw	n. p.	n. p.	n. p.	Yes	Yes	Yes
	EO900	Raw	n. p.	n. p.	n. p.			
	OTUS U135 HIGH DEF	Raw	n. p.	n. p.	n. p.	Yes	Yes	Yes
	OTUS-L205 HIGH DEF	Raw	n. p.	n. p.	n. p.			
	TASE 310	Raw	n. p.	n. p.	n. p.	Yes	Yes	Yes
	TASE 400HD	Raw	n. p.	n. p.	n. p.			

11.3.12 Sensor survey capabilities II

Table 23. Second set of survey capability criteria for sensors listed in Table 19. Given is the real-time data transmission capabilities incl. details wat is transmitted, the ability for clock synchronisation and its limitations and for acoustic sensors, if receiving levels of received signals is estimable as well as ambient noise levels, and if CTD data are obtained simultaneously. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: AAM: active acoustic monitoring, PAM: passive acoustic monitoring, NA: not applicable, n. p.: not provided.

		Real time data transmission		Clock synchronisation		Acoustic sensor specific		
						Estimation		
System class	System name	Possible	What is transmitted	Possible	Limitations	Receiving level	Ambient noise level	CTD data
AAM	Aquadopp	Partly	A ping can be transmitted, but multiple pings collected on a single dive	n. p.	n. p.	n. p.	n. p.	no
	ADP	Partly	A ping can be transmitted, but multiple pings collected on a single dive	n. p.	n. p.	n. p.	n. p.	no
	AZFP	Partly	A ping can be transmitted, but multiple pings collected on a single dive	n. p.	n. p.	n. p.	n. p.	no
	DT-X SUB	Partly	A ping can be transmitted, but multiple pings collected on a single dive	Yes	None	n. p.	n. p.	no
	ES853	Partly	A ping can be transmitted, but multiple pings collected on a single dive	Yes	n. p.	n. p.	no	no
	Gemini 720i	Yes	Currently alarms can be sent over COM (serial) or parallel ports. Tritech can adapt the software as required and is currently doing this for a customer that requires warnings to be sent as HTTP POST commands over the internet, which result in a mobile phone TEXT message when a target of a specific type is ifentified with high probability.	The software is developed inhouse and can be adapted as required. Basic levels of synchronisation are achieved or with purchase of extra hardware high performance clock synchronisation is available.	The software expects an input PPS and ZDA time string.	No	No	Additional data could be logged if required with software adaptation
	Gemini 720is							
	modular VR2C	Yes	Detected tag IDs	Yes	If detection data is transmitted in real time to on-board computer, the timestamp pf the detection can be corrected by the current time of the on-board computer	n. p.	No	No
	VMT	No	n. p.	No	n. p.	n. p.		

		Real time data transmission		Clock synchronisation		Acoustic sensor specific		
						Estimation		
System class	System name	Possible	What is transmitted	Possible	Limitations	Receiving level	Ambient noise level	CTD data
	WBAT	Partly	A ping can be transmitted, but multiple pings collected on a single dive	n. p.	n. p.	n. p.	n. p.	n. p.
	WBT mini			n. p.	n. p.	n. p.	n. p.	n. p.
PAM	A-Tag	No	NA	No	NA	yes	No	n. p.
	AUSOMS-mini Black	No	NA	No	NA	Yes	Yes	n. p.
	C-POD	No	NA	No	NA	Yes	Yes	n. p.
	C-POD-F	yes	Same data as stored i.e. compressed	Yes	Wired link between units			n. p.
	Cornell / AutoBuoys	Yes, with iridium/cell antenna	Detections/audio clips	Yes	GPS	Yes, with calibrated sensor	Yes, with calibrated sensor	n. p.
	Decimus	yes	Binary detection data / noise	Yes	in development	Yes	Yes	n. p.
	DMON	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SDA14	Yes	Wav files, precomputed noise data	Yes	GPS/PPS only	Yes	Yes	n. p.
	SDA416		n. p.	Yes	GPS/PPS, NTP,PTP	Yes	Yes	n. p.
	Seiche real time tranmission system	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.	n. p.
	SM2/SM3	No	NA	Yes	Use the SM3 GPS to synch the clock of the SM3M and then detach for deployment	Yes	Data has been used	n. p.
	SoundTrap 4 channel	n. p.	End user to implement	Yes	GPS input	Yes	Yes	n. p.
	SoundTrap HF	n. p.		Yes	GPS input	Yes	Yes	n. p.
	WISPR	Yes, with iridium/cell antenna	Detections/audio clips	Yes	GPS	Yes, with calibrated sensor	Yes, with calibrated sensor	n. p.
VIDEO	CM100	Yes	n. p.	n. p.	n. p.	NA	NA	NA
	CM202		n. p.	n. p.	n. p.	NA	NA	NA
	Dual Imager	Yes	n. p.	n. p.	n. p.	NA	NA	NA
	EO900		n. p.	n. p.	n. p.	NA	NA	NA
	OTUS U135 HIGH DEF	Yes	n. p.	n. p.	n. p.	NA	NA	NA

		Real time data transmission		Clock synchronisation		Acoustic sensor specific		
						Estimation		
System class	System name	Possible	What is transmitted	Possible	Limitations	Receiving level	Ambient noise level	CTD data
	OTUS-L205 HIGH DEF		n. p.	n. p.	n. p.	NA	NA	NA
	TASE 310	Yes	n. p.	n. p.	n. p.	NA	NA	NA
	TASE 400HD		n. p.	n. p.	n. p.	NA	NA	NA

11.3.13 Sensor operational requirements

Table 24. Operational requirements of the sensors listed in Table 19. Given is their level of autonomy, deployment and recovery procedure, their payload power, and internal as well as external payload capacity in terms of space and weight. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: AAM: active acoustic monitoring, PAM: passive acoustic monitoring, NA: not applicable, n. p.: not provided.

			Procedure			Internal payload capacity		External payload capacity	
System class	System name	Level of autonomy	Deployment	Recovery	Payload power	Space (cm)*	Weight (kg)*	Space (cm)*	Weight (kg)*
AAM	Aquadopp	Self-logging, programmed intervals	Mounted on glider	Mounted on glider	0.5 - 1.5 W at 1 Hz	0.47 - 0.71 length 0.08 m diameter	2.2 - 3.4 in air	n. p.	2.2 - 3.4 in air
	ADP	n. p.	Mounted on glider	Mounted on glider	200 - 1000 mW	n. p.	n. p.	n. p.	n. p.
	AZFP	n. p.	Mounted on glider/AUV	Mounted on gliderAUV	n. p.	n. p.	n. p.	0.17 m diameter, 1 m length	n. p.
	DT-X SUB	NA	Mounted on glider	Mounted on glider	11 - 24 volts	NA	NA	NA	NA
	ES853	Self-logging, fixed ping rate, polled by AUV/glider	Mounted on glider	Mounted on glider	< 250 mW	n. p.	1	n. p.	1
	Gemini 720i	The sonar is provided as a plug and play device. Target identification and classification with variable levels of probability is easily enabled through user selection.	Deployment on a subsea frame or on a pole	Retrieval using a lifting wire; no excessive strain on cable	35 W power requirement	n. p.	n. p.	n. p.	n. p.
	Gemini 720is				25 W power requirement	n. p.	n. p.	n. p.	n. p.

			Procedure			Internal payload capacity		External payload capacity	
System class	**System name**	**Level of autonomy**	**Deployment**	**Recovery**	**Payload power**	**Space (cm)***	**Weight (kg)***	**Space (cm)***	**Weight (kg)***
	modular VR2C	n. p.	Embedded in glider	Real time transmission of data thru glider comms	24 to 180 milliwatts	Pcb 21 (length), 2 (width)	99 g air	n. p.	n. p.
	VMT	n. p.	Mounted on glider	Mounted on glider	on-board C cell battery - factory replaceable	n. p.	n. p.	n. p.	n. p.
	WBAT	Self-logging, fixed ping rate	Mounted on AUV	Mounted on AUV	n. p.	n. p.	n. p.	n. p.	n. p.
	WBT mini	n. p.	Mounted on glider	Mounted on glider	n. p.	n. p.	n. p.	n. p.	n. p.
PAM	A-Tag	Fully autonomous after setting up	NA	NA	60m W	5 x 5 x 54	0.6 in air	5 x 5 x 54	0.6 in air
	AUSOMS-mini Black	Fully autonomous after setting up	NA	NA	75 mW	5.1 x 5.1 x 19.3 (Diameter 5.1, Length 19.3, Carbon Fiber Case)	0.6 in air (0.08 in water)	5.1 x 5.1 x 19.3 (Diameter 5.1, Length 19.3Carbon Fiber Case)	0.6 in air (0.08 in water)
	C-POD	400 years of data automatically process in 5 days, SAMBAH project	NA	NA	44 mW	cylinder 540 long/ 80 OD	n. p.	90 diameter, 606 length	n. p.
	C-POD-F	High	NA	NA	60 mW, less if quiet		n. p.	91 diameter, 640 length	n. p.
	Cornell / AutoBuoys	n. p.	NA	NA	< 2 Watts	NA	NA	Cylindrical Delrin housing (~40 x 20)	5
	Decimus	High	NA	NA	2/3 for device, comms dependant	20 x 20 x 10 approx.	1	20 x 20 x 10 approx.	n. p.
	DMON	n. p.	NA	NA	n. p.	n. p.	n. p.	n. p.	n. p.
	SDA14	Autonomous	NA	NA	600 Mw -1.8 W (multi channels)	14x6.5	200g	Depends if housing required, from recorder to buoy or other carrier	Variable
	SDA416		NA	NA	n. p.	14x6.6	300g		
	Seiche real time transmission system	n. p.	NA	NA	n. p.	n. p.	n. p.	n. p.	n. p.

			Procedure			Internal payload capacity		External payload capacity	
System class	**System name**	**Level of autonomy**	**Deployment**	**Recovery**	**Payload power**	**Space (cm)***	**Weight (kg)***	**Space (cm)***	**Weight (kg)***
	SM2/SM3	Can be easily programmed for autonomous automated recordings.	NA	NA	Power usage varies by sample rate. When idle, the SM3M consumes around 0.5 mW. Depending on accessories, sample rates, compression, and other variables, the SM3M can use as little as 500 mW of power when recording.	Dimesions of electronics: 22" long x 5.25"wide x 4.25" high	2.95 lbs	Length/Height of housing: 90.9 +/- 0.8 includes eyebolt and hydrophone cage. Diameter: 16.8. Eyebolt Anchor: 2.5 inner diameter, 4.3 outer diameter, 5.1 height off housing. Standard Hydrophone: 6.4 length, 1.9 diameter.	Weight (Dry) with electronics: 9.5 without batteries. 13.5 with 32 batteries. Buoyancy (salt water) with electronics: 5.5, without batteries. 1.5 with 32 batteries
	SoundTrap 4 channel	n. p.	NA	NA	70 mW	9.5 x 4 x 3 excluding hydrophones	0.12	21 x 8 dia	1
	SoundTrap HF	n. p.	NA	NA	35 mW	9.5 x 4 x 2.5 excluding hydrohone		21 x 6 dia	
	WISPR	n. p.	NA	NA	Power usage ~800 mW	8 x 6.5 (digital unit only)	< 50 g (digital unit only)	NA	NA
VIDEO	CM100	NA	NA	NA	12 W	n. p.	n. p.	n. p.	n. p.
	CM202	NA	NA	NA	na	n. p.	n. p.	n. p.	n. p.
	Dual Imager	NA	NA	NA	n. p.	n. p.	n. p.	n. p.	n. p.
	EO900	NA	NA	NA	n. p.	n. p.	n. p.	n. p.	n. p.
	OTUS U135 HIGH DEF	NA	NA	NA	15W	n. p.	n. p.	n. p.	n. p.
	OTUS-L205 HIGH DEF	NA	NA	NA	n. p.	n. p.	n. p.	n. p.	n. p.
	TASE 310	NA	NA	NA	Power: 20 W (average) 125 W (max)	n. p.	n. p.	n. p.	n. p.

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			Procedure			Internal payload capacity		External payload capacity	
System class	System name	Level of autonomy	Deployment	Recovery	Payload power	Space (cm)*	Weight (kg)*	Space (cm)*	Weight (kg)*
	TASE 400HD	NA	NA	NA	Power: 40 W (average) 125 W (max)	n. p.	n. p.	n. p.	n. p.

11.3.14 Sensor manning requirements

Table 25. Manning requirements for the sensors listed in Table 19. Given is the minimum number of people for operation, the vessel requirements, the manning requirements for deployment and recovery as well as the training needs for operating the sensor. Note that cells with the same kind of information for systems of the same manufacturer may be merged. Abbreviations: AAM: active acoustic monitoring, PAM: passive acoustic monitoring, NA: not applicable, n. p.: not provided.

		Manning requirements				
System class	System name	Min number of people for operation	Vessel requirements	Deployment	Recovery	Training needs
AAM	Aquadopp	NA	NA	NA	NA	Acoustic processing
	ADP	NA	NA	NA	NA	Acoustic processing
	AZFP	NA	NA	NA	NA	Acoustic processing
	DT-X SUB	1	Large enough to support small davit	2 people	2 people	Acoustic processing
	ES853	NA	NA	NA	NA	Acoustic processing
	Gemini 720i	1	Depends on deployment frame type	Depends on deployment frame type	Depends on deployment frame type	Low level of training (1 day)
	Gemini 720is					
	modular VR2C	NA	NA	NA	NA	Minimal - manual available
	VMT	NA	NA	NA	NA	
	WBAT	NA	NA	NA	NA	Acoustic processing
	WBT mini	NA	NA	NA	NA	
PAM	A-Tag	NA	NA	1 person	1 person	Yes
	AUSOMS-mini Black	NA	NA	1 person	1 person	Not really. It is simple recording system
	C-POD	NA	NA	Can be started ahead of mission, then = nil	Nil	Setup and start
	C-POD-F	NA	NA			Minimal
	Cornell / AutoBuoys	NA	NA	1	1	n. p.

		Manning requirements				
System class	**System name**	**Min number of people for operation**	**Vessel requirements**	**Deployment**	**Recovery**	**Training needs**
	Decimus	NA	NA	Deployment dependent	Deployment dependent	Depends on how in depth they to go
	DMON	NA	NA	n. p.	n. p.	n. p.
	SDA14	NA	NA	Depends on methodology and carrier	Depends on methodology and carrier	1-day training provides autonomy to operator
	SDA416	NA	NA			2-day training provides autonomy to operator
	Seiche real time tranmission system	NA	NA	n. p.	n. p.	n. p.
	SM2/SM3	NA	NA	1-3 persons depending on conditions	1-3 persons depending on conditions	Minimal
	SoundTrap 4 channel	NA	NA	n. p.	n. p.	n. p.
	SoundTrap HF	NA	NA	n. p.	n. p.	n. p.
	WISPR	NA	NA	1	1	n. p.
VIDEO	CM100	n. p.	NA	n. p.	n. p.	n. p.
	CM202	n. p.	NA	n. p.	n. p.	n. p.
	Dual Imager	n. p.	NA	n. p.	n. p.	n. p.
	EO900	n. p.	NA	n. p.	n. p.	n. p.
	OTUS U135 HIGH DEF	n. p.	NA	n. p.	n. p.	n. p.
	OTUS-L205 HIGH DEF	n. p.	NA	n. p.	n. p.	n. p.
	TASE 310	n. p.	NA	n. p.	n. p.	n. p.
	TASE 400HD	n. p.	NA	n. p.	n. p.	n. p.

11.3.15 Sensor further information

Table 26. Further information on the sensors listed in Table 19. Given is the raw data volume, the capabilities to reduce real-time data, links and comments. Abbreviations: AAM: active acoustic monitoring, PAM: passive acoustic monitoring, NA: not applicable, n. p.: not provided.

System class	System name	Raw data volume	Real time data reduction capabilities	Links	Further comments
AAM	Aquadopp	32 bytes +9*128 cells per ping	Both the sontek and the nortek have been put on gliders - typically strapped on as autonomous instruments		

System class	System name	Raw data volume	Real time data reduction capabilities	Links	Further comments
	ADP	n. p.	Both the sontek and the nortek have been put on gliders - typically strapped on as autonomous instruments		
	AZFP	The AZFP can operate in an internally recording mode or it can make data available in real time. Data rates vary substantially from 56124 to 1159 bytes per ping depending on the number of frequencies, bin size and range.	n. p.		
	DT-X SUB	10 MB/Sec	On board storage with low bandwidth summary reporting	https://www.youtube.com/watch?v=ISMQ5fzm26I https://www.youtube.com/watch?v=3A1aU2CNKhk https://planetos.com/blog/sonars-are-going-robotic-an-interview-with-biosonics-eric-munday/ https://www.google.com/url?q=http://www.biosonicsinc.com/pdf/BioSonics%2520LR%2520Wave%2520Glider%2520DTX%2520SUB%2520FLIER.pdf&sa=U&ved=0ahUKEwiqkl6xuvDJAhWikKYKHRVlAnYQFggEMAA&client=internal-uds-cse&usg=AFQjCNG2URYhnR2Mt7KLWZvqakPMYUvDOg	Good for fitting to waveglider
	ES853	256 bytes per ping	n. p.	Guihen et al. 2014	
	Gemini 720i	~3600 MB/hour	A rolling storage facility is available, where all files for the last week (for example) ae saved, but files that are detected to have a high probability target are saved to a permanent location. Also, compression can be applied to the recorded data (ECD) files that achieves ~50% reduction in size.	http://www.tritech.co.uk/product/gemini-720i-300m-multibeam-imaging-sonar	
	Gemini 720is				The Gemini 720is will provide all the current 720i functionality and additional improvements due to technology advances
	modular VR2C	depends on number of tagged fish - typically kbyes per month	n. p.		
	VMT		n. p.		
	WBAT	n. p.	n. p.		The mini WBT for glider, the WBAT for other AUV. They can also be put on surface vehicles.
	WBT mini	n. p.	n. p.		

System class	System name	Raw data volume	Real time data reduction capabilities	Links	Further comments
PAM	A-Tag	1-128 MB depends on the number of detected pulse events	Yes		
	AUSOMS-mini Black	2.54 GB/hour for Linear PCM (dependig on format)	yes		
	C-POD	3 MB/h	yes		
	C-POD-F	3 0MB/h	yes		
	Cornell / AutoBuoys	1 GB/hour/channel	Yes		
	Decimus	n. p.	yes		
	DMON	n. p.	n. p.		
	SDA14	variable	yes		
	SDA416				
	Seiche real time tranmission system	n. p.	n. p.		
	SM2/SM3	Recording MB per hour will vary by sample rate.	n. p.		
	SoundTrap 4 channel	up to 4 GB/h	Yes		
	SoundTrap HF				
	WISPR	880MB/hour/channel/uncompressed	Yes	http://embeddedocean.com/passive-acoustics-2/wispr-v1-0/ http://embeddedocean.com/	Already integrated into gliders and floats
VIDEO	CM100	n. p.	n. p.	http://uavvision.com/product/cm100-html/	
	CM202	n. p.	n. p.	http://uavvision.com/product/cm202-3/	
	Dual Imager	n. p.	n. p.	http://www.insitu.com/images/uploads/product-cards/ScanEagle_DualImager_ProductCard_PR041615_1.pdf	
	EO900	n. p.	n. p.	http://www.insitu.com/images/uploads/product-cards/ScanEagle_EO900_ProductCard_PR041615_1.pdf	

System class	System name	Raw data volume	Real time data reduction capabilities	Links	Further comments
	OTUS U135 HIGH DEF	n. p.	n. p.	http://uavvision.com/product/cm100-html/	
	OTUS-L205 HIGH DEF	n. p.	n. p.	http://www.dst.se/gimbal/otus-l205/otus-l205-high-def	
	TASE 310	n. p.	n. p.	http://www.cloudcaptech.com/products/detail/tase-310	
	TASE 400HD	n. p.	n. p.	http://www.cloudcaptech.com/products/detail/tase-400-hd	

11.3.16 List of Data Relay systems

Table 27. Data Relay systems that can be used for autonomous vehicles.

	System class	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	Ubiqiti	
	WiFi 2.4 GHz	Bullet		
	WiFi 5 GHz			
Satellite	Inmarsat	FleetOne	Cobham Sailor 250	
	Iridium	MCG-101	Aurora	
	Iridium	Pilot	Iridium	

	System class	System name	Manufacturer	Technology readiness level
	Iridium L-Band	L-Band		

11.3.17 Data relay technical details

Table 28. Technical details of the Data Relay systems: Their operational size and weight, power, bandwidth, range, purchase and operational costs as well as usage restrictions, data delay and further comments.

	System class	System name	Environmental performance limits	Operational size (height x width x depth in cm)	Operational weight (kg)	Power (W)	Band width	Range	Purchase costs	Operational costs	Usage restriction (geographical, political, etc)	Data delay	Further comments	
WiFi	900 Mhz Analog	Seiche Bespoke Solution	Suitable up to 20 km Range	37 x 30 x 18	< 5	30	250 kHz	10 - 20 km	n.p.	Free spectrum	Geographic restrictions apply on frequency choice	Negligible	No Antennas have been included as they are very dependent upon deployment requirements	All systems of this nature are performance dependent upon environment, antenna choice, antenna height, line of sight etc. so would require evaluating for suitability on a per project basis.
	1800 Mhz Analog								n.p.					
	3.65 GHz	Nano Station	15 km+	30 x 30 x 8	0.2	5.5	150 Mbps	15+ km	$150	Small Licence fee	In the US you need a non-exclusive nationwide licence, this is more a formality. Presently the base station and transmitter must be registered.	Negligible		
	WiFi 2.4 GHz	Bullet	0 - 50 km, in reality around 2 km for required bandwidths	15 x 4 x 3	0.2	10	50 Mbps	Up to 50 km	$120	Free Spectrum	Operates on consumer wifi freq so may be overloaded spectrum in certain environments	Negligible		
	WiFi 5GHz							Up to 50 km, less range than 2.4 Ghz version	$120					
Satellite	Inmarsat	FleetOne	Global	Dia 33 x 28	4	150	128 kbps	Global	$10,000+	From $1,300/ Month for 250 MB Data	n.p.	Negligible		Contract commitment may be requried

	System class	System name	Environmental performance limits	Operational size (height x width x depth in cm)	Operational weight (kg)	Power (W)	Band width	Range	Purchase costs	Operational costs	Usage restriction (geographical, political, etc)	Data delay	Further comments	
	Iridium	MCG-101	Global Reach	Dia 18 cm x 10	1.8	30	Short Burst Data solution	Global Reach	$1,600	$40 for 30,000 bytes of data (Monthly)	n.p.	Negligible		
	Iridium	Pilot		Dia 57 x 20	12.5	100	128 kbps	Global	$5,000+	From $2,000/ month for 200 MB Data	n.p.			
	Iridium L-Band	L-Band	n.p.	16.2 x 8.1 x 2.8	0.42	2.5 (0.2 standby)	2400 bps		$1099+	n.p.	Continuous Data Connection or Short Burst Data (SBD) for efficient transfer of small data packets up to 1960 bytes.	small (up to 20 s for SBD)		

11.4 Evaluation matrices

11.4.1 UAS sensor versus platform matrix

Table 29. Compilation of which Video sensor could potentially (o) or definitively be combined (x), which cannot be combined (-), and which combination will work but with limited mission duration (l). NA: not applicable.

		Video							
Sensor type	**Sensor name**	**TASE 400HD**	**TASE 310**	**CM202**	**CM100**	**OTUS U135 HIGH DEF**	**OTUS-L205 HIGH DEF**	**EO900**	**Dual Imager**
UAS	Trimble UX5	-	-	-	-	-	-	-	-
	BRAMOR C4EYE	-	-	-	-	-	-	-	-
	ScanEagle	-	-	-	-	-	-	x	x
	Penguin B	-	-	-	o	x	-	-	-
	Fulmar	o	o	o	o	o	o	-	-
	Jump 20	x	x	o	o	o	o	-	-
	Ocean Eye	-	-	-	-	-	-	-	-
	Swan X1	NA	NA	NA	NA	NA	NA	NA	NA
	Desert Star 10.	-	-	-	-	-	-	-	-

11.4.2 ASV/AUV sensor versus platform matrix

Table 30. Compilation of which PAM or AAM sensor could potentially or definitively be combined, sensor/platform combinations that are already integrated, which combinations cannot be combined and which combination will work but with limited mission duration.

Key:

Cannot be combined	N
Combination possible with known limitations in mission duration or depth	L
Could potentially be combined	o
Could definitely be combined	Y
Combinations already integrated	Y
Not known if combination is possible	

NA: Not applicable

		PAM sensors														AAM sensors										
	System name	A-Tag	AUSOMS-mini Black	C-POD	C-POD-F	Cornell / AutoBuoys	Decimus	DMON	SDA14	SDA416	Seiche real time tranmission system	SM2/SM3	SoundTrap 4 channel	SoundTrap HF	WISPR	Aquadopp	ADP	AZFP	DT-X SUB	ES853	Gemini 720i	Gemini 720is	modular VR2C	VMT	WBAT	WBT mini
ASV powered	ASV-6300	o	o	o	o	o	o	o	o		o	o		o	o	o	o	o	o	o			o		o	o
	C-Cat 2	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o			o		o	o
	C-Enduro	o	o	Y	o	o	Y	o	o	o	Y	o	o	o	o	o	o	o	o	o			o		o	o
	C-Stat	o	o	o	o	o	o	o	o		o	o		o	o	o	o	o	o	o			o		o	o
	C-Target 3	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o			o		o	o
	C-Worker 4	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o			o		o	o

		PAM sensors														AAM sensors										
	System name	A-Tag	AUSOMS-mini Black	C-POD	C-POD-F	Cornell / AutoBuoys	Decimus	DMON	SDA14	SDA416	Seiche real time tranmission system	SM2/SM3	SoundTrap 4 channel	SoundTrap HF	WISPR	Aquadopp	ADP	AZFP	DT-X SUB	ES853	Gemini 720i	Gemini 720is	modular VR2C	VMT	WBAT	WBT mini
	C-Worker 6	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o			o		o	o
	C-Worker 7	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o			o		o	o
	C-Worker Hydro	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o			o		o	o
	Delfim	o	o	o	o	o	o	o	o		o	o		o	o	o	o	o	o	o			o		o	o
	Mariner	o	o	o	o	o	o	o	o		o	o		o	o	o	o	o	o	o			o		o	o
	Measuring Dolphin	o	o	o	o	o	o	o	o		o	o		o	o	o	o	o	o	o			o		o	o
	ROAZ I	o	o	o	o	o	o	o	o		o	o		o	o	o	o	o	o	o			o		o	o
	ROAZ II	o	o	o	o	o	o	o	o		o	o		o	o	o	o	o	L	o			o		o	o
	RTSYS USV	o	o	o	o	o	o	o	o							o	o	o	o	o					o	o
ASV unpowered	AutoNaut 2	o	o	o	o	o	o	o	o	o	o	o	o	o	o	L	L	L	L	L					L	L
	AutoNaut 3	o	o	o	o	o	o	o	o	o	o	o	o	o	o	L	L	L	L	L					L	L
	AutoNaut 5	o	o	o	o	o	o	o	o	o	o	o	o	o	o	L	L	L	L	L					L	L
	AutoNaut 7	o	o	o	o	o	o	o	o	o	o	o	o	o	o	L	L	L	L	L					L	L
	Waveglider SV2	o	o	o	o	o	Y	o	o	o	Y	o	o	Y	o	L	L	L	L	L					L	L
	Waveglider SV3	o	o	o	o	o	o	o	o	o	o	o	o	o	o	L	L	L	L	L					L	L
AUV glider	ALBAC	o	o	N	N	N	L	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	Coastal glider	o	o	N	N	N	L	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	Deepglider	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	eFòlaga III	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y

		PAM sensors														AAM sensors										
	System name	A-Tag	AUSOMS-mini Black	C-POD	C-POD-F	Cornell / AutoBuoys	Decimus	DMON	SDA14	SDA416	Seiche real time tranmission system	SM2/SM3	SoundTrap 4 channel	SoundTrap HF	WISPR	Aquadopp	ADP	AZFP	DT-X SUB	ES853	Gemini 720i	Gemini 720is	modular VR2C	VMT	WBAT	WBT mini
	Liberdade Xwing/Zray	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	Petrel	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	SeaBird	o	o	N	N	N	N	o	L	L	N	N	o	o	o	N	N	N	N	N			N		N	N
	SeaExplorer	o	o	N	N	N	L	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	Seaglider (ogive)	o	o	N	N	N	N	Y	L	L	N	N	o	Y	Y	Y	Y	o	o	Y			Y		N	Y
	Slocum G2 glider	o	o	N	N	N	L	Y	L	L	N	N	o	Y	o	Y	Y	o	o	Y			Y		N	Y
	Slocum G2 hybrid	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	Slocum G2 thermal	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	Spray	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	Sterne glider	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
	TONAI	o	o	N	N	N	N	o	L	L	N	N	o	o	o	Y	Y	o	o	Y			Y		N	Y
AUV propeller	A18-D	o	L	L	o	o	o	L	o		N	o		L	o	o	o	o	o	L			L		L	o
	A9-M	o	o	L	o	o	o	o	o		N	o		L	o	o	o	o	o	o			o		o	o
	Bluefin-12D	o	L	L	o	o	o	o	o		N	o		L	o	o	o	o	o	L			L		L	o
	Bluefin-12S	o	o	L	o	o	o	o	o		N	o		o	o	o	o	o	o	o			o		o	o
	Bluefin-21	o	L	L	o	o	o	L	o		N	o		L	o	o	o	o	o	L			L		L	o
	Bluefin-9	o	o	L	o	o	o	o	o		N	o		o	o	o	o	o	o	o			o		o	o
	Bluefin-9M	o	o	L	o	o	o	o	o		N	o		o	o	o	o	o	o	o			o		o	o

		PAM sensors														AAM sensors										
	System name	A-Tag	AUSOMS-mini Black	C-POD	C-POD-F	Cornell / AutoBuoys	Decimus	DMON	SDA14	SDA416	Seiche real time tranmission system	SM2/SM3	SoundTrap 4 channel	SoundTrap HF	WISPR	Aquadopp	ADP	AZFP	DT-X SUB	ES853	Gemini 720i	Gemini 720is	modular VR2C	VMT	WBAT	WBT mini
	HUGIN 1000 (1000 m version)	o	o	L	o	o	o	o	o	o	N	o	o	L	o	o	o	o	o	o			L		o	o
	HUGIN 1000 (3000 m version)	o	L	L	o	o	o	L	o	o	N	o	o	L	o	o	o	o	o	L			L		L	o
	HUGIN 3000	o	L	L	o	o	o	L	o	o	N	o	o	L	o	o	o	o	o	L			L		L	o
	HUGIN 4500	o	L	L	o	o	o	L	o	o	N	o	o	L	o	o	o	o	o	L			L		L	o
	MUNIN	o	L	L	o	o	o	o	o	o	N	o	o	L	o	o	o	o	o	L			L		L	o
	REMUS 100	o	o	o	o	o	o	o	o	o	N	o	o	o	o	o	o	o	o	o			o		o	o
	REMUS 3000	o	L	L	o	o	o	o	o	o	N	o	o	L	o	o	o	o	o	L			L		L	o
	REMUS 600	o	o	L	o	o	o	o	o	o	N	o	o	L	o	o	o	o	o	o			L		o	o
	REMUS 6000	o	L	L	o	o	o	L	o	o	N	o	o	L	o	o	o	o	o	L			L		L	o
	RTSYS AUV	o	o	L	o	o	o	o	o	o	N	o	o	o	o	o	o		o						o	o

11.5 Supplier contacts

Table 31. List of supplier contacts of the platforms and sensors included in this review.

System class	Manufacturer	System name(s)	Street + No	Town	Post code	Country	Phone number	website
ASV - powered	ASV	C-Enduro, C-Worker 4 + 6 + 7 + Hydro, C-Cat 2, C-Target 3, C-Stat, ASV-6300	Unit 12 Murrills Estate, Southampton Road	Portchester	PO16 9RD	UK	T +44 (0)2392 382573	asvglobal.com
	Instituto Superior de Engenharia do Porto	ROAZ I and II	Rua Dr. António Bernardino de Almeida	Porto	431, 4200-072	Portugal	T +351 22 8340500	www.isep.ipp.pt
	RTSYS	Seaways USV	Rue Michel Mariono	56850 Caudan		France	T +33 297 898 582	www.seaways.fr
	Rostock University	Measuring Dolphin	Anwendungszentrum Regelungstechnik, Tannenweg 22d, im Rostockpark	Rostock	18059	Germany	T +49 381 498 7727	www.uni-rostock.de
	Instituto Superior Técnico	Delfim	Torre Norte, 7th Floor. Av. Rovisco Pais	Lisbon	1. 1049-001	Portugal	T +351 218418289	tecnico.ulisboa.pt
	Maritime Robotics AS	Mariner	Brattørkaia 11	Trondheim	7010	Norway	T +47 73 40 19 00	www.maritimerobotics.com
ASV - unpowered	Liquid Robotics	Waveglider SV2 + 3	1329 Moffett Park Dr	Sunnyvale	94089-1134	United States	T +1 408 636 4200	liquidr.com
	MOST (Autonomous Vessels) Ltd	AutoNaut 2 + 3 + 5 + 7	Unit A5 The Boatyard , Chichester Marina	Chichester	PO20 7EJ	UK	T +44 (0)1243 511421	www.autonautusv.com
AUV - glider	ALSEAMAR – ALCEN	Seaexplorer	9 Europarc	13590 Meyreuil		France	T +33 442 484 452	www.acsa-alcen.com
	Ecole Nationale Superiore D'Ingenieurs Brest	Sterne glider	No contact details	No contact details	No contact details	No contact details	No contact details	No contact details
	Exocetus Development LLC	Coastal glider	1444 East 9th Ave	Anchorage	99501	USA	907 227 8073	exocetus.com
	Graal tech	Folaga	vi J.Ruffini 9/r	16128 Genova		Italy	T +39 010 859 7680	www.graaltech.com
	Kongsberg	Seaglider (normal - also enquire deep)	19210 33rd Avernue West	Seattle	WA 98036-4707	USA	T +1 425 712 1107	www.km.kongsberg.com
	Kyushu Institute of Technology	SeaBird	1-1 Sensuicho	Tobata Ward, Kitakyushu	804-0015	Japan	T +81 93 884 3000	www.kyutech.ac.jp
	Nortek	Aquadopp	Vangkroken 2	1351 Rud		Norway	T +47 6717 4500	www.nortek-as.com

System class	Manufacturer	System name(s)	Street + No	Town	Post code	Country	Phone number	website
	SCRIPPS	Spray Glider, Liberdade Xwing/Zray	9500 Gilman Drive	La Jolla	92093-0230	USA	(858) 461 4728	www.scripps.edu
	Teledyne Webb	Slocum glider (electric, thermal and hybrid)	49 Edgerton Drive	North Falmouth	MA 02556	USA	T +1 508 548 2077	www.teledyne.com
	Tianjin University	Petrel	No contact details	No contact details	No contact details	China	No contact details	No contact details
	Tokai University	ALBAC	2-28-4 Tomigaya	Shibuya	151-0063	Japan	T +81 334672211	www.u-tokai.ac.jp
	Osaka Prefecture University, Taiji Whale Museum, Cetus	TONAI: Twilight Ocean-Zonal Natural Resources and Animal Investigator	No contact details	No contact details	No contact details	Japan	No contact details	No contact details
AUV - propeller	Bluefin Robotics	Bluefin 9, 9M, 12D, 12S, 21	553 South Street	Quincy	2169	USA	T +1 (617) 715 7000	www.bluefinrobotics.com
	ECA Group	A9-M, A18-D	Z.I. Toulon Est	262, rue des frères Lumière	83130 La Garde	France	T +33 (0)4 94 08 90 00	www.ecagroup.com
	Konsberg Maritime	REMUS, HUGIN, MUNIN	Kirkegårdsveien 45	NO-3616 Kongsberg		Norway	T +47 32 28 50 00	www.km.kongsberg.com
	RTSYS	AUV robots	Rue Michel Mariono	56850 Caudan		France	T +33 297 898 582	www.rtsys.eu
UAS kite	Flying Robots SA	Swan X1	Rue Thalberg, 2	Geneva	CH-1201	Switzerland		www.flying-robots.com
UAS l-t-a	Allsopp Helikites Ltd	Desert Star	Unit 2, Fordingbrigde Business Park	Fordingbridge, Hampshire	SP6 1BD	UK	T +44 1425 654967	www.allsopp.co.uk
	Maritime Robotics AS	Ocean Eye	Brattørkaia 11	Trondheim	7010	Norway	T +47 73 40 19 00	www.maritimerobotics.com
UAS - powered-fixed	Arcturus UAV	Jump 20	P.O. Box 3011	Rohnert Park	94928	USA	(707) 206 9372	arcturus-uav.com
	C-Astral d.o.o.	BRAMOR C4EYE, gEO, rTK	Gregorčičeva ulica 20	Ajdovščina	5270	Slovenia	T +386 (0) 40121119	www.c-astral.com
	Insitu	ScanEagle	118 East Columbia River Way	Bingen, Washington	98605	USA	T +1 509 493 8600	www.insitu.com
	Thales España grp, S.A.U.	Fulmar	Serrano Galvache, 56	Madrid	28033	Spain	T +34 91 273 72 00	www.thalesgroup.com
	Trimbe Navigation Limited	UX5	Buchtenstraat 9/1	Gent	9051	Belgium	T +32 9 335 05 15	uas.trimble.com

System class	Manufacturer	System name(s)	Street + No	Town	Post code	Country	Phone number	website
	Uavfactory	Penguin B	50 South Buckhout Street	Irvington	10533	USA	T +1 (914) 5913296	www.uavfactory.com
AAM	ASL	AZFP	#1-6703 Rajpur Place	Victoria, BC	V8M 1ZS	Canada	T +1-250-656-0177	www.aslenv.com
	Biosonics	Autonomous submersible echosounder	4027 Leary Way NW	Seattle	98107	U.S.A.	206 963 6369	biosonicsinc.com
	Imagenex	ES853	209-1875 Broadway Street	Port Coquitlam,	V3C 4Z1	Canada	604-944-8248	www.imagenex.com
	Kongsberg/Simrad	WBAT+WBT mini	P.O.Box 111	Strandpromenaden 50	3191	Norway	47 33 03 40 26	www.simrad.com
	Nortek	Aquadopp	Vangkroken 2	1351 Rud		Norway	T +47 6717 4500	www.nortek-as.com
	Sontek	ADP	9940 Summers Ridge Road	San Diego	CA	USA	T +1 (858) 546 8327	www.sontek.com
	Tritech	Gemini 720i & 720is	Peregrine Road, Westhill Business Park	Westhill	AB32 6JL	UK	T +44 (0)1224 744111	www.tritech.co.uk
	Vemco	modular VR2C+VMT	20 Angus Morton Drive	Bedford, Nova Scotia	B4B 0L9	Canada	T +1-902 450 1700	vemco.com
PAM	Aquasound Inc.	AUSOMS-mini Black	Kyoto Research Center, 46 Shimoadachi-cho	Yoshida Sakyo-ku	606-8501	Japan	T +81-075 753 9670	aqua-sound.com
	Chelonia	CPOD + C-POD-F	The Barkhouse, North Cliff	Mousehole	TR19 6PH	UK	T +44 (0)1736 732462	www.chelonia.co.uk
	Cornell (PAM) / EOS (buoy)	Cornell / AutoBuoys/DOSITS	Cornell Lab of Ornithology, 159 Sapsucker Woods Rd.	Ithaca	14850	USA	607-254 6250	www.birds.cornell.edu
	Embedded Ocean Systems	WISPR		Seattle		USA	(206) 766 0671	embeddedocean.com
	JASCO	AMAR	The Roundel, St Clair's Farm, Wickham Road,	Droxford	SO32 3PW	UK	(0) 1489 878439	www.jasco.com
	Marine Micro Technology	A-Tag	4-12-1 Takakura	Iruma City		Japan	04 2965 4127	
	Ocean Instruments NZ	SoundTrap HF + 4 channel	961 Sandspit Rd	Warkworth	982	New Zealand	64 9 9233601	www.OceanInstruments.co.nz
	RTSYS	PAM: RB-SDA14, BA-SDA14	Rue Michel Mariono	56850 Caudan		France	33 297 898 582	www.rtsys.eu
	SA Instrumentation Ltd	Decimus	Mill Court, Mill Lane	Tayport	DD6 9EL	UK	T +44 (0)1334 845260	www.sa-instrumentation.com
	Seiche Measurements Ltd	Seiche real time tranmission system	Bradworthy Industrial Estate, Langdon Road, Bradworthy	Holsworthy	EX22 7SF	UK	T +44 (0)1409 404050	www.seiche.com
	WHOI	DMON	266 Woods Hole Road	Woods Hole	02543-1050	USA	T +1 508 289 2906	www.whoi.edu

System class	Manufacturer	System name(s)	Street + No	Town	Post code	Country	Phone number	website
	Wildlife Acoustics	SM2/SM3	3 Clock Tower Place, Suite 210	Maynard	01754-2549	USA	T +1 (978) 369 5225	www.wildlifeacoustics.com
Video	Cloudcap Technology	TASE 400HD + 310	202 Wasco Loop, Suite 103	Hood River	97031	USA	(541) 387 2120	www.cloudcaptech.com
	DST	OTUS U135 + L205 HIGH DEF	Åkerbogatan 10	Linköping	582	Sweden	T +46 13 211080	www.dst.com
	Insitu	EO900 + Dual Imager	118 East Columbia River Way	Bingen, Washington	98605	USA	T +1509 493 8600	www.insitu.com
	UAV vision	CM202 + 100	10 Uralla Street	Port Macquarie	2444	Australia	T +61 2 6581 1994	uavvision.com

11.6 Surveying wildlife populations

This section provides further details on the statistical side of density estimates explaining how survey data are analysed (section 11.6.1) and which methods are currently available for estimating the detection probability (section 11.6.2), which serves for a better understanding on the relevance of retrieving appropriate survey data from a carefully planned and executed survey design.

11.6.1 Estimating absolute population density and abundance – an overview

Statistical data analysis methods have been developed that correct observed data for undetected animals, leading to absolute estimates of animal abundance or density (Borchers et al., 2002). At the data analysis stage, estimators are used to produce the required density or abundance estimates. A typical estimator for absolute density is:

$$\hat{D} = \frac{n}{\hat{p}a} \qquad \text{(Eqn. 1)}$$

Where

$\hat{D}$ is the estimated density,

n is the number of encounters made during the survey,

$\hat{p}$ is the estimated average probability of detecting an encounter and

a is the total surveyed area.

It is rare that an entire study area of interest can be completely covered by a survey (due to logistical and financial constraints) so it is often the case that the surveyed area is a subsample of the study area. Absolute abundance in the study area can be estimated using Eqn. 2, if the survey has been designed such that the surveyed area is representative of the study area, otherwise resulting abundance estimates may be biased.

$$\hat{N} = \hat{D} \times A \qquad \text{(Eqn. 2)}$$

Where

$\hat{N}$ is the absolute abundance in the study area and

A is the size of the study area.

The ability to rely on a survey's design to infer that estimated animal density is representative of density in the wider study area, and that abundance in the study area can be estimated using Eqn. 2, is known as design-based inference (Borchers et al., 2002). An adequate survey design comprises multiple samplers such as survey transects, which have been randomly sampled from all possible samplers in the study area (or stratum, if the survey is stratified geographically) with equal probability. A systematic random design is typically preferable to a completely random design because it produces more precise estimates. Furthermore, the samplers should be randomly distributed with respect to the study species' distribution (see Buckland et al., 2001; 2015 for more detail about survey design). If a survey has not been designed, or the realised survey has deviated from the planned design, then model-based inference can be used instead to infer density and abundance across the study area. This approach uses a statistical model to link estimated density in the surveyed area with spatial covariates. The model can then be used to predict the density/abundance in unsurveyed parts of the study area (e.g. Cañadas and Hammond, 2006; Miller, 2013). However, while this approach relaxes the need for a strict survey design, there is still a requirement that, for any selected covariate, the range of modelled values matches the range of values in the study area. Biased results may occur if the spatial model is used to generate abundance predictions using covariate values that are lower or higher than the values used to build the model (i.e. model extrapolation). Therefore, the surveyed area must be representative of the wider study area.

The definition of an encounter can change depending on the species of interest and the survey type. However, density estimators are flexible and can be altered accordingly. In some cases, it may be possible to count individuals (visually or acoustically) but in other surveys of highly social or shoaling animals, groups of animals may form the observed encounters. When groups are counted, average group size can be included as an additional multiplying parameter, or "multiplier", in the density estimator to convert estimated group density into estimated animal density. In the case of shoaling fish and zooplankton, where group size estimation is particularly difficult, there is a large literature on the conversion of echosounder data to estimates of density or abundance (e.g. Johannesson and Mitson, 1983; Foote, 2009). Alternatively, average biomass may be estimated (e.g. Cox et al., 2011). In passive acoustic monitoring, calls can often be readily counted and an average call production rate is then required to convert estimated call density to estimated animal density. Furthermore, acoustic data are often automatically processed and an additional multiplier is required to correct the number of observations for false detections. A typical density estimator for use with passive acoustic data is, therefore:

$$\hat{D} = \frac{n(1-\hat{f})}{\hat{p}a\hat{r}} \qquad \text{(Eqn. 3)}$$

Where

n is the number of acoustic encounters,

f is the proportion of false detections generated by the detection routine and

$\hat{r}$ represents the appropriate multiplier(s) that will convert the object density to animal density.

If, for example, individual calls were counted in a survey, then required multipliers would be an average call production rate (an estimated parameter) and the amount of time spent monitoring (a constant).

The probability of detection typically corrects encounters for *perception bias*. This is bias caused by missing encounters that were available for detection but were not detected e.g. because of high sea state during visual surveys or high background noise in acoustic surveys. Another form of bias that must be considered is *availability bias*. This is bias that arises from missing animals that were present in the survey area but were not available to be detected. In visual surveys from surface vessels or aerial platforms, animals are only available to be seen at the surface or at very shallow depths and are therefore only temporarily available during the survey. Therefore, an additional multiplier is required in the density estimator to account for the proportion of animals that were unavailable to be surveyed. Similarly, in acoustic surveys, animals are not constantly vocal, so a multiplier, such as call production rate, is required to account for animals in the population that were not vocalising at the time of the survey. Furthermore, some animals will be permanently unavailable in passive acoustic surveys if they never produce the specific vocalisation(s) that are being monitored. This proportion of the population must also be accounted for in the density estimator using an appropriate multiplier. It is important to recognise that any estimated multiplier (including the probability of detection) may show spatial and temporal variation. Using multipliers from the literature or that have been estimated from datasets collected from another study population (or even the same study population but at a different location and/or time) may result in the application of the wrong multiplier and, ultimately, biased results.

11.6.2 Methods to estimate detection probability

Wildlife surveys typically take place along planned survey transects or from static monitoring points. In some surveys, it may be possible to detect all animals within the transect lines or points. Such survey types are known as strip transect sampling (using transect lines) or plot sampling (using points).

When animals are suspected to be missed within surveyed areas, there are several methods that can be used to estimate the probability of detection. Distance sampling, for example, is a commonly-used, versatile method that has been widely applied to marine surveys (Buckland et al., 2001; 2015). Distance sampling has been applied to visual and acoustic (both active and passive) data to estimate the abundance of marine mammals, turtles and krill swarms. Distance sampling data have been collected from a variety of marine surveying platforms including vessels and aircraft that follow survey lines (line transect sampling) and stationary monitoring points (point transect sampling). Detection probabilities estimated using distance sampling can be used in density estimators such as those in Eqns 1 and 3.

Mark-recapture is another standard abundance estimation method (Borchers et al., 2002) but has an alternative estimation framework to distance sampling, involving different estimators to those in Eqns. 1 & 3. Mark recapture has been used with visual data to estimate marine mammal (e.g. Cheney et al., 2014), turtle (e.g. Dutton et al., 2005) and fish abundances (e.g. Bradshaw et al., 2007). Data from animal-borne active acoustic tags can also be analysed using of mark-recapture; tagged animals are re-identified as they swim past deployed acoustic receivers (e.g. Dudgeon et al., 2015). A difficulty of mark-recapture methods is that, while abundance can be estimated, it is non-trivial to determine the size of the surveyed area and, therefore, estimate animal density. However, spatially-explicit capture-recapture (SECR), a relatively recent extension to mark-recapture methodology, allows density, as well as abundance, to be inferred from the collected data. Despite being a recently developed method, SECR is considered to be a "standard" abundance and density estimation approach due to its links with mark-recapture and also distance sampling (Borchers, 2012; Borchers et al., 2015).

SECR has been used with both visual (Pirotta et al., 2014) and passive acoustic (Marques et al., 2011; Martin et al., 2012) data to estimate the abundance and density of marine mammals. The ability to estimate density is a major advantage of SECR over mark—recapture and, therefore, SECR will be discussed in preference to mark-recapture in the rest of the report.

If distance sampling or SECR cannot be used, detection probabilities can be estimated using alternative "non-standard" methods. Many of the non-standard methods were developed specifically for use with passive acoustic data to estimate marine mammal density. These methods often use auxiliary information. For example, a "trial-based" method implemented by Marques et al., (2009) used passive acoustic tag data (specifically DTag data: Johnson *& Tyack*., 2003) to cross reference whether clicks produced by the tagged animal were received or not on fixed hydrophones in the area. The probability of detecting a beaked whale on a fixed hydrophone could then be modelled as a function of range (Marques et al., 2009).

The various methods require different information to be recorded about encounters. In general, distance sampling requires that the horizontal and perpendicular range is measured from the transect line or point to each encounter. Range estimation methods using passive acoustic data that contain ambiguity about whether the encounter was on the left- or right-hand side of the transect line, or the bearing from a point, are acceptable. However, an estimate of horizontal range requires the depth of acoustically-detected animals to be estimated (but also see Cox et al., 2011 and Harris, 2014 for alternative approaches to extending standard distance sampling to account for animals at depth).

Spatially-explicit capture-recapture when used with visual data requires that individuals are re-identified, i.e. "re-captured" across surveying occasions and that the location of each encountered animal is recorded. In passive acoustic surveys, the data requirements for SECR are somewhat different. Hydrophones are considered to be "traps" of known location, and the same acoustic encounter can be "caught" on multiple hydrophones. The spatial pattern of captures of a given acoustic encounter provides information about the detection probability of the encounter. Received level and time-of-arrival of the acoustic encounters can also improve the precision of the results (Stevenson et al., 2015).

Non-standard methods can be implemented when there is less information available about the encounter (i.e., ranges, bearings or recaptures cannot be recorded) but the methods rely on more assumptions and modelling to compensate for the lack of empirical data and should not be considered in preference to standard approaches. Depending on the particular method being used, measures of received levels and noise levels, as well as estimates of transmission loss (estimated using sound propagation models) may be useful. These acoustic measures can be combined in a simulation framework that can be used to estimate detection probability (e.g. Kusel et al., 2011). Finally, like standard methods, any additional multipliers that have been identified as relevant for a given survey, e.g. call production rate or group size, will also be required.

Each density estimation method has associated assumptions of varying severity. Violation of key assumptions can lead to bias in estimated detection probabilities and, ultimately, abundance or density estimates. There are four main assumptions in distance sampling (Buckland et al., 2015). These are: (1) that transect lines or points have been placed randomly with respect to the distribution of the study species (this is important not only for the design-based abundance inference, but also for the detection probability estimation), (2) any encounter on (i.e., at zero distance from) the transect line or at the centre of the monitoring point is detected with certainty, (3) that encountered animals are detected at their initial location i.e., there is no animal movement and (4) that measured distances are accurate. The main assumption of SECR are that captures (whether individual animals or acoustic encounters) can be accurately re-identified across capture occasions. When using SECR with passive acoustic data, it is currently assumed that (1) all calls are emitted at the same source level and (2) that there is no effect of signal directionality on detection probability (Stevenson et al., 2015). Non-standard methods vary in their assumptions but a shared important assumption is that any auxiliary data used in the analysis is relevant to the study population at the time and place of the study.

The final aspect of abundance and density methodology to discuss is variance estimation. Estimating the uncertainty in a density or abundance estimate is a crucial part of an analysis. It is important to generate estimates that are as precise as possible so that they can be useful in management and mitigation decisions. The delta method is a convenient way in which the uncertainty associated with each parameter in a given density estimator can be combined to estimate an overall variance for the density or abundance estimate (Seber, 1982).

12 Glossary of Terms, Acronyms and Abbreviations

Term	Description
AAM	Active Acoustic Monitoring
ADCP	Acoustic Doppler Current Profiler
AMG	Aircraft Management Guidelines
AMOC	Alternative Method Of Compliance
ASV	Autonomous Surface Vehicles
ATC	Air Traffic Control
AUV	Autonomous Underwater Vehicles
BAS	British Antarctic Survey
BLOS	Beyond Visible Line Of Sight
bps, kbps, Mbps	Bits per second, Kilobits per second, Megabits per second. N.B. 8 bits are required to form one Byte of data. Most communications systems quote bandwidth in bps.
COTS	Commercial Off-The-Shelf
CREEM	Centre for Research into Ecological and Environmental Modelling
CT	Condutivity-Temperature probe
DS	Depth Sensor
DTAG	Digital Acoustic Recording Tag
DVL	Doppler Velocity Logger
E&P	Exploration And Production
ERMA	Energy Ratio Mapping Algorithm
EVLOS	Extend Visible Line Of Sight
FAA	Federal Aviation Administration
FLAC	Free Lossless Audio Codec
FLS	Forward-Looking Sonar
GENIoS	Glider-Environment Network Information System

Term	Description
GPS	Global Positioning System (simple or differential)
HSE	Health And Safety Executive
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IR	Infrared
Iridium	Iridium satellite communications
ISAS	Interferometric Synthetic Aperture Sonar
LBL	Long BaseLine
LFDCS	Low Frequency Detection And Classification System
LIDAR	Light Imaging, Detection, And Ranging
MBES	MultiBeam EchoSounder
MMO	Marine Mammal Observer
NCAA	National Civil Aviation Authority
NORUT	Northern Research Institute
PAM	Passive Acoustic Monitoring
PAR	Photosynthetically Active Radiation
PSO	Protected Species Observer
RF	Radio Frequency link
RHIB	Rigid-Hulled Inflatable Boat
RiNKO	Type of phosphorescent DO sensor
RPAS	Remotely Piloted Aircraft Systems
SAS	Synthetic Aperture Sonar
SBL	Short BaseLine
SBP	Sub-Bottom Profiler
SMRU	Sea Mammal Research Unit

Term	Description
SSS	SideScan Sonar (single or dual frequency)
SUNA	Submersible Ultraviolet Nitrate Analyzer
SVTP	Sound, Velocity, Temperature and Pressure
SVS	Sound Velocity Sensor
TS	Turbidity Sensor
UAS	Unmanned Aerial Systems
UNCLOS	United Nations Convention On The Law Of The Sea
USBL	Ultra-Short BaseLine
UTP	Underwater Transponder Positioning
VLOS	Visible Line Of Sight
WHOI	Woods Hole Oceanographic Institution
WiFi	WiFi link

13 Reference list

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