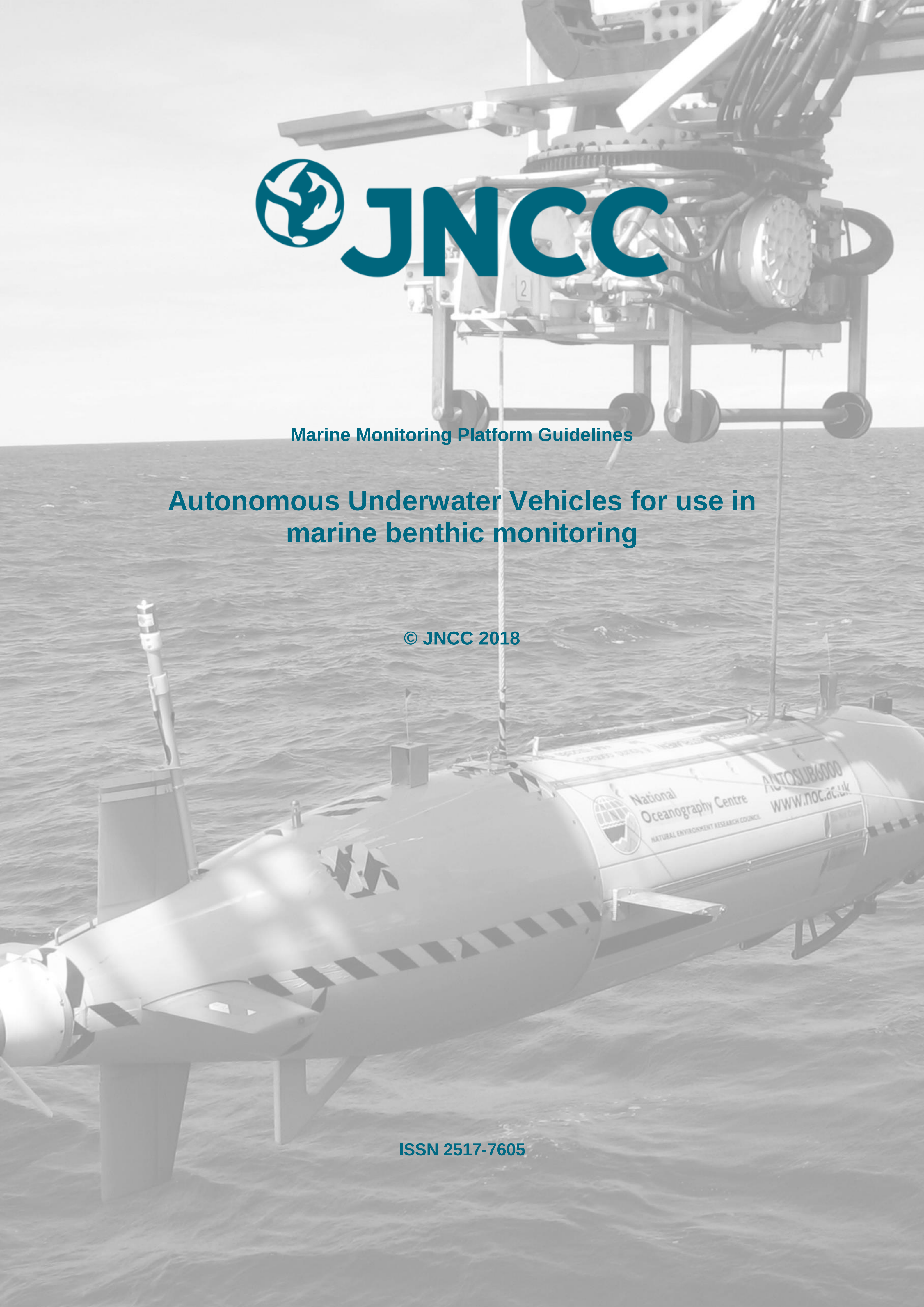

Marine Monitoring Platform Guidelines

Autonomous Underwater Vehicles for use in marine benthic monitoring

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Contents

Overview

An autonomous underwater vehicle (AUV) is an unmanned underwater robot, electrically powered by batteries, that operates independently of a surface vessel for a few hours to several days (see reviews by Wynn *et al* 2014 and Huvenne *et al* 2018). AUVs are capable of collecting geophysical, biological and oceanographic data from both the seafloor and water column. The AUV will either follow a survey plan that is entirely pre-planned before the mission, or a combination of pre-planning and re-planning during mission, as smarter modes of control are developed. The data gathered is downloaded from the AUV when it has surfaced via a WiFi link and/or data cable.

This procedural guideline is intended primarily for marine monitoring/survey managers and provides outline guidance on cruising AUVs that are presently the most widely available and applicable to the UK. Two broad classes of AUV can be defined: large AUVs such as the NOC *Autosub* family and small AUVs (typically <3m), such as the Kongsberg *REMUS* 100 and Teledyne *Gavia* that can be deployed by two people. The guideline includes information on equipment, survey planning and outline costs (see Table 1 for overview).

Table 1. Overview of two broad classes of cruising AUVs.

	Small AUV Class	Large AUV Class
Sampling platform	Smaller AUV classes such as Kongsberg *REMUS 100* or Teledyne *Gavia* (<3m).	Larger AUV models such as NOC *Autosub6000* (>3m).
Scale of operation	Meso – Broad (>25m^2 <1km^2)	Broad (>25m^2 <1km^2)
Habitat-type	Low relief subtidal environments including low salinity environments if properly ballasted (although turbidity and optical distortion in mixing waters reduces capability).	
Substratum -type	All substrata types, including static rock (bedrock, large boulder), mobile rock (boulder, cobble, pebble) and sediments (gravel, sand, mud). Cruising AUVs are unsuitable for low altitude (<2m) surveys in complex high relief terrain without careful planning and high quality bathymetric data. Unsuitable for vertical and near-vertical surfaces (e.g. underwater cliffs) unless the vehicle is reconfigured.	
Target community	Predominantly used to survey sessile / mobile epifauna, demersal fish and associated environmental variables. Particularly useful in approximately level-bottom broad-scale habitats in the case of photographic surveys, though more complex terrain can be successfully surveyed acoustically. May also be used to observe pelagic species and collect water samples. Not suitable to survey species within complex habitats e.g. matrix fauna within mussel beds, cryptic species within reefs or fauna within kelp beds (Hill *et al* 2014; Ling *et al* 2016; Smale *et al* 2012).	
Samples produced	Qualitative and quantitative survey data includes scaled still images of megafauna (>1-2cm), observations of lebensspuren (life traces: tracks, burrows, *etc*.), plankton, and habitat / substrata descriptions. Multibeam echosounder and sidescan sonar survey data. Physiochemical environmental data, e.g. CTD. Supported by vehicle attitude (pitch, roll, heading), altitude and geolocation data.	
Data products	Still images of species and habitats, environmental data (including temperature, salinity, depth, oxygen, *etc*.), vehicle telemetry (including navigation, attitude (e.g. pitch, roll, heading, altitude, *etc*.), acoustic data (used to produce bathymetric and, if data validation is available, habitat maps).	

<table>
<tr><th>Cost per day[1]</th><td>£900-1,400
(based on 5-7 days)</td><td>£1,800-5,800
(based on 7-9 days)</td></tr>
<tr><th colspan="2">Advantages of AUVs</th><th>Limitations of AUVs</th></tr>
<tr><td colspan="2">AUVs can operate independently of vessel between launch and recovery, allowing the vessel and crew to conduct other tasks maximising time (Strong 2015). However, AUVs are often followed by the survey vessel, especially in high risk areas with other human activities such as shipping and fishing.

Can carry a range of different survey equipment for biological, oceanographic and geophysical sampling (see Table 4).

As cruising AUVs can fly relatively close to the bottom (<5m altitude in areas of low relief), they provide stable imaging platforms collecting seafloor mapping, profiling and imaging data with lower spatial coverage but far higher spatial resolution (up to two orders of magnitude) than surface vessels.

AUVs follow pre-set courses and can achieve more complex survey patterns and maintaining precise altitude, speed and photo angle (pitch, roll, and yaw) control, than towed systems.

AUV surveys can cover large areas and yield high volumes of quality imagery. If properly archived with supporting metadata, these can be revisited in future and reanalysed. Photographic survey coverage rate by AUVs is typically much greater than alternative methods (ROV or tow camera).

Imagery and sonar can be used simultaneously, producing perfectly co-located acoustic and visual data, producing ground-truthed habitat maps (Wynn et al 2012).

AUVs provide non-destructive sampling platforms. As the AUV is not in contact with the seabed they are particularly useful sampling platforms for image surveys of abrasion sensitive areas, e.g. marine protected areas generally and particularly fragile biogenic habitats (e.g. including deep-water corals) (Huvenne et al 2016; Wynn et al 2012).

Small AUVs are relatively portable and can be manually deployed from shore or small vessels of opportunity reducing survey costs.</td><td>AUV missions may be compromised in areas of strong tidal currents and / or high turbidity. Cruising AUVs typically move at speeds of 1.5–2.0$m.s^{-1}$, and can be influenced by tidal (or other) currents approaching or exceeding these velocities, (although there are examples of AUVs working in tidal currents >2$m.s^{-1}$; Wynn et al 2014).

Streaming data from a submerged AUV conducting a seafloor survey is currently not a viable option in any respect. Some 2-way communication on navigation might be employed at best. Transferring survey data (photo or geophysics) is a currently impossible. Loss or corruption of data due to technical problems will only be discovered after the mission (Wynn et al 2014; Howell et al 2013).

Not capable of physical sampling of seabed or fauna, although some sampling of water column achieved

AUVs have much lower spatial coverage than ship borne seafloor mapping and profiling data.

In complex, high-relief terrain, cruising class AUVs are unsuitable to conduct low altitude surveys due to the risk of seabed collision (particularly limiting for photographic surveys.

Risks of damage / loss, especially in coastal/heavy human use environments; damage and entanglement from human (fishing gear, boat traffic, offshore structures) and natural (caves, ledges and macroalgae) sources.

Need extensive technical support team to be able to fix the AUV when it is damaged, physical failures delay/prevent missions e.g. running out of power, incorrect component installations (Huvenne et al 2011) camera failures (Huvenne et al 2016).

Large AUVs require a larger vessel with adequate stowage / working area and ship mounted launch and recover system (LARS), incurring greater vessel costs.</td></tr>
</table>

[1] Estimated cost based on planning, AUV and vessel hire, planning and day rate for on-board scientist/survey manager. Consumables, processing of samples and reporting are not included.

Logistics

A. Equipment

AUV classes

The aims, objectives and likely operating conditions will determine the type of AUV required for sampling aims. AUV systems are typically categorised depending on their weight, size, ability and power. Vehicles may be 'bespoke, developed' and operated by a research institution such as the *Autosub* family of vehicles based at the National Oceanography Centre (NOC) or Commercial Off-The-Shelf (COTS) systems. The focus of this guideline is on the 'torpedo-shaped' cruising AUVs (see Table 2) as they are presently the most widely available and applicable to the UK.

Table 2. A comparison of small (manually deployed) and large cruising AUV classes and description (L-R, images supplied by Ian Vincent of the *ecoSUB* and the NOC *Autosub6000* supplied by Josh Davison).

AUV type	***Manually deployed small AUVs***	***Large AUVs***
		
Definition and capability	Wide capabilities for data collection, primarily used in shallow waters. Can be used in as shallow as 1-2m depth (Wynn *et al* 2014).	Much larger vehicles with longer endurance capabilities and deeper diving capacity (>150km missions, 48h battery life at 1.7m.s^{-1}; Morris *et al* 2016).
Examples	ecoSUB: ecoSUBµ & ecoSUBm. Teledyne *Gavia.* Kongsberg *REMUS* 100. L3 IVER.	NOC *Autosub3, Autosub6000, Autosub Long Range.* Kongsberg *HUGIN 3000, HUGIN 450.* Kongsberg *MUNIN.* Kongsberg *REMUS 600.*
Dimensions and weight	Teledyne *Gavia:* 1.8-4.5m length, 50-130kg (configuration dependent). Kongsberg *REMUS 100*: 170cm length, 36kg.	NOC *Autosub6000:* 5.5m length, 1,800kg. *Autosub Long Range*: 3.6m length, 660kg. Kongsberg *HUGIN* series: 5.2-6.4m length, 1,000-1,550kg. Kongsberg *MUNIN*: 4m length, 300kg. Kongsberg *REMUS 600*: 2.7-5.5m length, 220-385 kg (configuration dependent).
Depth rating	Teledyne *Gavia* 500-1,000m. Kongsberg *REMUS* 100m.	NOC *Autosub6000 and Autosub Long range* 6,000m. Kongsberg *HUGIN* series 3,000-6,000m. Kongsberg *MUNIN* 1,500m. Kongsberg *REMUS* 600 1,500m.
Deployment type	Manual or using small cranes / A-frames, davits.	Bespoke LARS (Launch and Recovery System) e.g. stinger or gantry, or vessel crane or A-frame.
Vessel requirements	Fixed platform (jetty / pontoon) or a small vessel or RIB. Typically a 3m AUV with additional equipment such as a 10m USBL would require at	Suitably sized vessel with deck capacity for container storage and LARS (LARS can be retrofitted). *HUGIN* AUV requires a 10m container and stinger LARS requiring a 30m vessel.

	least 4m x 3m of deck space to safely deploy and retrieve. For an AUV >100kg a vessel with >0.5m freeboard is beyond scope of manual lift. Vessels with >0.5m require winches.	MUNIN AUV requires 12m vessel. *Autosub6000* requires 40m vessel, gantry requires minimum of 3.2 x 2.2m deck space but preferably 6 x 2.2m to accommodate the entire vehicle on-board.
Staff requirements	1-2 engineers/operators.	2-3 engineers/operators, e.g. NOC *Autosub3* -3 engineers/operators, NOC *Autosub Long Range* 1-2 engineers/operators.

Table 3 provides a brief outline of AUV classes that were considered outside the scope of this guideline. Gliders are buoyancy driven form of AUV that are not used for benthic monitoring (included within this guideline only as a case study). Another type of AUV that is excluded is the hover capable AUVs, as these are not presently available in the UK. They are used elsewhere in the world and have the advantage that they can be used in complex, high-relief habitats (see operation guidelines for a case study). Hybrid AUV / ROVs and autonomous bottom crawling vehicles are very specialised AUVs and are not yet used for habitat surveys in the UK.

Table 3. Brief outline of AUV classes not included in the procedural guideline.

	Description	**Key references**
Hover AUV SeaBED 	A number of AUVs have been designed with hover capability. The SeaBED AUV appears to be the most widely used for biological monitoring. It can fly slowly or hover over the seafloor conduct low altitude surveys (2.5 meters) above the seafloor and, unlike cruising AUVs, it can be used in complex terrain.	Recent guidelines developed for Australia (Monk *et al* 2018), provide useful guidance on the use of the hover AUV, SeaBED, these are available on-line.[2]
Glider AUV Slocom glider used by Rutgers University in Antarctica[3] 	Gliders use buoyancy changes and wings to ascend or descend through the water column. They can carry range of sensors, such as CTD (conductivity, temperature, depth), oxygen, fluorometer, turbidity, high frequency ADCP (Acoustic Doppler Current Profiler) and turbulence sensors. They are considered to be cost-effective for long-term monitoring of hydrography and pelagic ecosystems (deployments up to 18 months).	Feasibility study of using gliders and AUVs to map and monitor MPAs by Wynn *et al* (2012). Poulton (2015) monitors numerous hydrographic parameters using up to seven gliders over 18-month period.

[2] National Environmental Science Programme (Australia): https://www.nespmarine.edu.au/sites/default/files/FieldManuals_NESPMarineHub_Chapter4_AUV_v1.pdf
[3] Centre for Ocean Observing Leadership, Rutgers University: https://rucool.marine.rutgers.edu/

Hybrid AUV/ROV 	Vehicles that can be switched between AUV and ROV (tethered and manually operated) modes. Examples include the Saab *Seaeye Sabretooth* that can be docked underwater in a garage and the *Aquabotix Integra*.	For details on specification and deployment see company webpages on Saab *Seaeye Sabertooth*[4] and Aquabotix[5].
Benthic crawlers Alfred Wegener Institute (AWI) *Tramper* 	Crawlers in use for habitat surveying include the *MBARI Benthic rover* (about the size of a small car) and the Alfred Wegener Institute *AWI Tramper*. These are designed for long term deployment (several weeks) and move slowly across the seafloor on tracks. They can carry a range of equipment.	For details on specification see the MBARI[6] and Alfred Wegener Institute[7] web pages

Launch and recovery systems

Larger AUVs that are not manually lifted and deployed, are typically launched using either a bespoke launch and recovery system (LARS) or general ship lifting gear such as cranes, A-frames or davits (Figure 1). Smaller AUVs can be manually deployed by two people with a variety of options available (see Operation Guidelines section). For nearshore surveys an AUV can also be towed to the deployment site. Most AUVs are controlled and monitored using a surface laptop or PC.

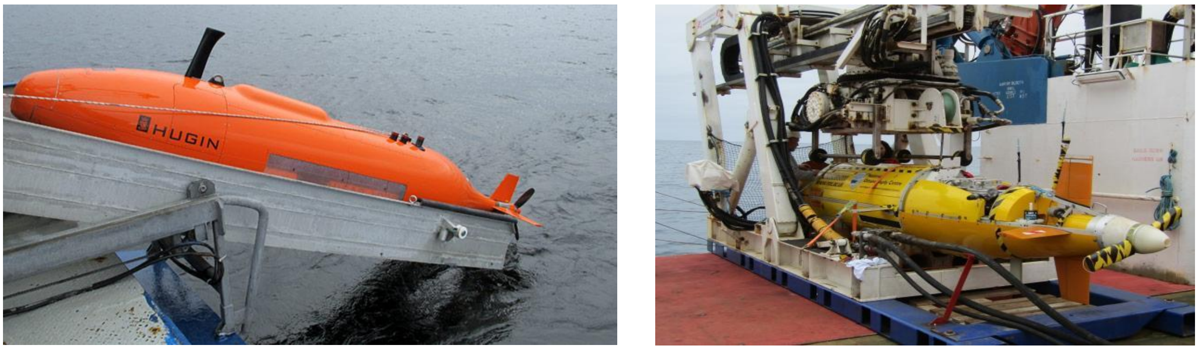

Figure 1. Examples of bespoke launch and recovery systems: L-R: Kongsberg *HUGIN* recovered via a stinger (Image supplied by Kongsberg) and NOC *Autosub6000* aboard gantry (image supplied by Josh Davison).

AUV accessories and other equipment

A range of sensor equipment and accessories can be carried by an AUV to achieve survey objectives (Table 4). The equipment options, configuration and capability will be AUV specific and depend on available accessories and AUV size and payload. It should be noted that sensor operation depletes batteries and results in reduced operation time.

[4] Saab Seaeye: http://www.seaeye.com/sabertooth.html
[5] Aquabotics Technology Corporation: https://www.aquabotix.com/hybrid-auvrovs.htm
[6] Monterey Bay Aquarium Research Institute (MBARI): https://www.mbari.org/benthic-rover/
[7] Alfred Wegener Institute (AWI): https://www.awi.de/nc/en/about-us/service/press/press-release/awi-unterwasserroboter-tramper-erfolgreich-geborgen.html

Table 4. Equipment / sensors available for AUVs. This list is not exhaustive and new technological developments and size reductions of equipment are resulting in more options becoming available to use with smaller AUVs with less payload.

Equipment / accessory type	Possibilities for AUVs
Cameras and lighting	Multiple still image camera and positioning options including stereo, oblique and downward facing Light Emitting Diode (LED) lighting Flashgun(s)
Acoustic surveying equipment	Multibeam echosounder Sidescan Sonar Sub-bottom profiler Passive acoustics (e.g. hydrophones for cetaceans) Synthetic Aperture Sonar Interferometric sonar
Navigation and positioning	Compass Pressure sensors Transponder beacons Ultra Short Baseline (USBL) / Short Baseline (SB) / Long Baseline (LBL) Doppler Velocity Logs (DVLs) Inertia Measurement units (accelerometers and gyroscopes) Scanning sonar for obstacle avoidance
Environmental sensor packages	Current meter Acoustic Doppler Current Profiler (ADCP) Turbulence sensors pH meters Electrochemical sensors (eH) Conductivity, temperature, depth (CTD) Fluorometers measuring Chl a / Dissolved Organic Matter (DOM) Turbidity meters (Light Scattering Sensor) Oxygen sensors Multi-spectral radiometers Laser line scanner

B. Communication, navigation and positioning

The type of navigation system selected will depend on the AUV payload, the sensors available and survey objectives, including the degree of positional accuracy required. Different systems can be combined to yield increased performance.

On the sea surface, AUVs can be positioned using the satellite-based Global Positioning Systems (GPS) to identify start and end points of missions and operators can communicate with the AUV via radio (with WiFi options available on some vehicles). An AUV can also be surfaced during a shallow mission to recalibrate positioning via GPS if required (Wynn *et al* 2014). As satellite signals do not penetrate into water, other underwater communication or compensation options are required to position the AUV to execute mission plans and georeference survey data (see review by Paull *et al* 2014). These include:

- **Dead reckoning**: is the simplest and the least accurate form of navigation. In essence, from a fixed point (known or unknown georeference) the vehicle advances its position mathematically based on knowledge of heading, speed, and elapsed time. At its very simplest, a propeller driven vehicle may simply count propeller revolutions as a measurement of distance (e.g. speed × time).

- **Inertial navigation**: Typically, an inertial navigation system (INS) uses data from specific motion sensors (accelerometers) and rotation sensors (gyroscopes) to calculate position by dead reckoning, without the need for external references. INS is often aided by other sources of information. In seafloor applications, Doppler Velocity Log (DVL) is particularly useful (e.g. McPhail *et al* 2009; Paull *et al* 2014). When within range of the seafloor, the DVL references the AUV's position relative to the Earth by providing speed in the x- and y-axes. INS will also take input from, and be aided by, depth sensors, GPS receivers, and acoustic navigation systems when available (see next section).

- **Acoustic transponders:** Long baseline (LBL) navigation uses seafloor mounted baseline transponders as reference points. This option is useful if a limited area requires repeated monitoring over a short-time period. Over wider areas it is unlikely to be cost-effective to deploy and recover a large array of transponders. Ultra-short baseline systems (USBL) consist of a transceiver mounted on the AUV, which communicates with two or more transceivers on a surface vessel typically mounted on a pole or drop keel (extending below the vessels hull). The position of the AUV is estimated by acoustically derived offsets from the surface vessel's position. AUV position may be tracked throughout its mission or simply from its start and end-points. The USBL transceivers can also be used to communicate navigational updates from the surface vessel to the AUV.
- **Feature-matching using SLAM (Simultaneous Localisation And Mapping software):** Mission positioning can be achieved using environmental features as reference points (landmarks) with data collected by sonar (bottom profilers, multibeam echo sounder, sidescan sonar) or photography. SLAM can accurately geo-locate the AUV to within 1m (Barkby *et al* 2009).

C. AUV safe operating conditions and timing of survey in relation to currents, terrain, weather, season, and visibility

If the survey area is wave exposed or has strong currents, consideration should be given to whether an AUV is suitable for deployment at that location. Survey requirements should be discussed with AUV suppliers/contractors who will define clear environmental limits for operating the AUV that they supply and can advise whether sampling aims are likely to be met with the available AUV.

The ability of AUVs to collect certain data (e.g. seafloor photos) and undertake spatially accurate repeat transects may be compromised in areas of strong tidal currents and / or high turbidity, e.g. near coastal headlands and in areas of high plankton biomass. Cruising AUVs typically move at speeds of 1.5–2.0$m.s^{-1}$ and can, therefore, be influenced by tidal (or other) currents approaching or exceeding these velocities (although there are examples of AUVs working in tidal currents >2ms^{-1}; Wynn *et al*, 2014). Currents can lead to sideways movement of the AUV (crabbing) and navigational drift, which can significantly affect data quality. In a transect survey of Icelandic scallop beds, image quality was impacted by increased tidal currents which resulted in increased turbidity from sediment resuspension and an inability of the AUV to maintain correct altitude (Singh *et al* 2014).

Likely weather conditions should be considered, with surveys planned for times of the year that are likely to be less stormy. As well as preventing missions, storms with high-levels of rainfall will also reduce visibility in estuaries and near-shore environments as increased sediments are washed into rivers and wave induced sediment re-suspension increases. In UK waters, visibility is generally reduced in spring and autumn as a result of phytoplankton blooms. As a general rule, summer may be the best time for AUV missions and slack water and neap tides (to limit resuspension) the best time of day. In nearshore areas with high tidal currents, this may mean a survey window of only an hour or so. Using an AUV at slack water will also increase the chances of good visibility.

D. Vessel Considerations for AUV operations (see also Annex 1)

The following key points should be considered when selecting a suitable vessel for the survey:

- Is the vessel suitable and capable for the area of deployment?

- Is there suitable deck space for safe working and sheltered dry cabin space to accommodate the laptop or PC used to control and monitor the AUV?
- Are there appropriate means of safe launch and recovery of the AUV?
- If the AUV is deployed and recovered manually, is the freeboard suitable or is an appropriate deployment platform such as a winch available?
- Does the vessel carry sufficient safety equipment and comply with current workboat codes of practice?
- If hired, does the vessel hire cost cover insurance, fuel or other costs such as winch operator?
- Are the skipper and crew competent (trained and / or experienced) in similar operations e.g. positioning of vessel, holding course, operating winches and working close to equipment in the water?

E. Personnel Requirements

A survey manager with responsibility for the role of survey planning is required to ensure all operational stages are planned and safely executed. They should be competent (skilled and experienced) to carry out survey planning and management. The survey manager should have previous experience of seagoing surveys with similar vehicles, vessels and operations, as well as in their planning and assessment of risk. It is recommended that the survey manager / fully-briefed scientific staff are present on operations to advise and modify plans as necessary.

For larger AUVs deployed on longer expeditions, three people are likely to be required to cover different skill sets. No formal qualification scheme exists but manufacturers may provide training courses in their systems. Typically, the AUV crew will be selected based on experience and competence. AUVs comprise numerous subsystems and sensors, and consequently, technical staff skilled in supporting numerous marine instruments are preferred. Smaller AUVs are typically deployed and recovered by a team of one to two persons. It will typically be a condition of AUV rental that competent engineers / operators contracted from the company undertake and oversee the operation.

For operations on vessels of opportunity, the crew may not have prior experience of AUVs or their launch and recovery. In those circumstances, vessel crews with experience of launching and recovering equipment from the sea may be a good option (e.g. diving support operations, mooring servicing, *etc*.).

F. Risk assessments and health and safety requirements

All elements of the survey, especially for potentially hazardous operations (e.g. under sea ice, deep-water or areas of static fishing activity) should be identified and the risks assessed.

The Health and Safety Executive (HSE) provides guidance on risk assessment and templates for use. The survey manager or scientists in charge of the survey are responsible for developing a risk assessment that considers all aspects of the operation, identifying what the risks are and how they should be managed. Survey plans and operational risk assessments should address the risk from working with the AUV. Risks include:

- Risks of injury from manual handling AUVs, associated risks of working with moving heavy objects, and risks from LARS or other launch or recovery systems such as winches;
- Battery risks from lithium and other types. Batteries are potentially hazardous, especially if damaged, exposed to fire or short-circuited when they may release gases, or in extreme circumstances, cause fires or explode;
- Electrical hazards and fire risks when working on or repairing the AUV; and
- Risks from gluing and soldering, and using tools when maintaining or repairing AUV.

Health and Safety briefings should discuss measures to mitigate risks and first aiders should refresh understanding of responding to / treating electrical shock. It is good practice to have additional powder and CO_2 fire extinguishers to hand to deal with electrical related fires.

For AUV operations, the risk of loss or damage to the AUV through entanglement with fishing gear or other marine debris and collision with shipping traffic or offshore structures (Wynn *et al* 2012) should be considered. In areas with high volumes of shipping traffic, the vessel may track the AUV rather than allowing it to survey unattended to reduce risks.

Launch and recovery of AUV systems are critical points in operations where injury to crew and damage to the AUV or vessel may occur (Dowdeswell *et al* 2004; McPhail 2008). The majority of risk can be mitigated with the use of experienced crew and by adherence to standard operating protocols around safe launch / recovery conditions. Launch / recovery risks increase in poor weather with associated higher wind speeds and sea states and the likely conditions for recovery should be taken into account before going ahead with a deployment. If sea state conditions are due to worsen during a mission, the mission should be aborted and the AUV recovered before the recovery risks to personnel and equipment increase.

Operational guidelines

A. Surface preparation

Mission plans may be designed well in advance of the survey, in order to meet sampling aims but during the expedition new sampling plans may be planned shortly before deployment based on data from previous missions (Dearden & Ernits 2013) or to respond to changes in operations such as undertaking contingency work in response to poor weather conditions, changed survey priorities, instructions from the coastguard or other activities taking place such as fishing.

If a low altitude (2-3m) mission is planned for a previously un-surveyed area, an investigative initial survey of the terrain using the ships MBES or AUV at higher altitude, e.g. 100m, will allow the suitability of the area to be determined. Slope and aspect (relative to the planned AUV track) should also be considered in dive plans. In areas of steep slope, cross-shelf missions are probably best to avoid collision with the seabed and to maintain correct altitude. Acoustic surveys (MBES, SSS) of the area may also allow the detection of isolated obstacles that could risk the AUV. In areas of high-relief complex terrain, cruising AUVs may be entirely unsuitable given the risk of collision. Hover AUVs or other alternate methods could be employed, if available (see Annex 3), or the mission aborted.

The dive plan should be checked independently and preferably plotted on a chart, before being uploaded to the AUV ready for deployment. Pre-deployment checks of the AUV should be undertaken on-board. These are typically carried out by AUV engineers following a prepared checklist, that includes a visual and physical inspection and tests of vehicle and sensor responses. The time synchronisation of the various on-board systems and sensors is important, especially where data from different systems is likely to be merged at a later date. Cameras and lights will need to be calibrated (if they operate in stereo) and set to the correct position before the deployment. Once the AUV is on mission this cannot be changed (Hitchin *et al* 2015). In high risk areas vehicle checks will be more rigorous and may include mini-missions to check that the sensors and AUV are working.

B. Deployment

Large AUVs

Large AUV systems will have standard operating protocols and for most rental vehicles, a condition of hire will be the supply of engineers / operators. Particular care is required during the mechanical launch phase and immediately after the vehicle is released – to prevent collision between AUV and launch vessel. LARS enable good positive mechanical control of the launch phase. Similarly, it is good practise to ensure that the range between AUV and launch vessel opens quickly immediately on release. The launch vessel's navigating officers should be made fully aware of the AUV's likely (and possible) manoeuvres once the mission is initiated to ensure that a safe range to the AUV can be maintained before it submerges to a depth that removes any immediate collision risk.

Small AUVs
Smaller systems, such as the Teledyne *Gavia* or Kongsberg *REMUS* 100, are manually deployed by being lowered over the vessel side (if configuration and vessel freeboard allow). Other deployment solutions include using cranes, small davits or lowering the AUV in a cargo net with poles. Small AUVs may also be launched from the shore or other structures such as pontoons and jetties. The vessels and the AUVs position, relative to the vessel, need to be carefully coordinated. On deployment, the AUV will move on the surface to the designated dive position. The vessel needs to move away from this position to ensure there is no risk of collision.

C. Mission operation

The mission plan uploaded to the AUV defines what the AUV should be doing at each step in a mission to execute the planned sampling. When within range, the AUV operators can communicate acoustically with the AUV. Although transmission may be limited, they can instruct the AUV to abort the mission if necessary. Increasingly, AUVs will be able to re-plan missions during the survey, e.g. to react to unexpected conditions or to locate interesting features.

Mission operations will be vehicle specific and suppliers will have their own operating procedures. Once the AUV is in the water, a location fix will be taken at the surface and a command to initiate the mission sent to the vehicle via WiFi (for example). Other options include the use of a countdown timer to start the mission. Optional commands for the AUV include a timeout option - if the AUV does not receive a ‘GO’ command within a certain time the mission is aborted.

Further checks on WiFi and acoustic communications and tracking, such as USBL and compass calibrations in mobilisation, are likely to continue until confidence is established that the vehicle and dive plan are working. The vessel may then move out of the area to conduct other plans or track and monitor the AUV. In high risk areas, the survey manager is likely to require the vessel to track the AUV rather than move on to other operations. The AUV operators can acoustically monitor the behaviour of the AUV as it carries out the mission and, if there are problems, an abort-weight release mechanism is activated which makes the vehicle significantly more buoyant, so it returns to the surface. Some AUVs may also include a recall system where the AUV is programmed to return to recovery location if a problem arises that it cannot handle autonomously.

Designing AUV surveys
An AUV can execute a range of sampling plans, allowing great flexibility in the design of transect placements. The decision as to which transect design is most appropriate is driven by the question being addressed, as well as the environment, available time and logistics of AUV deployment and retrieval. A number of sampling design options are shown in Figure 2 (A-F). Different transect designs can be employed at different stages of a mission. For example, an AUV can conduct a broadscale survey of a wider area and then move on to conduct a more thorough survey of a smaller area of interest.

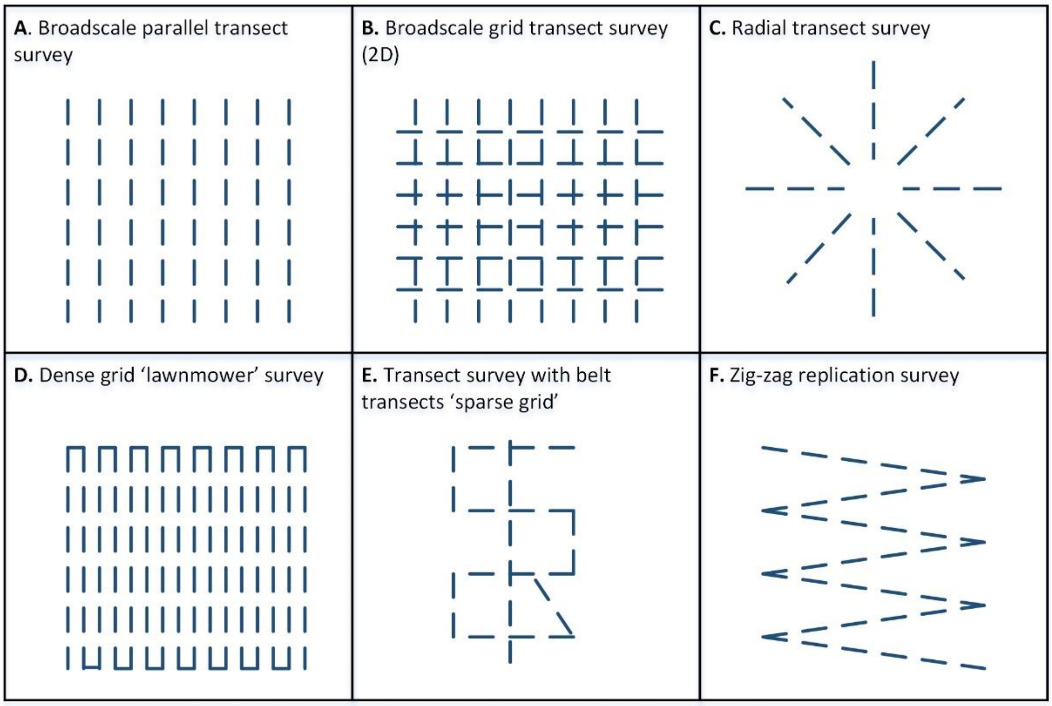

Figure 2. Survey designs A-F (from Foster *et al* 2014).

Transect design for areas with prior survey knowledge

To investigate broad community structure, community boundaries and transition zones can be identified with long transects (see Figure 2A, B and C). Transects may be randomly placed, stratified (spatially separated and randomly spaced) or systematically gridded (equi-distant transects). Although parallel transects can be used without crossover (Figure 2A), crossover transects in sparse grids support post-processing georeferencing and provide greater positional accuracy.

For some survey areas, monitoring may be concerned with variation across known environmental gradients, such as depth or substratum types. A sparse grid survey design (see Figure 2E), consists of a single long transect with shorter transects oriented perpendicular to the first. Sparse grids can be used to survey variation over a broad environmental gradient, with additional replication in bands. This design is implemented based on prior knowledge, e.g. where surveying across depth gradients or substrata gradients, with information provided by prior surveys.

Further survey designs that can be employed include zig-zag surveys (Figure 2F), circular / spiral trackways, and feature focussed designs e.g. radial surveys around a focal interest point such as a ridge or surveys that contours (Figure 2C). Contour following is useful in areas with steep slopes as AUVs may be unable to maintain altitude accurately when flying upslope (risk of collision) or downslope (altitude above seabed may increase resulting in poor image quality or unusable images).

To investigate small scale features and to conduct repeat monitoring of small areas, dense grids, or 'lawnmower' surveys (Figure 2D), can provide complete coverage of the feature, i.e. 100% cover of the seabed being surveyed. This design is most commonly used to investigate fine scale variation in habitats, such as processes driven by biological interactions, so that long-term monitoring programmes may be better established at sites of interest. The lawnmower technique can be hard to perform accurately as the tracks need to be parallel and closely spaced (Williams *et al* 2012). In areas where currents result in navigational drift this approach is unsuitable as the AUV may suffer some navigational drift and positional drift. This can result in the same areas not being resurveyed over time.

Monitoring of benthic assemblages from AUV imagery collected using dense-grid survey design

Smale *et al* (2012) used a modified SeaBED AUV to monitor hard coral and macroalgae habitats 15-40m deep at Rottnest Island and the Houtman Abrolhos Islands, Western Australia (Figure 3). Full coverage maps of nine areas 25 x 25m were produced from a dense grid (lawnmower) overlapping 25m long transects (Figure 3). Using differential GPS, USBL, and image referencing technology, the AUV was able to relocate and survey the same area of seabed the following year.

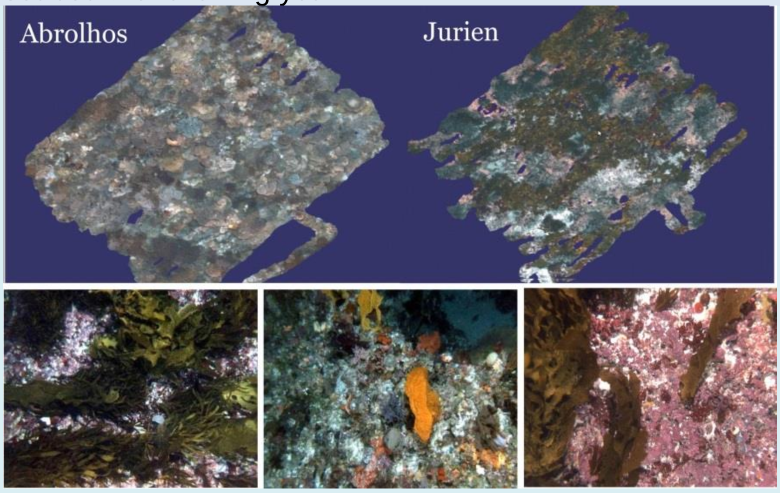

Figure 3. Representative meshes of 25 × 25m dense grids sampled at (L) Abrolhos and (R) Rottnest, showing both coral- and kelp-dominated benthic assemblages. Individual images are representative of assemblages dominated by (L-R) kelp, sessile invertebrates, and hard coral (including bleached corals).

Transect design for areas without prior survey knowledge

If there is little or no prior knowledge about the area and environmental gradients, then Foster *et al* (2012) suggest that surveys should adopt a structured, two-dimensional design that is gridded or stratified (Figure 2B) but not completely random. A one-dimensional design (e.g. Figure 2A) or a sparse grid (Figure 2E) should be avoided (Foster *et al* 2012).

The situations in which different survey designs are recommended is summarised in Figure 4.

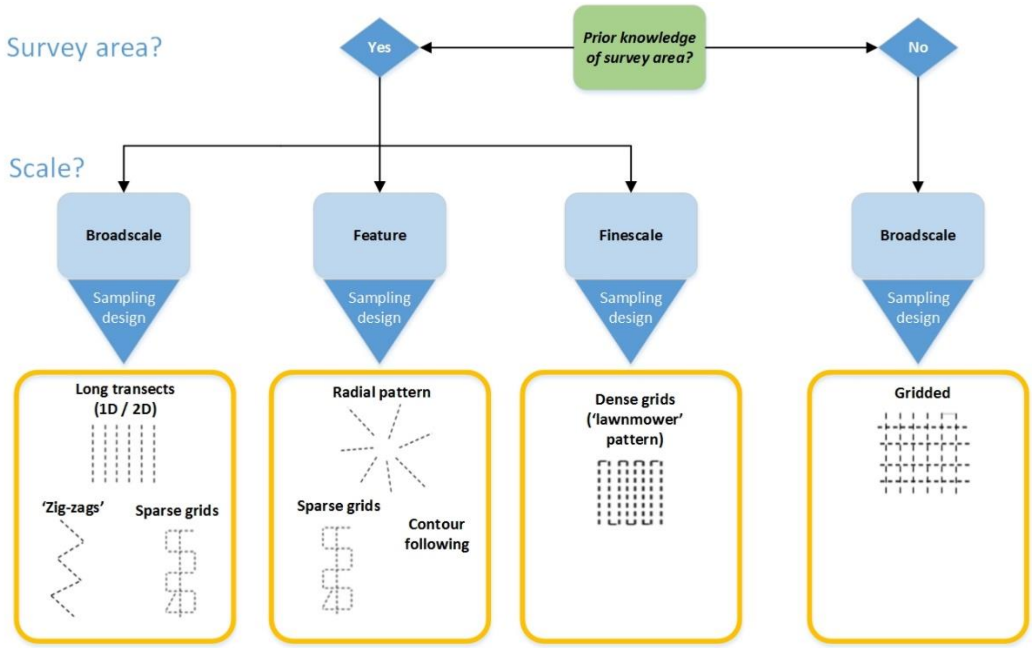

Figure 4. Decision-tree providing outline guidance on AUV sampling designs.

D. Recovery

The prevailing sea state and currents should be taken into account as this may result in the AUV not being able to go to the recovery waypoint.

It is recommended that the AUV is tracked for the last part of its survey track and as it surfaces. The position of the AUV is signalled by a number of aids that activate when it surfaces. These include radio beacons and satellite transmitter beacons, using either the ARGOS satellite constellation or Iridium beacons, that communicate via the Iridium Low Earth Orbit satellite communication system. Flashing strobe lights also aid location of a surfaced AUV. Note, in mountainous or high latitude regions the Iridium signal can be unreliable. In these instances, the vehicle location should be monitored using USBL and, at the end of the mission, by the vessel ‘standing off’ the surfacing location.

Recovery of large AUVs such as NOC Autosub6000 and Kongsberg HUGIN 3000
Large vehicles are typically recovered using ‘tag-lines’ that are stored in the body of the vehicle, that can be grappled from the surface vessel. These lines are then connected to winches on the outboard deployed LARS, hauled in to bring the vehicle tight to the LARS, and the LARS fully retracted inboard. To reduce the risk of collision, the surface vessel will typically move very slowly ahead once the AUV is connected to the LARS.

Recovery of small AUVs
Recovery of smaller AUVs will depend on the size and weight of the AUV and the vessel (if used). They can be manually hooked, grappled, or lassoed and either recovered by hand, or lifted using a crane or davit. The main survey vessel’s rescue or day-boat inflatable can be particularly useful by providing support and assistance in deployment and recovery.

E. Stowage

Following recovery, the main tasks are to conduct post-dive checks of the AUV and to identify any repairs or maintenance required. Data must be downloaded and stored appropriately. Clock drift should be checked and logged between AUV, GPS and other sensors.

The AUV logs and acoustic sensor data are downloaded from sensor hard drives via ethernet or WiFi. Download may require a few hours due to the large volume of data collected. Camera data is normally handled separately, either by a direct link to the sensor or by removing the storage device from the camera and reading it on an external computer. Data storage, back-up, file naming protocols and metadata standards (see ‘Data Management’ section for recommended standards) should have been developed at the survey planning stage and should be implemented to prevent loss or accidental over writing *etc*. When operating external to a network, it is recommended that all data be backed up on a RAID or a NAS that contain built-in storage redundancy in case of hard-drive failure. A duplicate copy of all data onto external hard drives for transportation back to host facilities is recommended (Monk *et al* 2018).

Time will also be required to recharge batteries (see ‘Survey Planning’ section in Annex 1 for indicative times). For modular systems such as the *Gavia* AUV, the battery pack can simply be replaced if spares are carried to eliminate recharging down time between missions.

Interpretation guidelines

The data extracted from an AUV depends on which sensors and equipment it was fitted with to meet the survey objectives and targets. It is beyond the scope of these guidelines to address the specific interpretation guidelines for all the data types collected by such range of sensors (Table 5). Further information is provided by the Marine Monitoring Method Finder[8], which brings together a wide range of monitoring guidelines and procedures, some of which cover aspects of data interpretation relevant to the acoustic, environmental and image data collected by AUVs.

No specific guidelines referring to data interpretation guidelines for acoustic surveys with AUVs are currently available (see 'Quality assurance measures' section for more details). However, there are some limited guidelines for interpretation of AUV imagery. The ability of cruising AUVs to fly at low altitudes (<5m) over the seabed, carrying high definition camera systems, coupled with developments in image processing, allows the generation of high volume imagery datasets that can be processed to provide continuous coverage georeferenced photographic datasets of the seabed.

The data extracted from stills imagery depends on the survey objectives and targets. Most benthic habitat surveys aim to extract biotope, taxonomic, and substratum information from the imagery and to enumerate taxa in some way (e.g. numerical density, percentage cover, frequency of occurrence), categorical scales: JNCC SACFOR (Connor & Hiscock 1996) or MSS ROCA (Allan *et al* 2012). Further imagery interpretation guidance is provided by the North East Atlantic Marine Biological Analytical Quality Control Scheme (NMBAQC; Turner *et al* 2016). See also Durden *et al* (2016b) for a review of the use of imagery in marine ecology.

For particularly large datasets, analysts may not have the time to analyse each image individually. Where complete analysis is not possible, the user must give attention to how any subset of images is selected to avoid bias – random selection within environmental stratum would generally be advisable. Similarly, where multiple users are engaged in extracting data from the images collected in a survey programme, care should be taken in how images are allocated to each user, again randomisation is likely to be essential (e.g. Durden *et al* 2016a). There has also been an increase in the development of algorithms to automatically recognise and assign categories to each image such as identifying the organisms present. Through a variety of approaches, algorithms can be trained to identify organisms of interest using manually identified specimens from previously collected images (e.g. Aguzzi *et al* 2009, 2011; Schoening *et al* 2012).

Photo-mosaicing can be a useful method of creating seabed maps. Mosaics range in size, from $1m^2$ (van Rein *et al* 2011) to $105,000m^2$ (Marcon *et al* 2013), with varying degrees of image discrimination. Large-area photo mosaicing (LAPM) tools have been developed that can create mosaics using both feature tracking and navigation data. Feature-based routines use image recognition algorithms to match and stitch the images together to build the mosaic while navigation-based routines use geo-referenced navigation data to do so (see Marcon *et al* 2013 for further information).

[8] Marine Monitoring Method Finder: http://jncc.defra.gov.uk/page-7171

Deep sea seafloor image collection, mosaicing and analysis
To investigate patterns in the spatial distribution of sessile and mobile megafauna on the Porcupine Abyssal Plain in the northeast Atlantic, the NOC Autosub6000 AUV surveyed over 165km of seabed using transects (Ruhl 2013). Both the vertical downward-facing and forward-facing (oblique-view) digital stills cameras were programmed to capture images at intervals of approximately 0.86 seconds at a target altitude of 3.2m above the seabed. Over 160,000 images of the seafloor were obtained from the vertical camera alone. The photographs recorded close to 10 species of fish, nearly 90 morphotypes of invertebrate epifauna, together with numerous types of lebenspurren (including feeding impressions, animal tracks and traces, burrows, nests, mounds holes and casts), and the occurrence of phytodetritus patches (Morris *et al* 2016). Human impacts were also observed with litter recorded in a number of images (Ruhl 2013).

Morris *et al* (2014) describe the image processing workflow, whereby images were processed to correct illumination, colour and then geo-referenced (correcting for vehicle heading, pitch, and roll). Images were then re-projected to seabed level and overlap between adjacent pairs of vertical images was removed. Cropped images were combined in groups of ten to form photomosaic 'tiles' representing 15-20m^2 of seafloor (Figure 5). Manual annotation was used to generate biological data, with individual organisms within the tiles categorised according to morphotype, they were then measured and georeferenced with information output to a database.

The AUV survey generated a near-continuous 2D visual image of the abyssal seafloor, about 1.5m wide that extends for some 160km and encompasses approximately 26ha. This work provides new insights into deep-sea diversity, habitat relationships and seafloor character at scales from centimetres to kilometres (Ruhl *et al* 2013; Morris *et al* 2014; Durden *et al* 2016c; Morris *et al* 2016). The annotations are now being used to develop computer vision tools to add efficiency to the processing of data from future missions.

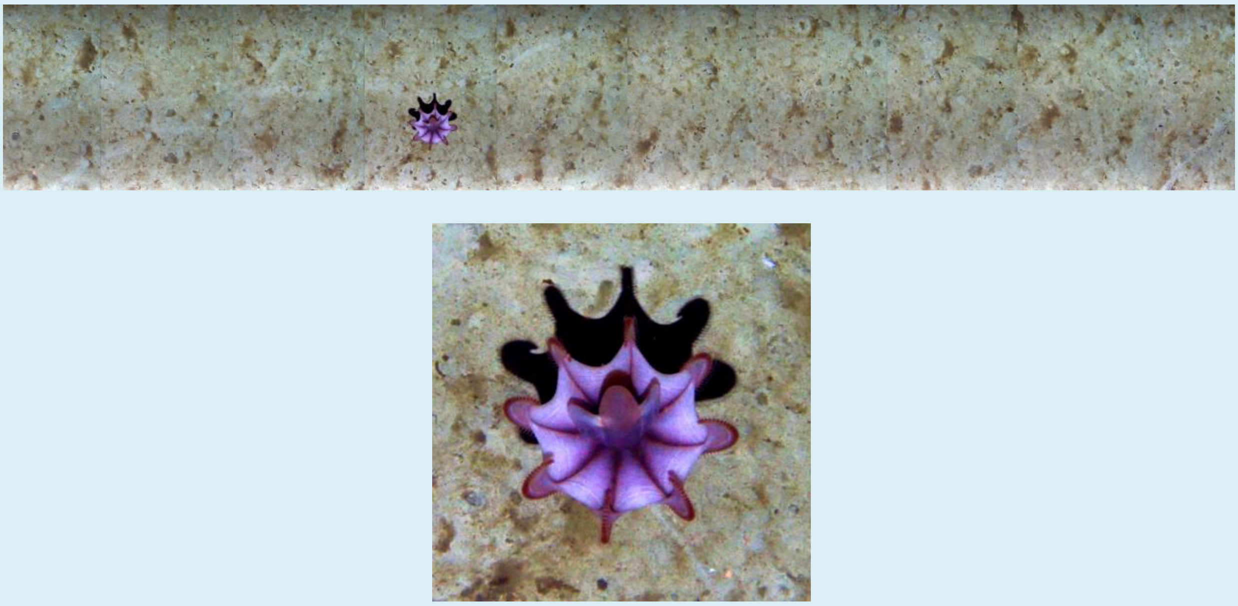

Figure 5. Example of a mosaic tile from the Porcupine Abyssal Plain, 4850m water depth, showing patchy cover of phytodetritus and a cirrate octopus (image courtesy of NOC).

Quality assurance measures

No specific quality assurance measures apply to AUV operations, although guidelines developed for specific data products, as outlined below for imagery, bathymetry and acoustic data are useful. The competence of personnel across survey planning, and the selection of the correct AUV and equipment to meet survey aims and operating conditions will increase the likelihood of acquiring high quality survey data and monitoring results.

The quality of images and interpretation will depend on a range of factors. Camera and light specifications are critical to obtaining usable images. Environmental conditions, such as turbidity or sediment resuspension will reduce visibility and factors such as speed of the AUV, positional certainty and consistency of field of view will also impact quality (Strong 2015). Best practice guidelines for interpreting still images of benthic substrata and epibenthic species have been developed and should be referred to (Turner *et al* 2016 and Hitchin *et al* 2015). These guidelines form part of the epibiota component of the NMBAQC, led by JNCC and developed on behalf of the UK competent monitoring authorities to provide assessment of marine biological data contributing to UK national or European monitoring programmes.

No specific guidelines referring to standards and quality procedures for acoustic surveys with AUVs are currently available. The GEOHAB Backscatter working group have provided recommendations on key issues, with applicable guidance on quality control for key operation stages, including equipment calibration and backscatter data processing (Lurton & Lamarche 2015). Bathymetric survey specifications, such as the International Hydrographic Organisation (IHO) S44 technical specification are available. Whilst most modern bathymetric systems used from AUV's can comply to this standard, typically it is navigational accuracy that can prove problematic for an AUV to adhere to the specifications. Course made good does not ensure optimal navigational accuracy. AUVs using inertial guidance systems can achieve excellent positional accuracy with reduced drift during mission (<1% per kilometre travelled), which is likely to improve the quality of acoustic data gathered from those AUVs.

Data products

AUV sensors and ancillary equipment collect a range of data during the mission. The different types of data products which can be collected using these sensors and equipment are outlined below in Table 5.

Table 5. Types of data collected by AUVs.

Equipment	Data collected
Still cameras, lights.	Scaled still images of epifauna and substratum type. Additional information on infauna components through Lebenspurren (life traces: tracks, burrows, *etc*.), and human impacts (litter, trawl marks).
Navigation system (GPS, USBL /SBL / LBL, compass, pressure sensor, inertial navigation unit, doppler velocity log).	Positioning / geolocation data provided by transponder beacons, GPS, and sensors providing depth, position, altitude, heading, pitch, roll, heave and velocity data.
Environmental sensors, CTD, turbidity, oxygen, magnetometers, ACDP, many other sensors exist (oil, chlorophyll, REDOX, *etc*.)	Conductivity (salinity), temperature, depth, turbidity, oxygen concentration, magnetic fields, current speed, *etc*.
Multibeam echosounder (MBES) and sidescan sonar (SSS) Sub-bottom profiler Interferometric sonar	Bathymetry and backscatter data (MBES and SSS) that discriminates between different types of sediment and reef (Hill *et al* 2014; van Rein *et al* 2009). Backscatter can distinguish small features such as tidally generated

Synthetic aperture sonar Laser line scan (LLS).	bedforms with wavelengths as low as 0.1m (Wynn *et al* 2014). Sub-bottom profiler for sub-seabed sediment geometry and acoustic characterisation (e.g. hazards such as shallow gas). LLS can produce georeferenced 3D optical maps of underwater scenes (Brigone *et al* 2011).

Data management

Post processing, biological, environmental and acoustic data records should be appropriately archived. In the UK, the Marine Environmental Data and Information Network (MEDIN) promotes sharing of and improved access to marine data. To that end, MEDIN coordinates a network of Data Archive Centres (DACs) to secure long-term management of data, improve access through a central metadata portal and provide common standards[9] (Figure 6). The MEDIN helpdesk can provide advice to data managers pre- and post-survey on metadata, as well as which DAC(s) are the most appropriate to use. The MEDIN helpdesk will also triage data to assess quality, ease of processing and ingestion. Appropriate data archived to MEDIN is shared among other relevant DACs. It is also automatically uploaded to a variety of other databases, including the European Marine Observation and Data Network (EMODNET).

Marine Recorder[10] is a UK database which supports the capture and storage of marine habitats and species data. The standard data entry forms and tools it uses originated from the JNCC Marine Nature Conservation Review (MNCR). Marine Recorder has been built to funnel records to the National Biodiversity Network (NBN Atlas). However, records are also shared with the MEDIN Data Archive for marine Species and Seabed Habitats (DASSH[11]). DASSH can receive data in Marine Recorder, MEDIN data guideline and Ocean Biogeographic Information System (OBIS-ENV) formats. If data are supplied to DASSH in one of the formats specified above, ingestion is also at zero cost to the data supplier.

MEDIN also manages and updates the United Kingdom Directory of the Marine Observing Systems (UKDMOS[12]). UKDMOS is a metadatabase of monitoring programmes and series in the UK. This national database provides a searchable tool to identify marine monitoring programmes around the UK and provides point information where sampling occurred and evaluation metadata such as the parameters measured or the frequency of measurements taken, but not the survey data itself. UKDMOS can be contacted directly[13] to obtain a standard template to add a new monitoring programme or a new series to an existing monitoring programme.

[9] MEDIN data guidelines: http://www.oceannet.org/marine_data_standards/medin_data_guidelines.html
[10] Marine Recorder: http://jncc.defra.gov.uk/page-1599
[11] Data Archive for Species and Seabed Habitats (DASSH): http://www.dassh.ac.uk/
[12] United Kingdom Directory of the Marine Observing Systems (www.ukdmos.org)
[13] UKDMOS email contact: ukdmos@bodc.ac.uk

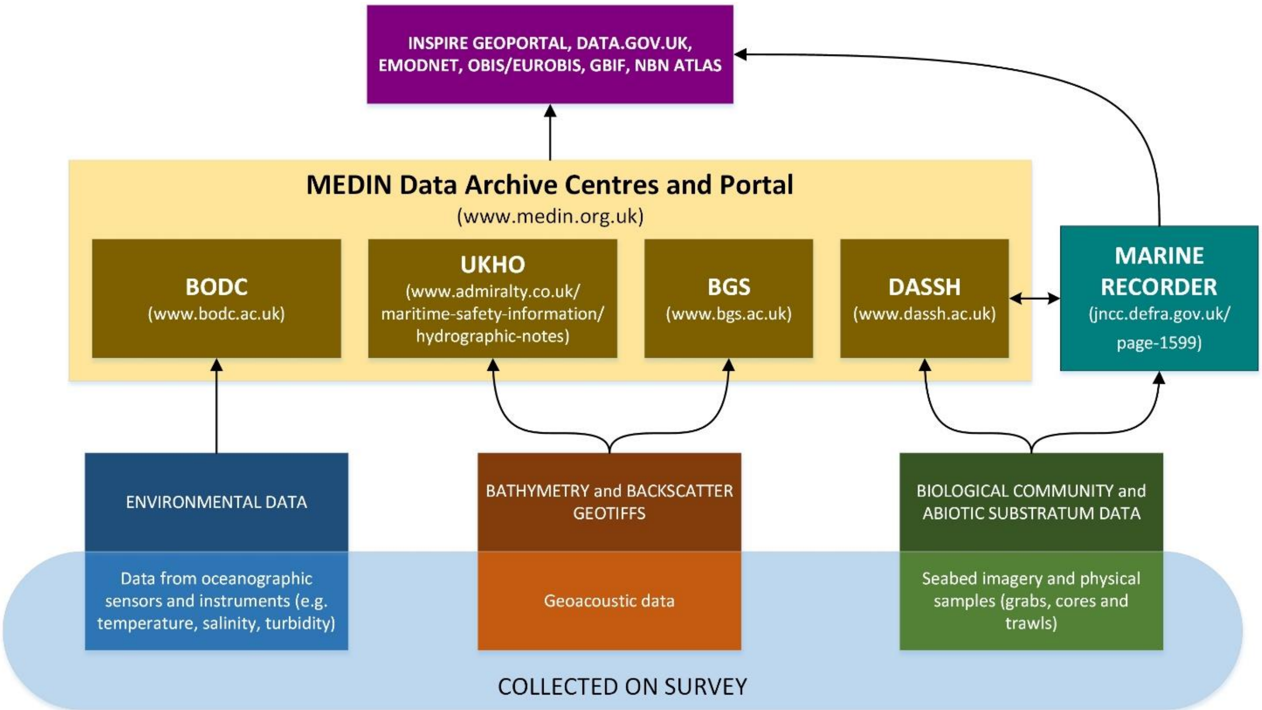

Figure 6. Diagram showing a simplified flow for marine data in the UK, from collection on survey to storage in MEDIN data archive centres, Marine Recorder and other databases as indicated.
MEDIN = Marine Environmental Data and Information Network; BODC = British Oceanographic Data Centre; UKHO = United Kingdom Hydrographic Office; BGS = British Geological Survey; DASSH = Data Archive for Species and Seabed Habitats; EMODNET = European Marine Observation and Data Network; OBIS = Ocean Biogeographic Information System; EUROBIS = European Node of the international Ocean Biogeographic Information System; GBIF = Global Biodiversity Information Facility; NBN Atlas = National Biodiversity Network Atlas.

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Annex 1. Additional survey planning considerations and health and safety

Survey planning

The level of planning required will depend on the survey requirements and complexity of the operations. When planning any survey the aim should be made clear. The survey manager should also provide a clear specification and briefing to the survey team and stakeholders, if they themselves are not accompanying the survey.

Before the survey, details of the survey objectives to be undertaken, personnel, transportation, equipment, timing, support, insurance and any special equipment handling, stowage or operational problems should be considered and resolved by the survey manager. Mobilisation and demobilisation plans should be in place.

Data collection, on-site processing, storage, and sample handling (if any) should also be resolved. This includes the datasets that will be produced, downloading and storage, and how the data will be managed and backed-up during and after the survey. AUVs can collect very large datasets for example, a one-month cruise with an NOC *Autosub* AUV could result in 20TB of data, which requires sufficient data storage and back-up storage during the survey and sufficient archive capacity afterwards. Good organisation of data, consistent methods of recording and maintenance of digital and paper logs are all good practice. All data log templates / proformas should be developed and agreed before the survey to ensure all the necessary metadata and data is being recorded on board the survey vessel. The MEDIN helpdesk (see 'Data management' in 'Data products' section) can provide advice on metadata and datalogs prior to the survey. Underway data (e.g. CTD) and survey metadata are all invaluable and should be treated in a similar manner. As a result of the volume of data collected (e.g. 1hr survey could be 5-10GB of data), download times can be lengthy (e.g. several hours for a long *Autosub6000* mission).

Time for battery charging and maintenance should also be factored into survey plans. Example battery recharge times are as follows: *Autosub6000,* 8 hours; Kongsberg *HUGIN*, 5-8 hours; Kongsberg *REMUS* 100, 6 hours, and 8 hours for the Teledyne *Gavia* AUV. Smaller modular AUVs, such as the *Gavia* have replaceable battery units (at additional cost) that can be swapped, reducing survey downtime.

Essential spares and back-up equipment

Provision of replacement parts including spare O-rings, motors, actuators, fins, panels and electronics should be considered. As a contingency for irreparable breakdown or loss of an AUV and/or to allow continuous 24-hour operations, two vehicles could be taken on the survey, if this is cost effective and deck space allows. It is also advisable to have contingency plans that do not rely on AUV operations (for example CTD deployments, multibeam survey, wire-deployed systems) to provide a back-up plan if the AUV fails or cannot be deployed due to adverse weather conditions (see Annex 3, for more information on advantages and limitations). A suitable Class II or Class III ROV may be able to aid recovery of a trapped or damaged AUV, as well as providing surveys of interesting small-scale habitat features.

Contingency (alternative) science plans

Ship and personnel costs represent a considerable investment. Ideally, contingency work should be planned in case survey and mission plans need substantial altering in response to poor weather or other issues

Planning meeting(s) prior to the survey should be held with the vessel skipper and AUV contractors (if used) to agree how operations will be conducted. The key points to be agreed are:

- Tasks and roles, including, crew requirements / expectations.
- Risk assessments, health and safety, particularly with regard to manual handling (see section on health and safety requirements, below).

- Power supply, winches, and equipment to be supplied / operated.
- Deck layout or plan agreed with all relevant parties to inform them of the equipment location and service connections to allow safe operation and stowage.
- All work required by ship's staff for mobilising / demobilising the survey.
- Vessel positioning and anchoring (shallow-water operations).
- Number of operational days required and likely operating windows with regard to weather conditions and poor weather contingencies.
- Any transect positions, geographic co-ordinates of areas and stations should be provided if required so that these can be loaded on to the ships chart plotter.
- Any additional, relevant ship operating protocols, e.g. shift work, catering *etc*.

Survey notification

Any notification or dispensation requirements (such as carrying out scientific research from a fishing vessel) to carry out the monitoring work should be acquired. The Marine Management Organisation, Maritime Coastguard Agency and Statutory Nature Conservation Bodies (Natural England, Natural Resources Wales, Scottish Natural Heritage, Department of Agriculture, Environment and Rural Affairs and the Joint Nature Conservation Committee) can provide up to date advice. For surveys within 6nm of the coast the relevant Inshore Fisheries and Conservation Authority can provide guidance on fishing activity and any relevant bye-laws. The survey manager should ensure that the Maritime and Coastguard Agency (MCA) and any relevant Port Control Authority are notified of the survey and they will in turn issue a Notice to Mariners.

Key risks associated with AUV launch and recovery are risk of injury to personnel from manual handling of small AUVs and operation of LARS and other systems. There is also a risk of fire associated with AUV battery packs.

Vessel and crew training and certification

The MCA is the main regulator of maritime safety and is responsible for the safety of everybody in a vessel in UK waters and the safety of all seafarers on UK flagged vessels. Shipboard activities should be carried out in accordance with the Merchant Shipping and Fishing Vessels (Health and Safety at Work) Regulations 1997 and also comply with the requirements of the Merchant Shipping (International Safety Management (ISM) Code) Regulations 2014. The MCA issues guidance, Code of Safe Working Practices for Merchant Seafarers (MCA 2016) as to how the statutory obligations under the Merchant Shipping Act 1 should be fulfilled. Hired equipment and vessel equipment should be compliant with the guidelines laid out in the Code and compliance documents provided.

Any vessel to be used must meet the requirements of the MCA code for the appropriate area and as such must show proof of licence and current SV1/2 Certificate. All skippers and crew should be commercially endorsed and hold appropriate experience and qualifications recognised and issued by the RYA (Royal Yachting Association) or the MCA for the task at hand. The crew should hold qualifications that include STCW Personal Survival Techniques, Personal Safety and Social Responsibilities (PSSR), First Aid at Sea, Fire prevention and Fire Fighting and be trained in the use of oxygen delivery systems and automated defibrillators.

For commercial work aboard vessels over 24m, crew should hold STCW Basic Safety Training course (STCW95 and STCW 2010) in accordance with the STCW Code A-VI/1. Crew should be trained in the use of all on-board machinery and hold a record of training recognised by the National Workboat Association (NWA). In accordance with the MCA Code of Safe Working Practices (COSWP) and the 2006 Maritime Labour Convention (MLC), a vessel should be able to provide documentation showing compliance, e.g. safe working practices, permit to work forms, crew certificates.

Scientific vessel users should be required to pre-register with the vessel manager in advance of any surveys at sea. This registration includes a medical questionnaire and the skipper will be notified of any issues arising from this.

Personal protective equipment (PPE)
Life jackets (275N) should be provided by the vessel for all survey members and the survey team should have PPE such as hard hats and steel toe-capped boots.

Communications
All personnel directly involved in the operation should be fully aware of the work being undertaken and the status of any unusual situation that may arise during operations. Safety briefings are an essential part of going to sea and all personnel should be present for these. During offshore survey cruises, morning / pre-shift briefings are held to discuss weather conditions, science goals for the day, safety and personnel matters. The AUV team is also likely to hold a 'Toolbox talk', each day to discuss plans and issues. Full handovers are essential for 24hr operations, a check list for handover will ensure all aspects are included, such as hazards in the area and equipment problems encountered during the shift

Annex 2. Survey costs and time

The overview table for this procedural guideline (Table 1) provides estimated survey day rates that include survey planning and the costs of hiring a vessel and AUV and technicians. It is intended that these costs serve as a guide only. For actual costs, a survey manager must always consult with organisations that hire AUVs or plan monitoring surveys for the most up to date information.

This annex expands on the costs estimated in Table 1 to provide additional budgeting support to survey managers. In Table 1, some staff costs for survey planning and an onboard scientist / survey manager are included in the overall estimate (as well as all equipment costs). However, post-survey data processing and reporting are not included in this estimate. Although these post-survey costs must be accounted for, it is not within the scope of this procedural guideline to estimate them. However, survey managers should be mindful of these additional costs when planning a survey and budget for them accordingly.

Equipment costs
Outline cost estimates for equipment hire (in 2018) are shown below in Table 6. These costs do not include mobilisation / demobilisation or the rates for operators.

Table 6. Summary table of estimated equipment hire costs (in 2018).

Equipment	Hire cost / day
Glider (cost related to ongoing survey of several months)	£1,000-2000
Small commercial AUV e.g. Kongsberg *MUNIN*	£7,500
Large commercial AUV e.g. Kongsberg *HUGIN*	£12-14,000
Small / moderate-sized vessel, suitable for AUV operations	£2,000-10,000
Larger research vessel shelf sea operations	£20,000-30,000
Large research vessel deep-water operations	£30,000-50,000

Personnel costs
Training and certification costs are not included in personnel costs for contracted AUV engineers / operators and taxonomic consultants (Table 7). It is assumed that services that are contracted out will include trained and certified staff and equipment to carry out the service. However, we have included costs for a scientist or survey manager from the commissioning organisation to gain a Personal Survival Techniques certificate and an ENG1 medical certificate (may be mandatory on some vessels) and the costs of basic personal protective equipment.

Day rates for taxonomic consultants vary between £200-600, depending on level of experience and seniority. The level of experience and competence rather than formal qualifications is important (although awareness of NMBAQC standards would be expected).

Staff costs are highly variable and depend on the service provided, qualifications, experience and seniority. Staff costs are, therefore, presented as a range. Due to the high variability of taxonomic consultancy work it is very difficult to provide a representative cost for this service.

Table 7. Summary table of estimated personnel costs to carry out survey and sample processing (in 2018).

Personnel	Day rates or other costs
Scientist/survey manager/data analysts/reporting staff	£225-700
Engineer/operator (supplied by contractors)	£950
Taxonomic consultants	£200-600
Personal Survival Techniques Certificate (and salary cost)	Certificate 1-3 days £100-500, salary costs to attend course £225-2100
ENG1 Medical Certificate	£80
PPE: foul weather gear, steel toe-capped boots, hard hat	£250-700 per/person

Data archiving

DACs have some funding available through MEDIN to process data and the United Kingdom Hydrographic Office (UKHO) will freely upload bathymetric data. Costs will vary for data processing and archiving. Three costings scenarios were supplied by the MEDIN Data Archiving Centre DASSH[14], based on a representative range of scenarios that they encounter (Table 8).

Table 8. Data archiving costs for three scenarios that are commonly encountered by DASSH (in 2018).

Scenario	Description	Day allocation and cost
1	DASSH is core funded by Defra to archive data in MEDIN format, so there is no charge for data archival if it is provided in this format. It is estimated that the MEDIN compliant data timeline for archiving would depend on the current workload within DASSH.	2 days of archival time, £0
2	Small to medium sized datasets (<1,000 samples) with species abundances and locations supplied in an Excel spreadsheet but not in MEDIN format.	10 days @ £340/day (Total cost £3,400)
3	Provision of a multi-disciplinary, large dataset (>1,000 samples) with species records provided as an Excel spreadsheet. Dates of samples; biotope locations provided as PDF map, i.e. no data is presented in MEDIN format and extensive processing and Quality Assurance (QA) procedures are required.	20 days @ £320/day*. (Total cost £6,400)

Cost variability

Key factors that lead to cost variation between surveys include:

- Complexity of operations, number of missions and areal coverage, distance from shore and water depth as:
    - Planning requirements will be greater due to the increased complexity, scale and risk of all survey stages when surveys are offshore in deeper water;
    - Length of survey increases vessel hire costs; *and*
    - Distance travelled by vessel will affect fuel consumption and length of hire.
- Mobilisation and travel and subsistence rates of staff will be highly variable, depending on distance travelled.
- Sample processing costs for stills are highly variable depending on data requirements, including:
    - Diversity in and between image sets both in terms of the physical environment and the number of taxa;

[14] Data Archive for Species and Seabed Habitats (DASSH): http://www.dassh.ac.uk/

- The level of taxonomic detail to be derived from the imagery and additional characteristics to be recorded, e.g. evaluation of the quality of features, evidence of damage, presence of litter *etc*;
- Level and type of breakdown of substratum composition required can be time consuming, especially for mixed sediments and variable seabed types;
- Cost of developing a reference collection of georeferenced images of both biotopes, taxa and sediment classes; *and*
- Quality control– how many samples are required to be re-analysed, both internally and externally, in line with NMBAQC best practice.

Annex 3. Alternative options for surveying / sampling

A range of platforms may be used in conjunction with AUVs as a combined nested survey approach to deliver survey aims. For example, a vessel may be used to conduct a broadscale survey with an AUV used to produce more finely resolved sidescan sonar mapping, while a ROV could be deployed to collect more finely resolved data, ground truth habitat maps derived from acoustic surveys and / or to collect physical samples in areas of interest.

Alternative options to AUVs for completing required surveying and monitoring should be considered, bearing in mind survey aims, costs and other factors. The following sections outline key advantages and limitations of other sampling platforms.

Aerial survey
In shallow water with low turbidity, satellite imagery, aerial drones (unmanned aerial vehicles) or small planes can map extents and produce good images of habitats such as seagrass and kelp (Duffy *et al* 2018) while covering wide areas. These survey options are limited to the shallowest habitats only and drones have limited payload and battery life.

SCUBA divers
At shallow, nearshore sites, the use of AUVs as an alternate survey option to SCUBA divers reduces the risks of surveying in potentially hazardous environments. Unlike divers, AUVs can conduct acoustic surveys and AUVs can conduct longer missions and multiple missions per day with a smaller survey team than diver operations require. Smale *et al* (2012), recorded the following image collection rates: divers 400 images/day, drop cameras 700 images/day and an AUV 15,000 images/day. AUVs can accurately relocate survey areas, precluding the use of tags to identify sites (Smale *et al* 2012).

However, AUV surveys are likely to be less successful than dive surveys to the point of being impossible, in instances where the target features occur in crevices or vertical surfaces or are obscured by large, complex organisms, e.g. canopy forming algae, bryozoans and encrusting organisms. In kelp beds in Tasmania, for example, belt–transect surveys by divers proved to be much better at quantifying the abundance of urchins. For kelp-dominated reef, the density of urchins detected by divers was on average 2.1 times higher than that detectable from using an AUV (Ling *et al* 2016).

Towed systems: benthic sleds, towed cameras and trawls
Unlike AUVs that can operate independently of vessels, towed systems always require dedicated ship time to complete missions. A key advantage of towed systems over AUVs is that real time data (video data, sidescan data) can be transmitted via cables, so that adjustments to mission and sampling plans can be made. Similar to AUVs, sleds and drop-down cameras can be fitted with ancillary equipment such as CTD sensors and laser scales and typically will be cheaper to hire or buy. Towed sidescan sonar systems are cheap, easy to use and can easily be deployed from vessels of opportunity. They are, however, sensitive to sea state and ship motions and have limited positional accuracy.

A key disadvantage of towed systems compared to AUVs is their lack of manoeuvrability, as there is limited control over position, altitude and speed of the camera. The tether to the vessel means that swell influences the camera position and this can lead to a large proportion of photographs being unsuitable for quantitative analysis.

Towed benthic sleds have better stability than off-bottom towed systems and the camera is kept at a constant altitude above the seabed, however, turbidity caused by sediment resuspension may result in poor quality images (Wakefield & Genin 1987). Sleds are also likely to cause damage to seabed habitats from contact with sled runners. Areas of high relief terrain will be unsuitable for both towed benthic systems and low altitude cruising-AUV survey.

Trawls are a destructive method of directly sampling benthic organisms. Spatial interpretation of trawl data is not possible at fine scales as the catch is amalgamated in the net and samples are often damaged with soft-bodied organisms in poor condition or lost (Morris *et al* 2014). Trawl samples substantially under-represent some fauna, particularly smaller size classes. A comparative assessment by Morris *et al* (2014), found that trawls underestimated megabenthos density by about an order of magnitude when compared with photographic surveys.

Remotely operated vehicles (ROVs)

A remotely operated vehicle (ROV) is an unmanned underwater vehicle that is connected to, and operated from, a surface support vessel via a tether (umbilical). As ROVs are electrically powered via the tether they are not subject to battery limitations. Compared to AUVs, ROVs have drawbacks for large-scale surveying as they are much slower and large amounts of ship time being required for their operation. A ROV conducting photographic transects can survey about 0.2ha.h^{-1} of seabed operation[15], this value will be lower when deploy / descend and ascend / recover time is included in the calculation. Note that the AUV survey rate reported by Morris *et al* (2016) of 1.2ha.h^{-1} is scaled to ship operation time not vehicle operation time, i.e. the ship was free to conduct other work. In comparable terms, the survey rate used by Morris *et al* (2016) would be about 0.5ha.h^{-1} [16].ROVs can augment AUV surveys in nested survey approaches, as they are highly manoeuvrable and stream image data to the surface in real-time which allows reactive investigative surveys of features of interest. They can also be used to collect physical samples, including organisms and sediment samples using manipulator arms. Survey planning should consider having an ROV available to recover the AUV if this becomes damaged or entangled.

Shipboard MBES

Shipboard MBES has better positioning than AUV, but the resolution that can be achieved is fully dependent on the water depth. AUVs can keep a constant altitude above the seabed, which results in a constant swath width (makes for easier survey planning) and a constant resolution.

[15] Based on a speed of 0.5 knots and an image scale of 2m.
[16] Based on vehicle speed of 1.4ms^{-1} and visual swath of 1m.

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