



**Marine
and Coastal**

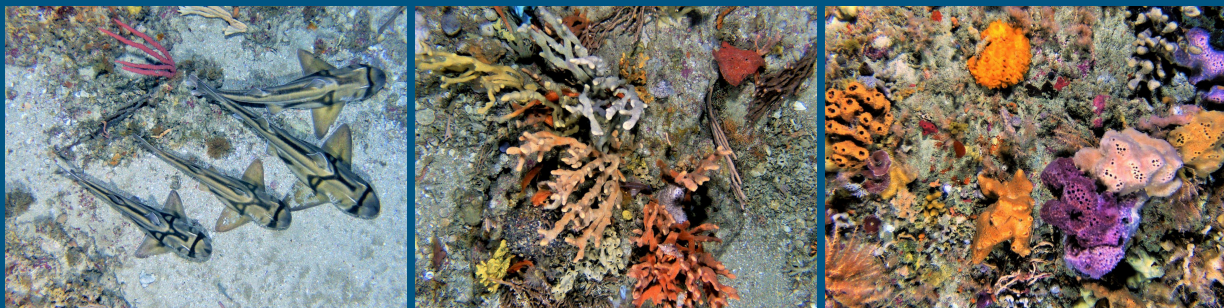
National Environmental Science Program

4. Marine Sampling Field Manual for AUVs (Autonomous Underwater Vehicles)

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Platform Description

Autonomous Underwater Vehicles (AUVs) are untethered robotic platforms that operate independently to complete pre-determined surveys. The endurance of AUVs typically range from hours to several days (Huvenne et al. 2018). However, with the rapid development of battery technology long-period deployments ranging from weeks to months are now possible (Furlong et al. 2012; Hobson et al. 2012). Maximum operational depths range from a few hundred metres for the smaller vehicles (Wynn et al. 2014) to over 6000 m for larger units (Huvenne et al. 2009).

Huvenne et al. (2018) classify AUVs as either "cruising" or "hovering" vehicles (Figure 4.1). Cruising AUVs are traditionally torpedo-shaped, driven by a single propeller at speeds up to 2 ms⁻¹, and are optimised to cover large distances along pre-designed survey tracks (Wynn et al. 2014). These cruising AUVs are usually not well suited to photographically surveying high-relief seabed terrain due their lack of vertical agility. Traditionally, cruising AUVs are the main type of AUVs used in the commercial world, with prominent scientific examples including the Autosub series from the National Oceanography Centre (UK), the AsterX and IdefiX from French Research Institute for Exploitation of the Sea (IFREMER; France) and the Dorado series from Monterey Bay Aquarium Research Institute (USA) (Furlong et al. 2012; Rigaud 2007). By contrast, hovering AUVs are equipped with several propellers, which facilitate multi-directional manoeuvrability capabilities, similar to a remotely operated vehicle (ROV). Hovering AUVs are designed for precision operations, slow motion surveys (e.g. seabed photography) and work in distinctly 3-dimensional terrains, such as around high-relief reefs (Williams et al. 2012). Among the best-known scientific examples of hovering AUVs are ABE and Sentry from Woods Hole Oceanographic Institute (USA) (e.g. Tivey et al. 1998; Wagner et al. 2013) and Sirius from Australian Centre for Field Robotics (Australia) (e.g. Bewley et al. 2015; Williams et al. 2016; Williams et al. 2012).

Depending on the size of an AUV they can be equipped with a range of sensors such as conductivity, temperature, depth, acoustic doppler current profilers, chemical sensors, photo cameras, sonars, magnetometers and gravimeters (Connelly et al. 2012; Sumner et al. 2013; Williams et al. 2010). Importantly, on-board battery capacity is the primary limitation to the number of sensors and survey duration for AUVs. Furthermore, AUVs are currently not yet equipped for extensive physical sampling of seabed or fauna, although sampling of the water column can be achieved (Pennington et al. 2016). Overall, AUVs are more suited for survey operations, acquiring sensor data along pre-programmed transects, while ROVs are optimal for high-resolution, highly detailed and interactive work, including high-definition video surveying and physical sampling. An extensive review of the use and capabilities of AUVs for geological research was recently published by Wynn et al. (2014). There is, however, no equivalent review discussing the capabilities of AUVs for ecological research (but see section 3.3 in Wynn et al. 2014; Durden et al. 2016).

This document focuses on hover class AUVs can control their position and heading at very low speeds, which makes them suitable for operations over rough terrain while maintaining an

appropriate altitude for imaging small scale targets. When equipped with navigational sensors such as GPS, Ultra Short Baseline Acoustic Positioning System (USBL), acoustic doppler profiler, and forward-looking obstacle avoidance sonar, hover class AUVs enable precise tracking along the pre-programmed routes. These characteristics make them particularly suited to collecting highly detailed sonar and optical images over high-relief seabed terrain, which can be geo-referenced with high precision. These can then be stitched together into photomosaics to focus on large features or specific details on the seafloor.

While most of the well-known AUVs used in scientific research are custom built, technological developments over the last five years have seen a number of ready-built, commercial units becoming available, with examples such as the cruising [Iver](#) and hovering [Subsea 7](#) AUVs. The release of these units into the market will likely increase the uptake of AUVs for scientific research.

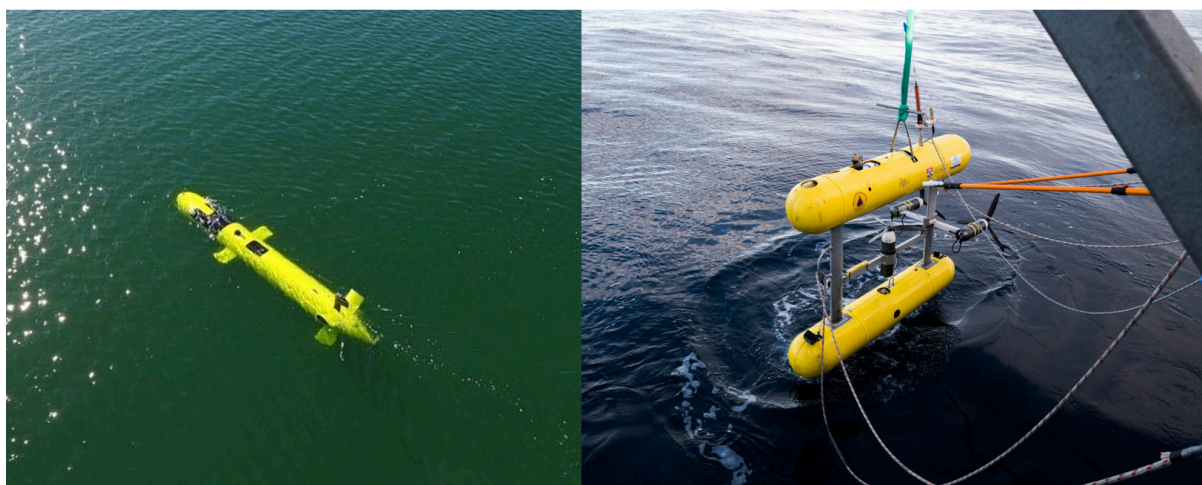


Figure 4.1: Examples of AUV classes. Left: an example of the cruising class AUV *Nupiri muka* operated by the University of Tasmania (photo credit: Damien Guihen). Right: an example of the hovering class AUV *Sirius* operated by Australian Centre for Field Robotics for Integrated Marine Observing System (Photo credit: Asher Flatt).

Scope

The primary aim of this field manual is to establish a consistent approach to marine benthic sampling using AUVs and facilitate statistically sound comparisons between studies. This manual will focus on hover class AUVs designed to survey the seabed due to their proven use in marine benthic monitoring compared to other marine imagery platforms (described in the next section of this chapter). It will not consider cruising class AUVs. The scope of the manual is to cover everything required from equipment, pre-survey preparation, field procedures and post-survey procedure for using hover class AUVs to photographically survey seabed assemblages found on Australia's continental shelf regions. Deep-sea environments are currently excluded from this field manual as we do not currently have an AUV in Australia capable of image-based surveys at these depths. Although it should be noted that AUV-based photographic surveys of the deep-sea benthos have been successfully undertaken

internationally (e.g. Morris et al. 2014; 2016; Milligan et al. 2016).

For further information on the advantages and disadvantages of AUVs compared to other benthic imagery and sampling platforms, refer to *Comparative assessment of seafloor sampling platforms* Przeslawski et al 2018).

AUVs in Marine Monitoring

Application of AUVs for monitoring benthic marine ecosystems has experienced a rapid increase over the past two decades. Researchers have used hover class AUVs in monitoring the impacts of invasive species (Ling et al. 2016; Perkins et al. 2015), for ecosystem-based fisheries management (Smale et al. 2012), assessing population trends in demersal fishes (Clarke et al. 2009; Seiler et al. 2012), mapping of benthic habitats (Lucieer et al. 2013), examining diversity in reef communities (Bridge et al. 2011; James et al. 2017; Monk et al. 2016), changes in structural complexity of coral reefs (Ferrari et al. 2016a, b), and mapping the spatial and depth extent of kelp forests (Marzinelli et al. 2015).

Compared to other marine imagery platforms (e.g. towed systems), hover class AUVs have several strengths applicable to marine monitoring:

- They navigate precisely defined flight paths and the geolocation of individual images along this path. The geolocation of imagery and flight paths allows relatively precise repeat transects to be conducted, and also for the imagery to be used to ground-truth multibeam sonar (Lucieer et al. 2013) as well as for modelling the environmental factors driving species' distributions (Hill et al. 2014).
- The time-gain it provides over an ROV. This particularly the case if the AUV system can be left alone (i.e. that are truly autonomous).
- An AUV will follow the set path, will not slow down or divert for something pretty, exciting or scary in the water: something that tends to happen to humans when piloting an ROV.
- They generate spatially accurate photomosaics and finescale digital elevation models. Multibeam data which is often available with accurate georeferencing can provide important information regarding habitat types and structural complexity but is often limited to cell resolutions of 50 cm to 5 m. Finescale digital elevation models from AUV photomosaics can be done at 1-10cm cell resolution, thus enabling extremely detailed structural information to be extracted (Ferrari et al. 2016a,b). Additionally, and perhaps more importantly, the benefits of using AUV to provide digital elevation models is that the AUVs also provide colour information (via the photomosaics), which is crucial for species identification and the evaluation condition (e.g. live vs. dead coral).

The manner that data is extracted from imagery (i.e. image annotation) is context-dependent and ranges from the simple scoring of presence-absence of indicator organisms or habitats within individual images (e.g. Perkins et al. 2016) to automated habitat classification that uses sophisticated algorithms (e.g. Friedman et al. 2011). Random point count is one of the commonly employed approaches in the quantification of the cover of benthic habitats or

organisms (e.g. James et al. 2017; Monk et al. 2016; Perkins et al. 2016). Whilst pattern recognition annotation has the potential to substantially speed up the image scoring process, it is not a point yet where it is accurate enough to replace manual point-counts. Accordingly, this manual will focus on point-count annotation approaches.

Pre-Survey Preparations

Ensure all permits, safety plans and approvals have been obtained. Any research undertaken within Australian Marine Parks (AMPs) requires a research permit issued from Parks Australia. Refer to AusSeabed's permit guide for further useful information: www.ausseabed.gov.au/resources/permit.

Define question/aim of project. This may be done in conjunction with local communities including Traditional Owners. See [Indigenous Leadership and Collaboration](#) in Chapter 1 for further details.

Confirm sampling design is statistically sound with adequate spatial coverage and replication, and addresses the initial question/aim. This is generally achieved through the use of an explicit randomization procedure to ensure that independent replicates are obtained (Foster et al. 2017; Smith et al. 2017). See Chapter 2 for further details on sampling design.

Select appropriate transect design for AUV deployment. Two AUV transect designs are recommended for marine monitoring: 1) broad grids and 2) dense grids. Foster et al. (2014) evaluated a number of broad grid designs and determined that a grid consisting of three long parallel transects, with each transect separated by ~150-200 m (each generally covering a total of 2000-4000 m) was generally the most optimal design for monitoring purposes (Figure 4.2). The dense grid transects are used to get a complete coverage photomosaic that covers a 25 x 25 m scale (Figure 4.2). Combinations of both within a survey can be applied if required (e.g. Morris et al. 2016). Essentially, broad grids cover more ground but are less repeatable, whereas dense grids are more repeatable but less general (essentially you get more information about less).

The decision 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. For example, in the deeper regions (> 100m) within the AMPs that are exposed to strong currents, dense grids are not recommended for temporal monitoring purposes because the challenges with maintaining physical position in these conditions make it difficult to successfully repeat the same 25 x 25 m grid. This ultimately results in limited temporal overlap between sampling points over time (Figure 4.3). Where inference is the primary objective of the study it is recommended that broad grids are used to increase sampling power (Chapter 2). Conversely, if the physical structure of the seafloor or biota (e.g. corals; Ferrari et al. 2016a) are the focus then dense grids are best suited.

Broad grids are generally used in mid-outer continental shelf Tasmanian waters as a result of strong currents. Conversely in Western Australia, the patchy nature of inshore reefs, coupled with a lack of shelf slope to encompass a wide depth range along broad grid designs meant that dense grids surveys undertaken within each of a replicate number of patch reef systems and depths was the most pragmatic solution. In southern Queensland, dense grids were the primary method used due to the initial process-based research focus, however, the missions are time intensive, as is post processing and analysis, and could readily be modified to a broad grid design in the future to simplify analysis. In NSW a combination of both broad and dense grids has been conducted at most sites over several time periods, although more recent surveys in the Sydney region have just used broad grids.

Stereo-cameras must be pre- or post-calibrated in shallow water using the techniques similar to those outlined in Boutros et al. (2015).

Decide on appropriate navigational systems (e.g. USBL). Accurately geo-referenced imagery is crucial to the success of any AUV deployment, and appropriate effort must be given to this during the survey planning phase.

Ensure appropriate software is installed on onboard laptops (e.g. AUV navigation software platform, GIS, etc), and potential users are familiar with it so that the AUV can be tracked and its mission success monitored while underway.

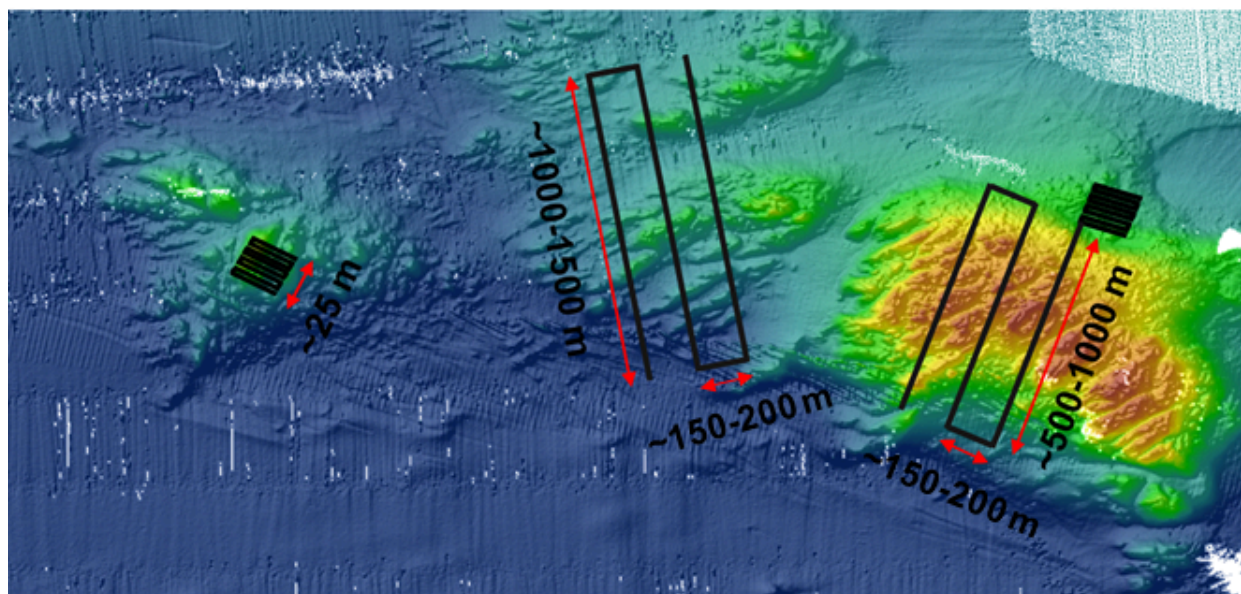


Figure 4.2: Examples of AUV transect designs over multibeam mapped reef features. Left: stand-alone 25 x 25 m dense grid transect. Middle: stand-alone broad grid. Right: combination of broad grid with a dense grid embedded. Note with this design broad grid transects are usually shorter due to the time required to complete both grid types.

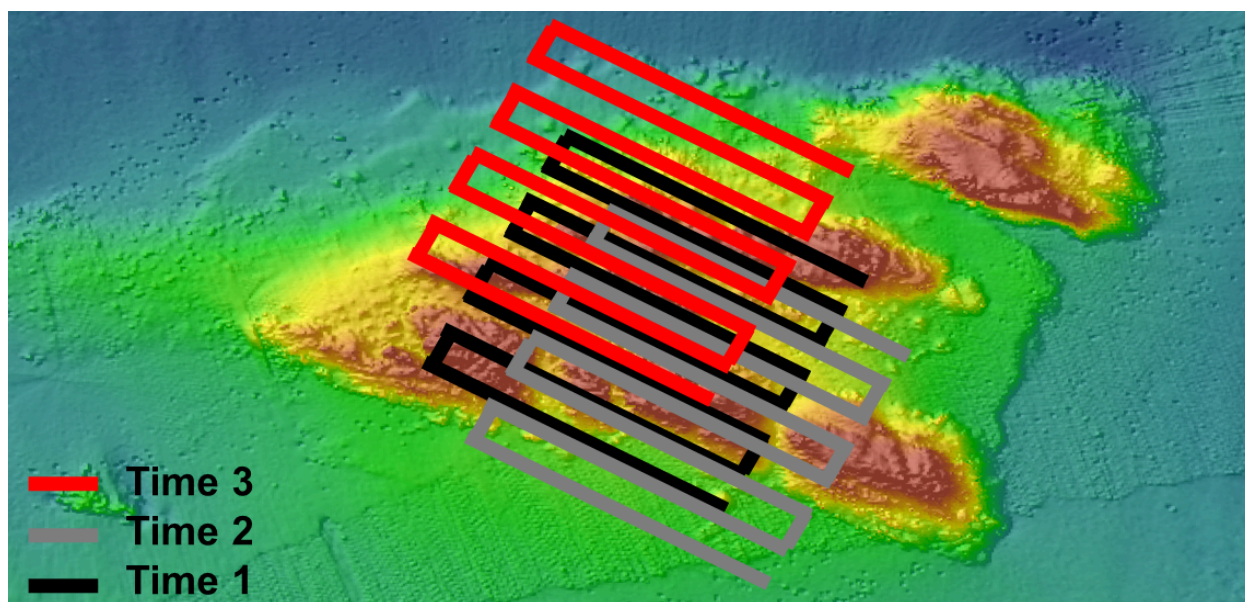


Figure 4.3: Example of spatial mismatch between sample time points for a 25x25 m grid in a high current/wave action environment. Note the limited overlap between all three sampling points.

Field Procedures

Onboard sample acquisition

Complete an on-site briefing.

Prior to deployment, a deployment briefing should always be completed to ensure the operation can be completed safely. Always take a precautionary approach to risks associated with vehicle deployment. See Chapter 1 for further information about risk assessments.

Set up and test the AUV system.

Allow sufficient time during survey mobilisation to undertake system checks, calibrations and testing of equipment and account for unforeseen problems; in most cases it will be possible to complete all system setup and tests within half a day. The conduct of pre-start checks should be noted in the trip log and any test failures specifically recorded for later-reference. Detailed settings for each component should be made using relevant operations manuals (e.g. USBL operations manual etc.).

On-deck tests should include, but not limited to, the following checks:

- on-board data storage
- on-board power
- cameras

- strobe lighting
- iridium beacon, RF and emergency strobes
- propellers
- all blanking plugs are installed
- correct and new corrodible link attached emergence ascent drop weight
- crane and associated shackles are working order
- check all seals/o-rings and blanking plugs are good working order
- check all surface communications

Wet testing should include checks of the following:

- USBL and internal navigation (e.g. compass and avoidance sonar)
- cameras and strobes
- through-water communications

Acoustic tracking setup

- Set position of GPS receiver. *Differential GPS is mandatory for repeat site monitoring.*
- Deploy USBL transceiver (e.g. pole or vessel mounted).
- Measure offsets of USBL transceiver head to GPS receiver and put offsets into navigation system.

Conduct AUV transects

Pre- deployment

- Transects should only be undertaken in areas where the substratum is known/mapped (often in the form of multibeam mapping) as to avoid entrapment and potential loss of AUV. Do not deploy blind, as this increases the risk of equipment loss and damage, as well as unnecessary impact on potentially vulnerable ecosystems.
- Once final transect locations have been determined, provide the locations of the transects (usually in ESRI shapefile format) and associated multibeam maps (in geotiff format) to the AUV engineers responsible for uploading missions. Cross-check the

uploaded transect corresponds to the correct area on the geotiff (i.e. ensure the geographic coordinates are defined for all spatial data).

- The flight elevation of AUV should be set and maintained at ~ 2m from the seafloor to facilitate a consistent field of view. General sampling methodology can be found in Williams et al. (2012). Although this needs to be informed by 'survey question', camera type and performance, illumination type and output power, etc.
- Prepare for AUV launch and recovery on deck, and ensure only essential personnel participate in its preparation and deployment.
- Place USBL transceiver in water and ensure functionality.
- Correctly insert the deployment release pin.

AUV deployment and retrieval

1. Disconnect any power or data cables, ensuring any blanking plugs are fitted prior to deployment.
2. Install sacrificial ballast weights. Ensure that there is sufficient time allocated to transect when selecting a corrodible link.
3. Vessel master must ensure the vessel is positioned at the start of the transect start location.
4. Following the signal to deploy from the vessel Master, use the crane and/or A-Frame to lift and guide the AUV from the deck into the water.
5. Minimise the time taken from when the AUV is let out of reach, to when it is lowered in the water, so as to reduce potential swing and impact against the vessel.
6. Using appropriate software (see Pre-Survey Preparations), monitor the AUVs progress to the seabed and start of transect location. Note the start time of transect using a timer as this will be used to determine when the sacrificial weight will be automatically released (if fitted) in the case of an emergency.
7. Confirm data are being recorded where possible (e.g. recording indicators, hard drive operating).
8. Ask the vessel's Master to follow the AUV during transects, to maintain USBL communication and AUV tracking.
9. Monitor weather forecast conditions prior to and during deployment to maintain a safe working environment. Consider aborting operations if local weather and forecast conditions are marginal.

10. When the transect is complete or if the transect is being aborted, advise the vessel Master of the intention to retrieve the AUV.
11. Watch for the AUV to resurface, ensuring only required personnel are near open transom. Avoid approaching the AUV looking into the sun as this increases the risks of collision.
12. Use a grapple hook to connect the lift line to the AUV for retrieval. At least three personnel should be present with hooks to avoid the AUV colliding with the vessel [Recommended].
13. Shut down the AUV and connect relevant power or data cables.
14. Remove the sacrificial ballast weights.
15. For the last transect of the day, wash down the AUV with freshwater, unplug the USBL and turn off emergency beacons.
16. Raise the USBL transducer (if pole mounted) before moving the vessel to the next location.

Procedures for seabed entanglement or loss of communications with AUV

Potential entanglement of the AUV is always a possibility. The following procedures should be followed upon entanglement:

1. Log the last known position of the AUV.
2. Send an abort code to AUV to manually end the transect.
3. If the AUV appears entangled (i.e. not moving), a mini remotely operated vehicle (ROV) should be used to locate and retrieve the unit. If the AUV is trapped under a ledge/cave, or ensnared in fishing line or kelp, the automatic release of the sacrificial weights may cause issues with recovery of the unit. Under such circumstances it is recommended that a ROV is deployed to recover the AUV.
4. If the AUV is fitted with a sacrificial dump weight, which automatically releases after a user defined period, it may surface on its own. Once it's on the surface, use the fitted iridium beacon, RF, GPS and emergency strobes to locate the unit.
5. Ensure that you check AUV thoroughly for damage before redeployment.

Completion of operations

Prior to any vessel movement or engine start-up, operators should check the following:

- All equipment is clear of the water, including the USBL transducer pole.
- AUV is shut down.
- All gear is safely stowed.
- All power and data cables are connected.
- An “All Clear to Move” command is given to vessel Master when the AUV team is satisfied it is OK for the vessel to move on.

Onboard data processing and storage

1. Once the AUV transect is complete, it is good practice to download associated raw imagery and associated positional data. Imagery and associated positional data should be checked to ensure no failures have occurred, including but not limited to the following:
 - Miss-timing between image capture and strobes (i.e. dark/black imagery)
 - Failure of one of the stereo cameras
 - Failure of positional logging
2. Name data files according to established conventions. File naming conventions are important for ensuring both efficient and effective management of field data and its integration into appropriate data management repositories. It is important to note that these conventions will differ among agencies and academic institutions.
3. Ensure accurate recording of metadata. Metadata are descriptive data sources composed of information that may be used to process the images or information therein Durden et al. (2016). While it is important to follow agency specific protocols for capturing metadata, it is also essential that metadata are sufficient enough in detail to satisfy conformance checks for subsequent data release via AODN. Minimum data for each transect should contain as follows:
 - Campaign (i.e. Survey identifier)
 - Station/event number
 - Platform

- Latitude and longitude (WGS 1984 in decimal degrees with a minimum of 6 decimal places [*Recommend*])
 - Altitude in m
 - Depth in m
 - Time and date stamp in UTC
 - AUV orientation (roll, pitch, heading) in degrees
 - Precision details (e.g. type of navigation system used and its associated errors)
 - Data provenance
4. Backup data. This is necessary to ensure all data collected in the field is safely returned and securely backed-up at host facilities, prior to quality control and public release. Onboard copies of data should be made as soon as practical following acquisition. 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*].

Post-Survey Procedures

Data processing

A general workflow for data processing methodology can be found in Williams et al. (2012). Key requirements for raw image processing and positional data are as follows:

- It is recommended that at least one of the stereo images is in colour and enhanced following similar procedures as outlined by Bryson et al. (2016).
- All stereo images should be georectified following Williams et al. (2012). If not stereo then processing routines can be found in Morris et al. (2014).
- Positional data should be post-processed using Simultaneous Localisation and Mapping (SLAM) as demonstrated in Barkby et al. (2009) and Palomer et al. (2013)

Data annotation

Scoring of individual images can be done using a number of annotation software tools. Examples include, Transect measure, Coral Point Count, CoralNet and Squidle+. For national consistency, Squidle+ (<https://squidle.org>) is recommended as it is free and allows for different approaches in image subsampling, which appears to influence inferences from data (Monk et al.

unpublished data), as well as stratified and random point count distribution on images. It also automatically imports the collected AUV data once it is uploaded to the AODN making it ready for analysis, and has tools for exploring survey data as well as analysis. In addition, it supports multiple annotation schemes, and will provide consistency through translation between schemes, which is an important point that differentiates Squidle+.

There are three approaches recommended for annotating georeferenced imagery from AUVs:

- Annotation of individual images
- Annotation of photomosaics
- Extracting structural complexity from orthomosaics

A how-to guide about setting up annotation media sets within Squidle+ is provided at <https://squidle.org/wiki>. Annotation of individual images or photomosaics can be undertaken using three methods:

- Full assemblage scoring of imagery across space and time. It is important to note that this is a time-consuming process, requiring a lot of replicate images to be scored to enable sufficient power to detect biologically meaningful change as most morphospecies are < 10 % cover within images. This approach appears to be good for delineating bioregional and cross-shelf patterns at a morphospecies (Monk, et al. unpublished data) and CATAMI (Althaus et al. 2015) level (James et al. 2017; Monk et al. 2016). This approach will no doubt be effective in choosing an initial suite of indicators for national level monitoring and reporting.

As a general guideline, and dependent on the survey question, we recommend that 25 random points per image from at least 50 images per transect leg are a good starting point for recording most morphospecies present within images (based on Perkins et al. 2016). It is important to note that the properties of the organisms themselves will also influence the number of points/images to score. Obviously, morphospecies that are less abundant require more effort, but also the 'clumpiness' of species will affect the scoring effort needed (Perkins et al. 2016). Van Rein et al. (2011) and Perkins et al. (2016) suggest that, while a higher number of points per image can increase the detection rate of more organisms within an image, increasing the number of scored images using fewer points is likely to have a similar (or greater) effect. Ideally, increasing both the number of images scored and the number of points scored within an image would result in greater power (Roelfsema et al. 2006), but preference is usually for increasing the number of images (Perkins et al. 2016). Unfortunately, the adoption of this approach is likely to result in substantial increases in processing time and thus cost.

- Targeted scoring of indicators or proxies (such as grouping fine level morphospecies into broader level CATAMI classes; Monk et al. unpublished data). This approach has been shown to work very well at an indicator morphospecies level for detecting change at a regional level (Perkins et al. 2017) as well as for detecting invasive species trends (Ling

et al. 2016; Perkins et al. 2015). More recently this approach has been extended to mobile species, such as fish (Seiler et al. 2012) and lobster (Bessell et al. unpublished data). Care needs to be taken if length data (using photogrammetry or structure from motion) is extracted from stereo pairs from Sirius data as both Seiler et al. (2012) and Bessell et al. (unpublished data) found precision can be poor for mobile species if camera separation is inadequate (see Boutros et al. 2015)

Since this approach requires substantially less effort to score each image, more images (i.e. often all images) can be scored and, thus, increased statistical power. The drawback is that narrower understanding of the environment is produced.

- Automated analysis of imagery potentially provides a cost-effective alternative to annotating imagery from AUVs. It is important to note that automated imagery analysis is a relatively new, and largely developmental, way of annotating images. Despite this some studies suggest that coral and macroalgae can be reliably identified using automated image analysis (Table 7). In 2023, Squidle+ implemented automated annotation tools for the detection of urchins and the classification of *Ecklonia radiata*, canopy-forming macroalgae, mud/sand, hard-coral, seagrass and sponges.

The last approach to annotating AUV imagery involves extracting 3D structural information from stereo images using structure from motion techniques outlined in Ferrari et al. (2016) and Pizarro et al. (2017). This approach works particularly well too for sessile species to track changes in growth form through time at a 25 x 25 m scale (Ferrari et al. 2016).

Table 4.1: A brief summary of methods for automated benthic image classification. The number of classes and the main taxa included in the respective studies are also shown.

Authors	Classes	Main Species
Marcos et al. (2005)	3	Corals
Stokes & Deane (2009)	18	Corals, Macroalgae
Pizarro et al. (2008)	8	Corals, Macroalgae
Beijbom et al. (2012)	9	Corals, Macroalgae
Denuelle & Dunbabin (2010)	2	Kelp
Bewley et al. (2012)	19	Corals, Algae and Kelp
Bewley et al. (2014)	19	Corals, Algae and Kelp
Beijbom et al. (2016)	10	Corals, Macroalgae
Mahmood et al. (2016a)	9	Corals, Macroalgae

Mahmood et al. (2016b)	2	Corals, Macroalgae
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Data curation and quality control

A national AUV steering group has been set up to oversee a nationally coordinated AUV benthic monitoring program which is supported by the Integrated Marine Observing System (IMOS) (Table 4.2). Any new AUV deployments should be discussed with this steering group to ensure that, wherever possible, they can be integrated within the national program [*Recommended*].

Table 4.2: Key contacts in national AUV steering group as of Jan 2018

Name	State	Organisation
Neville Barrett*	Tasmania	IMAS
Craig Johnson	Tasmania	IMAS
Jacquomo Monk	Tasmania/Victoria	IMAS
Peter Steinberg	New South Wales	SIMS
Alan Jordan	New South Wales	NSW DPI
Stefan Williams	New South Wales	USyd
Gary Kendrick	Western Australia	UWA
Russ Babcock	Western Australia	CSIRO
Paul Van Ruth	South Australia	SARDI
Hugh Sweatman	Queensland	AIMS
Tom Bridge	Queensland	JCU/QLD Museum
Daniel Ierodiaconou	Victoria	Deakin

* Chair

Data quality control at both the collection and annotation stage is critical. Most importantly, the annotation schema needs to be consistent between studies. Squidle+ has a built-in QAQC interface to ensure the consistency of annotations with exemplars managed by schema custodians. Morphospecies and associated CATAMI parent classes be used [*Recommended*]. An initial morphospecies catalogue for southeastern shelf waters is currently held and maintained at the Institute for Marine and Antarctic Studies (IMAS) (contact Dr Neville Barrett or Dr Jacquomo Monk).

Other annotation schemas are available, and can be applied. In such situations where an alternative schema are used to annotate AUV imagery, it must be able to be mapped to CATAMI so that comparisons can be made with previous studies or between regions. Translations between schema can be readily applied within Squidle+.

The quality control of all annotations undertaken by novice scores should be assessed against an experienced analyst (e.g. using confusion matrices; Figure 4.4). Logically, it is important to correct any discrepancies between annotators. This can be done by re-examining the images to ensure an agreement can be reached between annotators. Alternatively, if an agreement cannot be reached, then the miss-classified morphospecies could be potentially grouped into a higher level CATAMI class.

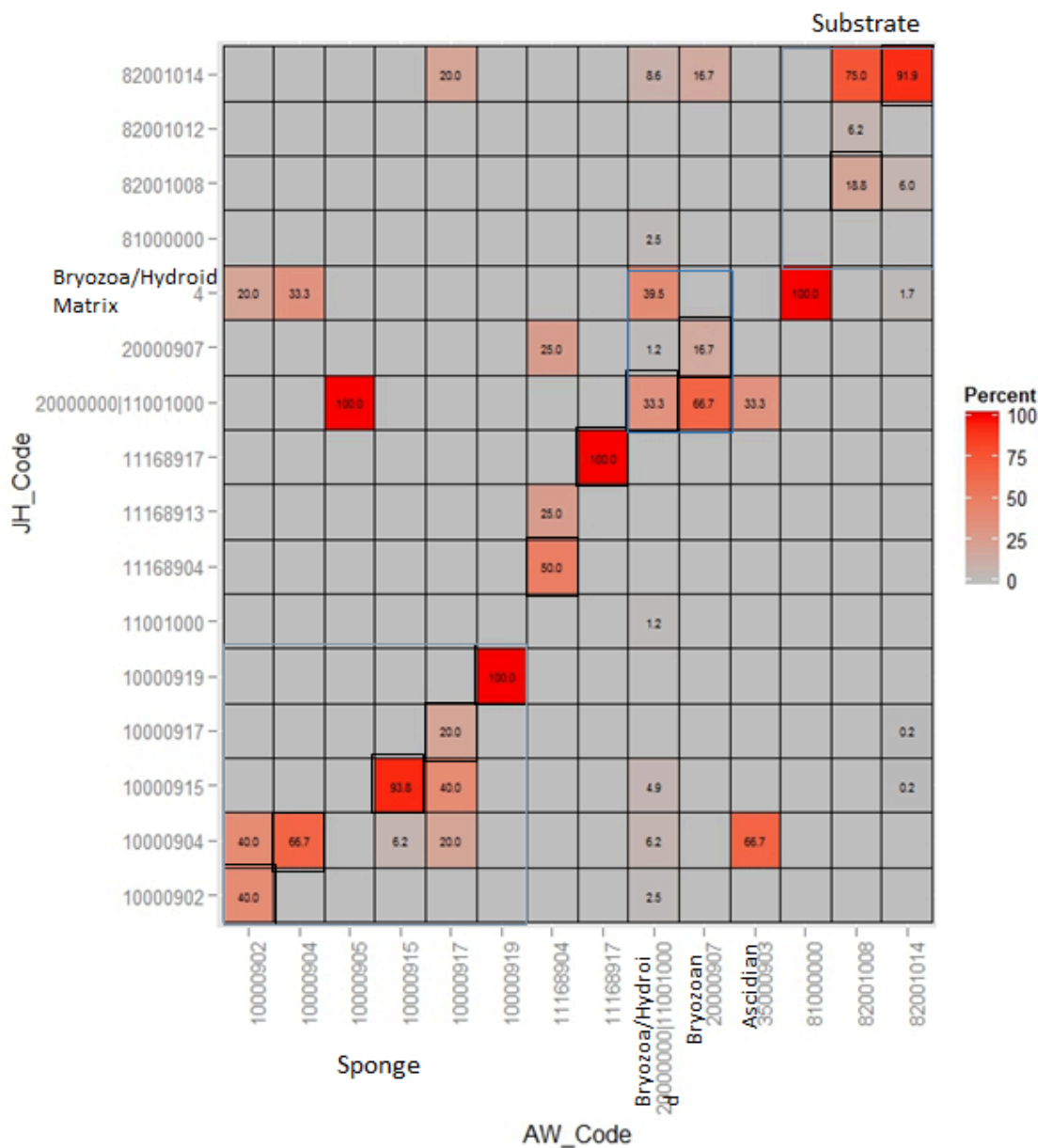


Figure 4.4: Confusion matrix showing the CATAMI classes scored by novice 1 (AW) and experienced (JH) for 30 co-scored images. Black outlined boxes indicate consistent classification between scorers, the percent of all points scored as any particular class are shown in each box and colour-coded. Blue outlined boxes indicate sponge, bryozoan/hydroid and substratum respectively moving from left to right across the image.

Data release

[Squidle+](#) is a centralised online platform for standardised analysis and annotation of georeferenced imagery and video. Many national marine observing programs (for example

IMOS through the Australian Ocean Data Network (AODN) or the Marine Geoscience Data System (MGDS) in the USA) routinely store imagery data online in an openly accessible location. Squidle+ operates based on flexible distributed data storage facilities (i.e. imagery can be stored anywhere in an openly accessible online location) to reduce data duplication and inconsistencies, and provides a flexible annotation system with the capability to translate between different annotation schemes.

Following the steps listed below will ensure the timely release of imagery and associated annotation data in a standardised, highly discoverable format.

1. Create a metadata record describing the data collection. Provide as much detail as possible on the deployment (either directly in the metadata record itself, or in the form of attached field sheets as .csv, .txt or similar). Details of minimum metadata requirements are provided in Onboard Data Processing and Storage section above.
2. Publish metadata record(s) to the [Australian Ocean Data Network \(AODN\) catalogue](#) as soon as possible after metadata has been QC-d. This can be done in one of two ways:
 - If metadata from your agency is regularly harvested by the AODN, follow agency-specific protocols for metadata and data release.
 - Otherwise, metadata records can be created and submitted via the [AODN Data Submission Tool](#). Note that user registration is required, but this is free and immediate.

Lodging metadata with AODN in advance of annotation data being available is an important step in documenting the methods and location of acquired imagery and enhancing future discoverability of the data.

3. Upload raw imagery from the survey to a secure, publicly accessible online repository ([contact AODN](#) if you require assistance in locating a suitable repository).
4. Create a Squidle+ campaign as soon as possible after imagery is uploaded, choose the most appropriate annotation schema, and commence annotation of imagery.
5. Add links to the location of the Squidle+ campaign to the previously published metadata record. You may also wish to attach or link a copy of the annotation data directly to the record.
6. Produce a technical or post-survey report documenting the purpose of the survey, sampling design, sampling locations, sampling equipment specifications, annotation schema (e.g. morphospecies, CATAMI, etc.), whether the survey was assemblage-based or targeted towards key (morpho)species, number of points, interval between images (e.g. every 50th image), and any challenges or limitations encountered. Provide links to this report in all associated metadata. See Appendix C for a suitable template [*Recommended*].

Data analysis

The breadth of research questions precludes any detailed advice on the analysis of data from AUV transects. However, one common attribute of the image-based data that will have to be contented with for all analyses is spatial proximity. The closeness of images, within and sometimes between transects, means that image data are unlikely to be independent (due to spatial autocorrelation). Yet, this is an assumption that many statistical methods rely upon. The failure to meet this assumption means that the inferences from the statistical analysis may be: (i) over-confident, e.g. having a p-value that is too small; (ii) biased, i.e. the estimates do not reflect the truth; (iii) both, or; (iv) no effect. Obviously, the fourth category is what a researcher hopes for, but it is improbable and must be validated. However, if it is known that the study organism exhibits particularly low autocorrelation then the analysis need not consider it explicitly.

Methods to analyse data, accounting for autocorrelation are available. These include geostatistical models (see Foster et al. 2014 for AUV-based examples). However, in certain situations subsampling images will help (see Mitchell et al. 2017 for a marine based example), but not necessarily alleviate completely. Further, if the study is for a broad area, where transects are small and are well-separated, then amalgamating data to transect level may also be appropriate.

Field Manual Maintenance

In accordance with the universal field manual maintenance protocol described in [Chapter 1](#) of the Field Manual package, this manual was updated in 2024. Updates reflect user feedback and new developments. There is currently no long-term plan or support for future updates. See Chapter 1 (Introduction to field manual package) for further details.

The version control for Chapter 4 (field manual for AUVs) as part of the whole field manual package is below:

Version Number	Description	Date
0	Submitted for review (NESP Marine Hub, GA, external reviewers as listed Appendix A.	22 Dec 2017
1	Publicly released on www.nespmarine.edu	28 Feb 2018
1.1	Link to Squidle+ corrected	March 2018
2	Relevant updates, including Data Release sections based on NESP, AODN, IMOS, GA, and CSIRO projects	Mid 2019
3	Minor updates	March 2024

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References

- Althaus, F., Hill, N., Ferrari, R., Edwards, L., Przeslawski, R., Schönberg, C.H., Stuart-Smith, R., Barrett, N., Edgar, G., and Colquhoun, J. 2015. A standardised vocabulary for identifying benthic biota and substrata from underwater imagery: the CATAMI classification scheme. *PLoS ONE* 10:e0141039.
- Barkby, S., Williams, S.B., Pizarro, O., Jakuba, M., 2009. An Efficient Approach to Bathymetric SLAM. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 219-224.
- Beijbom, O., Edmunds, P.J., Kline, D., Mitchell, B.G., Kriegman, D. 2012. Automated Annotation of Coral Reef Survey Images. *IEEE Conference on Computer Vision and Pattern Recognition*, 1170–77.
- Beijbom, O., Treibitz, T., Kline, D.I., Eyal, G., Khen, A., Neal, B., Loya, Y., Mitchell, B.G., Kriegman D. 2016. Improving Automated Annotation of Benthic Survey Images Using Wide-Band Fluorescence. *Scientific Reports* 6: 23166.
- Bewley, M.S., Douillard, B., Nourani-Vatani, N., Friedman, A., Pizarro, O., Williams, S.B. 2012. Automated Species Detection: An Experimental Approach to Kelp Detection from Sea-floor AUV Images. <http://www.araa.asn.au/acra/acra2012/papers/pap140.pdf>.
- Bewley, M.S. Nourani-Vatani, N., Rao, D., Douillard, B., Pizarro, O., Williams, S.B. 2015. Hierarchical Classification in AUV Imagery. L. Mejias, P. Corke, and J. Roberts (eds.), *Field and Service Robotics*, Springer Tracts in Advanced Robotics 105
- Bewley, M., Friedman, A., Ferrari, R., Hill, N., Hovey, R., Barrett, N., Marzinelli, E.M., Pizarro, O., Figueira, W., Meyer, L., Babcock, R., Bellchambers, L., Byrne, M., Williams, S.B., 2015. Australian sea-floor survey data, with images and expert annotations. *Scientific Data* 2, 150057.
- Boutros, N., Shortis, M.R., Harvey, E.S., 2015. A comparison of calibration methods and system configurations of underwater stereo-video systems for applications in marine ecology. *Limnology and Oceanography Methods* 13, 224-236.
- Bridge, T.C.L., Done, T.J., Friedman, A., Beaman, R.J., Williams, S.B., Pizarro, O., Webster, J.M., 2011. Variability in mesophotic coral reef communities along the Great Barrier Reef, Australia. *Marine Ecology Progress Series* 428, 63-75.
- Bryson, M., Johnson-Roberson, M., Pizarro, O., Williams, S.B., 2016. True Color Correction of Autonomous Underwater Vehicle Imagery. *Journal of Field Robotics* 33, 853-874.
- Clarke, M.E., Tolimieri, N., Singh, H., 2009. Using the Seabed AUV to Assess Populations of Groundfish in Untrawlable Areas, in: Beamish, R.J., Rothschild, B.J. (Eds.), *The Future of Fisheries Science in North America*. Springer Netherlands, Dordrecht, pp. 357-372.
- Connelly, D.P., Copley, J.T., Murton, B.J., Stansfield, K., Tyler, P.A., German, C.R., Van Dover, C.L., Amon, D., Furlong, M., Grindlay, N., Hayman, N., Huhnerbach, V., Judge, M., Le Bas, T., McPhail, S., Meier, A., Nakamura, K., Nye, V., Pebody, M., Pedersen, R.B., Plouviez, S., Sands, C., Searle, R.C., Stevenson, P., Taws, S., Wilcox, S., 2012. Hydrothermal vent fields and chemosynthetic biota on the world's deepest seafloor spreading centre. *Nature Communications* 3.
- Denuelle, A., Dunbabin, M. 2010. Kelp detection in highly dynamic environments using texture recognition. *The Australasian Conference on Robotics & Automation*.
- Durden, J. M., Schoening, T., Althaus, F., Friedman, A., Garcia, R., Glover, A.G., Greinert, J., Stout, N. J., Jones, D.O.B., Jordt, A., Kaeli, J.W., Koser, K., Kuhnz, L.A., Lindsay, D., Morris, K.J., Nattkemper, T.W., Osterloff, J., Ruhl, H.A., Singh, H., Tran M., Bett, B.J., 2016. Perspectives in visual imaging for marine biology and ecology: from acquisition to understanding. *Oceanography and Marine Biology: An Annual Review* 54, 1-72.
- Ferrari, R., Bryson, M., Bridge, T., Hustache, J., Williams, S.B., Byrne, M., Figueira, W., 2016a. Quantifying the response of structural complexity and community composition to environmental change in marine communities. *Global Change Biology* 22, 1965-1975.
- Ferrari, R., McKinnon, D., He, H., Smith, R.N., Corke, P., González-Rivero, M., Mumby, P.J., Upcroft, B., 2016b. Quantifying Multiscale Habitat Structural Complexity: A Cost-Effective Framework for Underwater 3D Modelling. *Remote Sensing* 8, 113.

- Foster, S.D., Hosack, G.R., Hill, N.A., Barrett, N.S., Lucieer, V.L., 2014. Choosing between strategies for designing surveys: autonomous underwater vehicles. *Methods Ecology and Evolution* 5, 287-297.
- Foster, S.D., Hosack, G.R., Lawrence, E., Przeslawski, R., Hedge, P., Caley, M.J., Barrett, N.S., Williams, A., Li, J., Lynch, T., Dambacher, J.M., Sweatman, H.P.A., Hayes, K.R., 2017. Spatially balanced designs that incorporate legacy sites. *Methods in Ecology and Evolution*, 8, 1433-1442.
- Friedman, A., Steinberg, D., Pizarro, O., Williams, S.B., 2011. Active Learning Using a Variational Dirichlet Process Model for Pre-Clustering and Classification of Underwater Stereo Imagery. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1533–1539.
- Furlong, M.E., Paxton, D., Stevenson, P., Pebody, M., McPhail, S.D., Perrett, J., 2012. Autosub Long Range: A Long Range Deep Diving AUV for Ocean Monitoring. *IEEE/OES Autonomous Underwater Vehicles (AUV)*, 1-7.
- Hill, N.A., Lucieer, V., Barrett, N.S., Anderson, T.J., Williams, S.B., 2014. Filling the gaps: Predicting the distribution of temperate reef biota using high resolution biological and acoustic data. *Estuarine and Coastal Shelf Science* 147, 137-147.
- Hobson, B.W., Bellingham, J.G., Kieft, B., McEwen, R., Godin, M., Zhang, Y., 2012. Tethys-class long range AUVs - extending the endurance of propeller-driven cruising AUVs from days to weeks. *IEEE/OES Autonomous Underwater Vehicles (AUV)* 1-8.
- Huvenne, V.A.I., McPhail, S.D., Wynn, R.B., Furlong, M., Stevenson, P., 2009. Mapping Giant Scours in the Deep Ocean. *Eos, Transactions American Geophysical Union* 90, 274-275.
- Huvenne, V.A.I., Robert, K., Marsh, L., Lo Iacono, C., Le Bas, T., Wynn, R.B., 2018. "ROVs and AUVs." In *Submarine Geomorphology*, edited by A. Micallef, S. Krastel, and A. Savini, 572. Springer Geology. Cham, Switzerland: Springer.
- James, L.C., Marzloff, M.P., Barrett, N., Friedman, A., Johnson, C.R., 2017. Changes in deep reef benthic community composition across a latitudinal and environmental gradient in temperate Eastern Australia. *Marine Ecology Progress Series* 565, 35-52.
- Ling, S.D., Mahon, I., Marzloff, M.P., Pizarro, O., Johnson, C.R., Williams, S.B., 2016. Stereo-imaging AUV detects trends in sea urchin abundance on deep overgrazed reefs. *Limnology and Oceanography Methods* 14, 293-304.
- Lucieer, V., Hill, N.A., Barrett, N.S., Nichol, S., 2013. Do marine substrates 'look' and 'sound' the same? Supervised classification of multibeam acoustic data using autonomous underwater vehicle images. *Estuarine and Coastal Shelf Science* 117, 94-106.
- Mahmood, A., Bennamoun, M., An, S., Sohel, F., Boussaid, F., Hovey, R., Kendrick, G., Fisher, R 2016. Automatic annotation of coral reefs using deep learning, *IEEE OCEANS Monterey*, 1–5.
- Mahmood, A., Bennamoun, M., An, S., Sohel, F. 2016. Resfeats: Residual network based features for image classification, *arXiv preprint arXiv:1611.06656*.
- Marcos, M.S.A., Soriano, M., Saloma, C. 2005. Classification of Coral Reef Images from Underwater Video Using Neural Networks. *Optics Express* 13: 8766–71.
- Marzinelli, E.M., Williams, S.B., Babcock, R.C., Barrett, N.S., Johnson, C.R., Jordan, A., Kendrick, G.A., Pizarro, O.R., Smale, D.A., Steinberg, P.D., 2015. Large-scale geographic variation in distribution and abundance of Australian deep-water kelp forests. *PLoS One* 10, e0118390.
- Milligan, R., K. Morris, B. Bett, J. Durden, D. Jones, K. Robert, H. Ruhl & D. Bailey, 2016. High resolution study of the spatial distributions of abyssal fishes by autonomous underwater vehicle. *Scientific Reports* 6:26095 doi:10.1038/srep26095.
- Mitchell, P.J., Monk, J., Laurenson, L. 2017. Sensitivity of Fine-Scale Species Distribution Models to Locational Uncertainty in Occurrence Data across Multiple Sample Sizes. *Methods in Ecology and Evolution*. 8:12-21.
- Monk, J., Barrett, N.S., Hill, N.A., Lucieer, V.L., Nichol, S.L., Siwabessy, P.J.W., Williams, S.B., 2016. Outcropping reef ledges drive patterns of epibenthic assemblage diversity on cross-shelf habitats. *Biodiversity and Conservation* 25, 485-502.
- Morris, K., B. Bett, J. Durden, V. Huvenne, R. Milligan, D. Jones, S. McPhail, K. Robert, D. Bailey & H. Ruhl, 2014. A new method for ecological surveying of the abyss using autonomous underwater vehicle photography. *Limnology and Oceanography: Methods* 12:795-809.
- Morris, K., B. Bett, J. Durden, N. Benoist, V. Huvenne, D. Jones, K. Robert, M. Ichino, G. Wolff & H. Ruhl, 2016. Landscape-scale spatial heterogeneity in phytodetrital cover and megafauna biomass in the abyss links to modest topographic variation. *Scientific Reports* 6:34080 doi:doi:10.1038/srep34080.
- Palomer, A., Ridao, P., Ribas, D., Mallios, A., Vallicrosa, G., 2013. A Comparison of G2o Graph SLAM and EKF Pose Based SLAM with Bathymetry Grids. *IFAC Proceedings Volumes* 46, 286-291.
- Pennington, J.T., Blum, M., Chavez, F.P., 2016. Seawater sampling by an autonomous underwater vehicle: "Gulper" sample validation for nitrate, chlorophyll, phytoplankton, and primary production. *Limnology and*

- Oceanography: Methods 14, 14-23.
- Perkins, N.R., Foster, S.D., Hill, N.A., Barrett, N.S., 2016. Image subsampling and point scoring approaches for large-scale marine benthic monitoring programs. *Estuarine and Coastal Shelf Science* 76, 36-46.
- Perkins, N.R., Foster, S.D., Hill, N.A., Marzloff, M.P., Barrett, N.S., 2017. Temporal and spatial variability in the cover of deep reef species: Implications for monitoring. *Ecological Indicators* 77, 337-347.
- Perkins, N.R., Hill, N.A., Foster, S.D., Barrett, N.S., 2015. Altered niche of an ecologically significant urchin species, *Centrostephanus rodgersii*, in its extended range revealed using an Autonomous Underwater Vehicle. *Estuarine and Coastal Shelf Science* 155, 56-65.
- Pizarro, O., Rigby, P., Johnson-Roberson, M., Williams, S.B., Colquhoun, J. 2008. Towards image-based marine habitat classification. *IEEE explore OCEANS* 1-7.
- Pizarro, O., Friedman, A., Bryson, M., Williams, S.B., Madin, J., 2017. A simple, fast, and repeatable survey method for underwater visual 3D benthic mapping and monitoring. *Ecology and Evolution* 7, 1770-1782.
- Przeslawski, R., Foster, S., Monk, J., Langlois, T., Lucieer, V., Stuart-Smith, R. 2018. Comparative Assessment of Seafloor Sampling Platforms. Report to the National Environmental Science Programme, Marine Biodiversity Hub. Geoscience Australia. 57 pp.
- Rigaud, V., 2007. Innovation and operation with robotized underwater systems. *Journal of Field Robotics* 24, 449-459.
- Roelfsema, C., Phinn, S., Joyce, K., 2006. Evaluating benthic survey techniques for validating maps of coral reefs derived from remotely sensed images 10th International Coral Reef Symposium, pp. 177-1780.
- Seiler, J., Williams, A., Barrett, N., 2012. Assessing size, abundance and habitat preferences of the Ocean Perch *Helicolenus percoides* using a AUV-borne stereo camera system. *Fisheries Research* 129-130, 64-72.
- Smale, D.A., Kendrick, G.A., Harvey, E.S., Langlois, T.J., Hovey, R.K., Van Niel, K.P., Waddington, K.I., Belchambers, L.M., Pember, M.B., Babcock, R.C., Vanderklift, M.A., Thomson, D.P., Jakuba, M.V., Pizarro, O., Williams, S.B., 2012. Regional-scale benthic monitoring for ecosystem-based fisheries management (EBFM) using an autonomous underwater vehicle (AUV). *ICES Journal of Marine Science* 69, 1108-1118.
- Smith, A.N.H., Anderson, M.J., Pawley, M.D.M., 2017. Could ecologists be more random? Straightforward alternatives to haphazard spatial sampling. *Ecography* 40, 1251-1255.
- Stokes, M.D., Deane G.B. 2009. Automated Processing of Coral Reef Benthic Images. *Limnology and Oceanography, Methods / ASLO* 7: 157-68.
- Sumner, E.J., Peakall, J., Parsons, D.R., Wynn, R.B., Darby, S.E., Dorrell, R.M., McPhail, S.D., Perrett, J., Webb, A., White, D., 2013. First direct measurements of hydraulic jumps in an active submarine density current. *Geophysical Research Letters* 40, 5904-5908.
- Tivey, M.A., Johnson, H.P., Bradley, A., Yoerger, D., 1998. Thickness of a submarine lava flow determined from near-bottom magnetic field mapping by autonomous underwater vehicle. *Geophysical Research Letters* 25, 805-808.
- Van Rein, H., Schoeman, D.S., Brown, C.J., Quinn, R., Breen, J., 2011. Development of benthic monitoring methods using photoquadrats and scuba on heterogeneous hard-substrata: a boulder-slope community case study. *Aquatic Conservation* 21, 676-689.
- Wagner, J.K.S., McEntee, M.H., Brothers, L.L., German, C.R., Kaiser, C.L., Yoerger, D.R., Van Dover, C.L., 2013. Cold-seep habitat mapping: High-resolution spatial characterization of the Blake Ridge Diapir seep field. *Deep Sea Research Part 2 Topical Studies in Oceanography* 92, 183-188.
- Williams, S., Pizarro, O., Jakuba, M., Johnson, C., Barrett, N., Babcock, R., Kendrick, G., Steinberg, P., Heyward, A., Doherty, P., Mahon, I., Johnson-Roberson, M., Steinberg, D., Friedman, A., 2012. Monitoring of Benthic Reference Sites: Using an Autonomous Underwater Vehicle. *IEEE Robotic Automation Magazine* 19, 73-84.
- Williams, S.B., Pizarro, O., Steinberg, D.M., Friedman, A., Bryson, M., 2016. Reflections on a decade of autonomous underwater vehicles operations for marine survey at the Australian Centre for Field Robotics. *Annual Reviews in Control* 42, 158-165.
- Williams, S.B., Pizarro, O., Webster, J.M., Beaman, R.J., Mahon, I., Johnson-Roberson, M., Bridge, T.C.L., 2010. Autonomous underwater vehicle-assisted surveying of drowned reefs on the shelf edge of the Great Barrier Reef, Australia. *Journal of Field Robotics* 27, 675-697.
- Wynn, R.B., Huvenne, V.A.I., Le Bas, T.P., Murton, B.J., Connelly, D.P., Bett, B.J., Ruhl, H.A., Morris, K.J., Peakall, J., Parsons, D.R., Sumner, E.J., Darby, S.E., Dorrell, R.M., Hunt, J.E., 2014. Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience. *Marine Geology* 352, 451-468.

