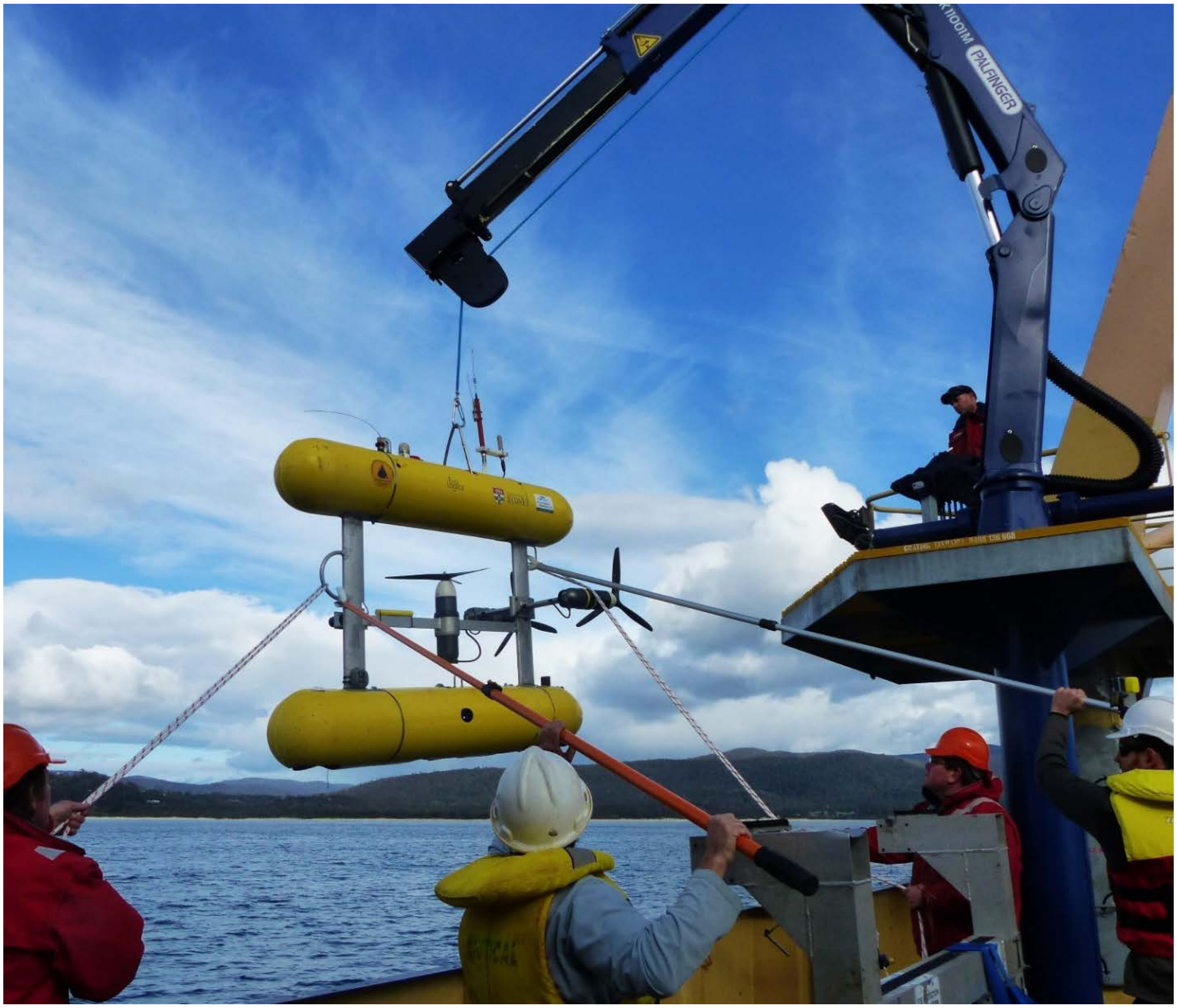
Independent External Review of the Integrated Marine Observing System (IMOS) Autonomous Underwater Vehicle (AUV) Facility



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Reviewer's foreword

Soon after commencing this review, I discovered that Unmanned Underwater Vehicles (UUVs) are described by a very rich literature of reports and publications. In the Australian context, some of this material is generated by the internal processes of IMOS. This collaborative program is characterised by a high level of reporting and transparency, culminating in Annual Planning Meetings where IMOS Facilities meet a broad cross section of the Australian marine community to discuss progress and plans. A larger source of reports and publications is from the researchers using IMOS infrastructure or accessing the data streams generated by it. To keep this review to a readable length, I will not rephrase what has been said before. If a cogent document exists, and many are long reports, I will provide a link to it and restrict myself to a summary of its significance. Some sections, attached as Appendices, have been authored by others to avoid me getting their details wrong. These statements are credited to their authors.

Apart from background literature and web searches, my effort concentrated on establishing direct contact with a wide range of stakeholders. Active contact was chosen over alternatives such as voluntary surveys because the latter often have a low return rate that is unbalanced by sector. My outreach has included persons from IMOS, the AUV Facility and its subordinate programs (IBMP, UMI), the national science agencies (AIMS, CSIRO, GA), researchers, marine managers, environmental consultants, and Faculty from every Australian University except those not engaged in marine research. Due to the travel restrictions in 2020 imposed by the Covid-19 pandemic, all contacts had to be remote (phone, email, videoconference). I was gratified to get a perfect response rate from my initial email enquiries and remain indebted to more than 90 persons who made time to write and/or speak with me last year (Appendix 1).

Executive Summary

Australia has the third largest EEZ in the World giving this nation stewardship over marine ecosystems from the tropics to Antarctica. In 2012, a National Representative System of Marine Protected Areas (NRSMPA) covering most of the EEZ was completed with the declaration of an extensive network of Commonwealth Marine Reserves (CMR). The management objectives for the NRSMPA range from various restrictions on human activities to the preservation of undisturbed reference sites. The effects of a warming ocean are superimposed upon these management objectives. Climate signals include a 350 km poleward drift of the East Australian Current since 1944 and short-term variability expressed as marine heatwaves impacting ecosystems on both west and east coasts since 1998.

The IMOS Autonomous Underwater Vehicle (AUV) Facility operates AUVs that collect high quality photographs of habitats and seabed life from downward facing cameras. While the IMOS AUVs have surveyed many locations around the Australian coastline between 2007 and 2020, the sampling program falls well short of a national program to monitor anthropogenic and climatic change. Unlike the National Reference Stations established by the IMOS Mooring Facility, the AUV program did not start with a national plan supported by the Australian science marine community. Instead, the network of observations was established by regional demand and since 2009 has had a focus on temperate reefs.

IMOS planning documents provide inconsistent direction to the AUV Facility. The IMOS Strategy 2015-25 document states that the AUV Facility will respond to demand for a national capability to cover a national network of reference sites. An internal review of the AUV Facility in 2016 declared three objectives for the benthic surveys: (1) long-term monitoring of deepwater reefs, (2) long-term monitoring of a major habitat-forming kelp, and (3) interpreting the dynamics of benthic reef systems in the context of biophysical coupling. The IMOS Strategy 2015-25 is clear about the need for sustained observations from a national network of reference sites. The IMOS Five Year Plan 2017-22 repeats the objectives identified by the 2016 review. Hence there is tension between the Strategy and the operating Plan that needs to be resolved and shared with the AUV Facility Director.

R1. IMOS Office clarify expectations about the purpose of the AUV Facility

The IMOS Office should resolve the inconsistent mission statements expressed in the IMOS Strategy 2015-25 and the IMOS Five Year Plan 2017-22 and communicate the resolution to the AUV Facility as part of the development of the next five-year plan.

My analysis reveals that the strongest demand for the capability of the IMOS AUVs will be for surveys to support marine biodiversity conservation rather than fisheries management. WA Fisheries said that the AUV sites established along the south-west coast provide data on habitat change at a scale too local to be relevant to ecosystem-based fisheries management (EBFM) across the broad continental shelf of WA. NSW Fisheries has made greater use of the IMOS AUV on the narrower shelf of the east coast but not as the preferred observing technology. I suggest quick engagement with key agencies responsible for managing marine biodiversity in their jurisdiction to establish their level of interest in the AUV capability.

R2. IMOS office engage marine management agencies in Victoria, NSW, and the Australian Government in 2021 to establish their demand for observations provided by the AUV Facility

Priority should be given to engagement in 2021 with Parks Victoria, NSW DPI, Parks Australia, and GBRMPA. The choice of these potential partners for immediate engagement is because each is currently preparing operational plans for monitoring MPAs. All plans are due for finalisation by the end of 2021. Comparable agencies from the other States should be engaged subsequently.

Throughout the history of IMOS, the AUV Facility has provided sampling tools to researchers from the Marine Biodiversity Hub. MBH is a national collaborative marine research network funded by successive departments of environment from the Australian Government. The Hub's multi-year research plan (2011-2014) was agreed with the Department of Sustainability, Environment, Water, Population and Communities. The Plan was built around research themes designed to strengthen the Department's capacity for evidence-based decision making in the marine environment including design considerations for cost-effective marine monitoring.

MBH researchers used a third of the capacity of the AUV Facility between 2009 and 2018 to explore locations around Tasmania with the greatest focus being repeat observations in four marine parks from the Commonwealth South-east Marine Parks network. A report due for submission in early 2021 was preannounced and welcomed in a media release dated 30 October 2020 on the home page for Australian Marine Parks.

During an internal review of the AUV program in 2016, the Facility established an independent working group to advise on an "Integrated Benthic Monitoring Program". The IBMP has considered matters like sample design, statistical rigour, and temporal effort but has not taken ownership of, nor produced a blueprint for, a national sampling program. This cannot be the responsibility of the excellent engineering team delivering results from the AUVs but the current form of the IBMP WG is too informal to be effective.

R3. The AUV Facility's Integrated Benthic Monitoring Program (IBMP) be separated from the Facility and report to the IMOS Senior Science Officer during the preparation of a national sampling plan

The existing IBMP WG is best placed to lead the design of the national sampling plan required by the AUV Facility but it has not been effective over almost five years. I suggest that it be given formal terms of reference and report to the IMOS Senior Science Officer until an adequate sampling plan is agreed with the IMOS Director, and later confirmed by the next Annual Planning Meeting involving the national marine science community.

All IMOS Nodes should be represented on the IBMP and additional expertise may need to be co-opted. If the leader of this task should be considered eligible for a responsibility allowance, the opportunity should be advertised to the marine science community by IMOS.

The IBMP will be informed by the feedback from **R2**. It should consider the opportunities represented by the NESP Marine and Coastal Hub (2021-27) to propose national reference sites in both temperate and tropical waters. NOTE: If there are no sites in Queensland north of Brisbane, this would leave a continental observing gap larger than that in the Great Australian Bight.

The Terms of Reference for this review require consideration of Remotely Operated Vehicles (ROVs) as well as AUVs. ROVs are tethered (hence not autonomous) marine robots offering a wide choice of functions. All require human pilots but most offer dexterity (controllable motion in six degrees), and the ability to perform manipulative tasks as directed by the ROV pilot. Large vehicles supplied by electrical power through the tether have greater mission endurance than those reliant on batteries. The industrial behemoths are powered hydraulically rather than electrically to match the energy demands of their tasks. ROVs are the subsea tool of choice by offshore industry rather than AUV even for light tasks that require only inspection of infrastructure. A possible exception in the future will be the routine and repeated inspection of subsea pipelines.

Given their high cost, work-class ROVs are not used for surveying or monitoring marine benthic communities. Despite this, a partnership between industry and science (SERPENT) has used the down time available in some of these systems to collect observations on the marine life around fixed infrastructure and/or to make experiments on the adjacent seabed. Australia has been a leading partner in collecting such collateral benefits from oil and gas infrastructure operating in the EEZ.

The visitation to Australia of vessels from the global research fleet equipped with deep sea ROVs dedicated to scientific discovery has demonstrated the value that can be extracted from tethered cameras capable of operating thousands of metres below the surface. While capable of exploring the deep seabed, these tethered robots are the only tool capable of surveying vertical transects on steep relief such as canyon walls or the flanks of seamounts and oceanic reefs. The Marine National Facility Vessel (RV Investigator) has plans to acquire this capability to complement its deep towed camera system.

R4. IMOS note the plans by the MNFV (RV Investigator) to acquire a deep ROV system

A deep ROV Facility on the MNFV would satisfy the national need for science surveys below 200m, which establishes a lower depth limit on the observing space to be serviced by IMOS AUVs.

Because most of the life on Earth depends on sunlight for its primary energy source, benthic marine life is crowded into the photic and mesophotic zones. While the depth cut-off for these zones varies a bit with local factors, a general guideline for the lower limit of the mesophotic zone is around 200m. This factor is the primary determinant for nominating 200 m as the maximum operating depth required from the IMOS observing infrastructure.

In shallow water (<100 m), a new class of battery powered ROV has been introduced to the Australian market with costs like those of towed camera systems operating in the same depths. Because an ROV allows hovering, close inspection, and potentially collection, this class of ROV has been purchased in significant numbers by academic researchers and others. Use cases so far include surveys of ship anchor damage, fish and benthos on pipelines and artificial reefs, and surveys of Antarctic benthos by ROVs deployed through holes in the ice.

Most commercial companies offering marine surveys in shallow water achieve them with ROVs. Depending on the market segment, these range from large inspection class ROVs operating to several hundreds of metres to mini-ROVs designed to operate in enclosed spaces such as inside pipelines and tunnels. The most common use of observation class ROVs by the commercial sector is the inspection of infrastructure although many advertise their availability to deliver environmental surveys. Such surveys are typically done by specialist marine environmental consulting companies. The relatively recent proliferation in the Australian marine science community of ROVs with a depth limit of 100 m adds to the competition from other devices that have already eased demand for observations by autonomous vehicles in coastal waters, especially in water shallower than 50 m.

The IMOS AUV Facility owns and operates an ROV (Seabotix VLBV 300) capable of operations down to 300 m. The only purpose of this ROV is support for the AUVs in case of the latter not returning to the surface. This ROV has been used once to free AUV Sirius from entanglement in ghost fishing net. Despite the growing popularity of light inspection class ROVs in the Australian marine science community, I find no case for the AUV Facility to acquire or support this technology, which is well supported by local distribution networks. A clear example was provided by the support given by SOSub to the Australian Antarctic Division to customise a recently acquired ROV for deployments to map marine benthos under floating ice shelves.

R5. IMOS note that AUVs compete with several other remote observing technologies, including light inspection class ROVs, offering more cost-effective benthic imaging in depths under 50 m

Along with the light inspection class ROVs, other remote tools producing images of shallow benthic habitats include dropped cameras (with and without bait to attract fish), towed cameras, and new towed gliders.

Competition from the variety of options for marine observing in shallow waters and the lower limits for mesophotic life, establishes a vertical opportunity space in the ocean (50 - 200 m) where there is potential need for surveys and monitoring of marine benthos, and where current capabilities are most sparse. Technologies competing with hovering AUVs are inspection class ROVS with a 300 m operating limit and towed camera systems. The latter are less competitive in complex or rugged terrain because of the need to manage the risk of collision. The former are less efficient at monitoring change at the kilometre scale because of the search limits imposed by tether length. ROVs would be the tool of choice for surveys on very steep surfaces.

R6. IMOS note that the least contested niche space for AUV observations is between 50 and 200 m

The IMOS AUV Sirius can operate to 700 m. The IMOS AUV Nimbus can operate to 300 m. Both are hovering vehicles capable of working from the surface down to their respective depth limits. Consequently, the AUV Facility owns two vehicles of delivering high quality imagery from the ideal niche space. **R2** will identify users with potential demand for benthic observations in this depth range.

Over the last 13 years, the IMOS AUV Facility has collected a large and unique archive of images on seafloor habitats and their associated biota. More than five million of these images have been curated in the Australian Oceans Data Network (AODN), where they remain discoverable and retrievable. While this deposition is the essential first step, these images have no value until they are converted to useful information. The post-harvest task of annotating images and analysing their information content represents a significant bottleneck on the flow between observation and reporting for all technologies producing visual imagery. In 2020, IMOS funded a sub-Facility for Understanding Marine Imagery (UMI) to facilitate this flow.

The objectives of UMI are to establish a national repository for annotations of marine imagery, and to extend tools that support annotation, exploration, validation, sharing and exporting of this data. This will include tools for summarising and reporting on the resulting data streams related to species and habitat distributions around Australia. Tool development will also be designed to support the integration of automated labelling but UMI has no plans to implement automated algorithms. This position contrasts with that of competitors in the same market such as CoralNet, which offers automated classifiers to allow users to analyse new data sets with existing annotation schemes.

The Catlin Seaview Surveys used artificial intelligence to automatically estimate the proportional cover of benthic components in over a million photographic quadrats in a short period of time to produce the first quantitative baseline for global reef condition. Capability statements from QUT, CSIRO, and AIMS all nominate automated image analysis as essential to progress. AIMS plans to rely on automated image analysis to support marine monitoring reports from 2022. CSIRO has developed new technology (towed gliders) through a collaborative partnership that has demonstrated an ability in 2020 to classify reef substrates in real time based on the use of automated visual classification machine learning algorithms running on fast computers in the surface vehicle during the acquisition of the raw data streams.

R7. IMOS consider options to expedite automated classification of benthic imagery

The greatest impediment to using benthic imagery as a routine tool for marine monitoring programs is the latency between collecting observations and converting them to useful results. The bulk of observations collected by IMOS AUVs (>95%) remain unexamined in the AODN archive, while a horizon scan shows other groups getting useful results from applying automated classifiers. IMOS cannot risk being left behind in this highly competitive field and should explore all options to accelerate its progress towards more automation.

UMI is the place to focus this effort but has not been resourced to deliver this outcomes. The extra funding given to the AUV Facility recently to subsidise vessels costs could be diverted to this purpose. The sum is insufficient to solve the “vessel problem” and would be better invested here.

If UMI can make significant progress with the automated classification of benthic imagery, IMOS could share these resources with users collecting photographic images of seabed communities using any method in exchange for the lodgement of copies of the data streams in the AODN. If this attracted enough interest from the Australian marine science community, UMI might be raised to Facility Status with the AUV Facility becoming one of multiple clients.

The IMOS AUV Facility currently has two hover capable vehicles that can survey and monitor benthic communities in the optimal niche space between 50 and 200 m. AUV Sirius has a mass of 250 kg and a depth limit of 700 m. AUV Nimbus has a mass of 130 kg and a depth limit of 300 m. The smaller AUV was acquired and customised by the ACFR to overcome the “vessel problem”.

AUV Sirius requires vessels with large deck crane or stern A-frame for safe deployment and recovery. AUV Nimbus can be deployed and retrieved from a portable ramped gantry that can be attached to smaller vessels with an open stern, widening the pool of available support vessels. The AUV Facility has proposed the acquisition and testing of an off-the-shelf hovering AUV with a mass of 50 kg, which could be deployed from the smallest class of surveyed vessel operated by marine agencies.

R8. IMOS delay a decision on investing in a 50 kg hover capable AUV with depth limit of 200 m

The AUV Facility has identified an off-the-shelf vehicle with suitable operating characteristics. However, there is no urgency to induct new technology because the AUV Facility has twice the capacity in 2021 than in 2019 (with the operational readiness of AUV Nimbus) and this fleet is still to be tested against the demand revealed by **R2** and the sampling plan to be established by **R3**.

The case for a smaller AUV with the capabilities of AUV Sirius (the benchmark) is that it would allow use of smaller vessels, provide greater flexibility, and drive down the cost of observations. The future composition of the IMOS AUV fleet should be based, however, first on the demonstrated demand for sustained observations and second on the most cost-effective solutions.

The Terms of Reference for this review ask whether observations from the IMOS AUVs should continue to be delivered by a centralised Facility or through more distributed models.

R9. The IMOS AUV Facility remain as a centralised Facility while it is operating just two platforms

While the Facility's proposal to develop a smaller cheaper AUV as the optimal tool and replicate its numbers has been expressed, it will operate with just two vehicles for the foreseeable future including for a significant period after any decision is made to invest in a smaller AUV. Under these circumstances, the current centralised model of delivery seems most appropriate.

While the current Facility with support from the MBH has done a good job to establish the IMOS brand and standards, it has done so largely in isolation from other groups (AIMS, QUT, CSIRO) sharing the same ambitions. From a national perspective, it would be desirable to unify these independent group efforts if only to prevent them from diverging on the essential matter of data standards. Regular communications among the groups is the least effort that should be made to encourage more collaboration.

R10. IMOS consider sponsoring an annual forum for marine benthic imaging

It is desirable that a regular (at least annual) forum be established before the end of 2021 to encourage exchanges among all groups with an interest in collecting marine benthic observations using remote imaging technologies. This open forum could be promoted under the banners of IMOS and the NESP Marine and Coastal Hub. A specialised sub-group could be convened by UMI under the Forum umbrella to consider technical matters like automation and data vocabularies.

Terms of Reference

Purpose

This is a forward-looking review to evaluate the stakeholder and end user needs for sustained benthic observing in Australia and to evaluate mechanisms for delivery of an efficient and effective program. The review will consist of two components:

1. Consultation to determine current and future need for sustained benthic observations by researchers, industry, end-users, and stakeholders.
2. Review of benthic observing technologies and programs in Australia to inform an optimised approach to sustained benthic monitoring in IMOS.

Review Scope

For *component 1* the review should aim to define the existing needs and use case for sustained autonomous benthic observing in Australia:

1. Define the need for sustained autonomous benthic observing (e.g. repeat photo observations from the same location through time).
2. Identify the source of current benthic imagery or data used by the groups identified above.
3. Identify future needs for sustained automated benthic observations to management, policy and industry operations.

For *component 2* the review should examine the existing delivery models and methods (e.g. technology/vehicles) available (including the IMOS AUV program):

4. Based on item 2, summarise the programs, institutes or industries currently collecting autonomous benthic observations and methods employed (e.g. AUV, Remotely Operated Vehicles, etc). This analysis should consider the role of the IMOS AUV Facility relative to these programs (e.g. does the IMOS program fill a specific niche?).
    a. In the context of current programs and future needs, propose a model for an optimised program to deliver sustained autonomous benthic observing in Australian waters including:
    b. Method or methods (i.e. type of technology) to employ, including comments on ease of use and technical readiness.
5. Evaluation of delivery such as centralised or dispersed models of operation (e.g. one central vehicle operated nationally or a range of vehicles or teams operating simultaneously).
6. Assess the optimised program model relative to the current operational approach employed by the IMOS AUV Facility and provide recommendations for program configuration to meet current and future end-user and stakeholder needs (as identified in item 1).

Background

A quick history of autonomous vehicles

Wikipedia defines autonomous underwater vehicles (AUVs) as robots that travel underwater without requiring input from an operator. AUVs constitute part of a larger group of undersea systems known as unmanned underwater vehicles (UUVs), a classification that includes non-autonomous remotely operated underwater vehicles (ROVs). The latter are tethered by a cable (or umbilical) that transmits power from the surface and carries two-way communications between the operator/pilot and the device. These features allow ROV missions to have greater endurance and to undertake more complex interventionist tasks.

AUV development started in the 1960s but the last Century was primarily about prototypes and proof of concept (Appendix 11). Commercial manufacture of AUVs started around the turn of the Century and was followed quickly by a rapid rise in publications on UUVs from less than one a week in 2000 to more than one a day in 2020 (Figure 1). The divergence in the growth rate of publications coming from the two platforms is likely a reflection of the relative maturity of the ROV and AUV technologies.

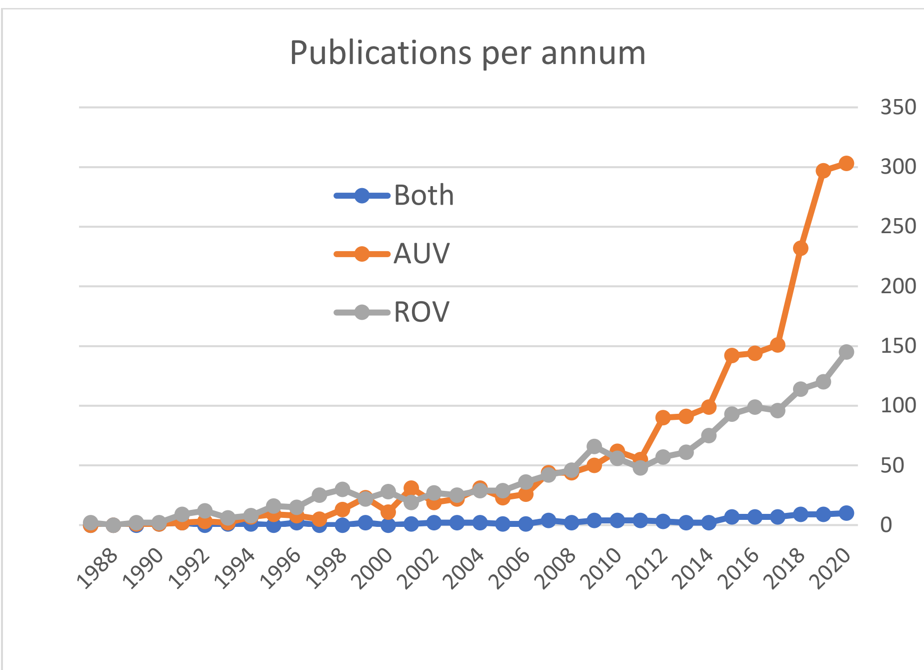


Figure 1. Three decades of publications in UUVs revealed by a search of the Web of Science using the following filter (TS=("AUV" OR "ROV") NOT TS=(lumin* OR ovar* OR aUV-vis OR vaso* OR vesicl* OR poll* OR recombin* OR phil* OR ureth* OR metrol* OR AUV.V) NOT WC=(Biochem* OR Med* OR Nucl*)) AND LANGUAGE (English). Indexes=SCI-EXPANDED Timespan=All years) for the full subset (n=3414). The purity of the output was confirmed by checking the first and last 100 entries after every search when sorted on relevance. The number of publications including both AUV and ROV (n=92) was surprisingly low (less than 0.3% per annum) indicating little overlap between the communities.

AUVs have had to solve additional technical challenges due to their autonomous operation such the complexity of unsupervised navigation and collision avoidance, the energy density of batteries, power and mission management, and the optimisation of sensor payloads constrained by limited power and form factor. While the faster growth of publications from the AUV sector in the last decade will be partially due to solutions to engineering problems from a maturing technology, the IMOS experience demonstrates the growth in publications is also arising from the application of this technology.

The case for sustained benthic observing in Australia

The ocean is a dynamic space and constantly changing. Since Australians crowd around the coastal fringes, many of us share personal memories of change such as larger fish catches, clearer water, and more kelp or coral. Over generations, older records are lost resulting in a shifting baseline against which to measure historical change (1). Attempts to recover lost baselines are confounded by changes in sampling design due to the lack of program continuity (2). When consistent time series are available (e.g. aerial surveys over Cockburn Sound, WA, since 1954), reanalysis can reveal abrupt change rather than steady decline (3).

The difficulty of predicting long-term changes in marine benthic communities is partly due to natural long-term fluctuations in the oceans, which challenge attempts to define baseline states for marine ecosystems (4). The adaptive environment for most poikilotherms is one of constant sea temperatures at short time scales with larger-amplitude changes at longer time scales (5). The latter have been associated with cycles and regime shifts in plankton communities and commercial fish catches (6). Despite this dynamic climate, the evidence of human-driven change in the ocean is undeniable (7).

Since the industrial revolution, the burning of fossil fuels has added an anthropogenic component to climate change. The key effects are ocean temperatures and chemistry. These changes are predicted to have many impacts on Australian marine life (8). Ocean warming has been followed by the predictable redistribution of marine biota. Some of these latitudinal shifts have had profound consequences such as invasive sea urchins clearing kelp forests in north-east Tasmania (9). Marine heatwaves since 1998 driven by short-term ocean variability have resulted in mass coral bleaching on the Great Barrier Reef (10) and massive loss of seagrass from Shark Bay (11). Both marine ecosystems are inscribed on Australia's World Heritage Register and the recent changes are matters of global concern.

In Australia, as elsewhere, one response to the threat of fishing has been to create "no-take-zones" (aka marine reserves, marine sanctuaries). In addition to the benefits of protecting habitats from disturbance and species from exploitation, marine protected areas (MPA) preserve critical reference points that can be compared with adjacent areas open to general use. If used in an appropriate design, MPAs can support evidence-based management decisions for marine conservation in the surrounding estate (12).

Australia committed to the protection of marine biodiversity by ratifying the UN Convention on Biological Diversity in 1993. A Taskforce on Marine Protected Areas was established to provide a mechanism for all jurisdictions to collaborate on the development of a National Representative System of Marine Protected Areas (NRSMPA). A useful progress report was provided in 2007 for the period 1993-2003 and a network of Commonwealth Marine Reserves (CMR) was in place by 2012. The first five-year review in 2016 resulted in modest changes. These managed areas have become an important target for the AUV Facility.

In 2013, the Oceans Policy Science Advisory Group (OPSAG) released Marine Nation 2025 which identified biodiversity and ecosystem health among six national challenges. In 2014, OPSAG was rebadged to the National Marine Science Committee (NMSC), which retains oversight of marine matters today. In 2015, the

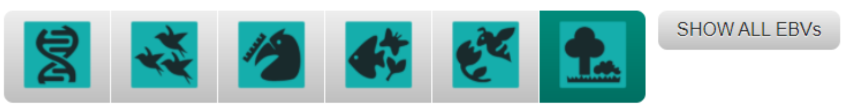
NMSC issued the National Marine Science Plan 2015-2025 to drive the development of the Blue Economy (13). The Plan added a seventh grand challenge recognising that the greatest conflicts were in urban coastal environments.

The Plan recommended that stakeholders "Establish and support a National Marine Baselines and Long-Term Monitoring Program, to develop a comprehensive assessment of our estate, and to help managed Commonwealth and State Marine Reserves". It noted that "The recent commitment by the Department of Environment to develop a national marine monitoring program in the Commonwealth Marine Reserves is a good first step towards establishing such a coordinated, national long-term ecosystem monitoring program". It also recommended "Facilitate coordinated national studies on marine system processes and resilience to enable understanding of development and climate change impacts on our marine estate".

The Plan noted that Australia has benefited immensely from the development of an Integrated Marine Observing System (IMOS), and that it provides the opportunity for a coordinated, long-term national marine system monitoring program. Begun in 2006 under the Australian Government National Collaborative Research Infrastructure Scheme, IMOS is one of 13 regional observing networks that form The Global Ocean Observing System (GOOS). IMOS invests in mature observing technologies and follows the Framework for Ocean Observing (FOO). This requires sustained delivery of quality data streams on Essential Ocean Variables (EOV) from its domain (14). While the focus of EOVs is physical variables, the Group on Earth Observations Biodiversity Observation Network (GEO BON) has developed six classes of Essential Biodiversity Variables (15). From an IMOS perspective, the EBV class of most relevance is Ecosystem Structure (Figure 2).

EBV classes and names

There are 6 EBV classes and 20 EBV names. By clicking on the icon you will get more detailed information.



Ecosystem structure

The spatial arrangement of ecosystem units collectively defined by organisms forming these units.

EBV name	EBV description
Live cover fraction	The horizontal (or projected) fraction of area covered by living organisms, such as vegetation, macroalgae or live hard coral.
Ecosystem distribution	The horizontal distribution of discrete ecosystem units.
Ecosystem Vertical Profile	The vertical distribution of biomass in ecosystems, above and below the land surface.

Figure 2. Essential Biological Variables (EBV) that can be recovered from marine benthic mapping.

The National Marine Science Plan 2015-2025 also noted that the Commonwealth Department of the Environment has made a sustained investment in collaborative research to undertake public-good science targeted at key policy and end user questions and geographic areas of strategic interest. Successive Marine Biodiversity Hubs have been funded by the 2007-2010 Commonwealth Environment Research Facilities (CERF) program, the 2011-2014 National Environmental Research Program (NERP), and the 2015-2021 National Environmental Science Program (NESP). A renewal of the NESP recently announced will support a Marine and Coastal Hub until 2027.

The current Marine Biodiversity Hub has released a synopsis of impacts from 13 years of research (2007-2020). The report provides examples of scientific information and advice to support decision making by the Australian Government with an important influence on the sustainable management of Australia's marine environment. Several examples involve data streams generated by the IMOS AUV Facility. This demonstrates the mutual dependence that has existed between the IMOS Facility and Hub researchers. Most of the ecological outputs described in this report would not exist with the contributions from both partners.

The IMOS AUV Facility is supported by IMOS to collect high-quality benthic imagery and associated water column data at selected locations around Australia for the purpose of understanding habitat condition and change over time. As the review will show, an AUV is simply one method of collecting underwater imagery and a significant contribution from the MBH has been the creation a suite of field manuals to ensure that data collected by many different sampling platforms are directly comparable and connected with the Oceans Best Practices System. These dynamic manuals include best practices for AUV and ROV operations, and a third manual on sampling design to inform evidence-based decision-making.

AUV assets in Australia

IMOS

IMOS has invested in an Autonomous Underwater Vehicle (AUV) Facility since 2007. The operating partner and host for this Facility has been the Australian Centre for Field Robotics (ACFR) at the University of Sydney. Over the 13 years, the ACFR has invested in three vehicle designs (Figure 3).

All are designed to collect optical and acoustic data near the seabed (more details in Appendix 2).

Throughout the last 14 years, AUV Sirius has remained the workhorse platform collecting the overwhelming bulk of observations. Sirius is a slow speed, terrain following, hovering craft with passive stability and excellent capabilities for precise navigation along programmed routes.

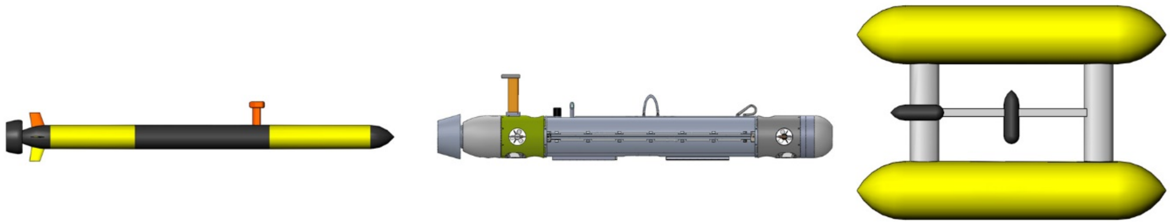


Figure 3. AUVs operated by the ACFR in 2020. From left to right: Holt (IVER2), Nimbus (NextGen), Sirius (WHOI Seabed). Images not to scale.

At 250 kg, Sirius is a large device. Its form factor and slow operating speed in water provide some operating limits, such as strong bottom currents and/or turbulent flows in wave exposed environments. The latter is mitigated substantially by operating in waters deeper than 15 metres, which complements the depth limits on SCUBA divers. Although capable of operations down to 700m, community demand has been for images from the upper 50m and not more than 125m (Figure 4). Size is also its greatest weakness of Sirius, which requires a large surface support vessel with either A-frame or extendable hoist for safe deployment and recovery.

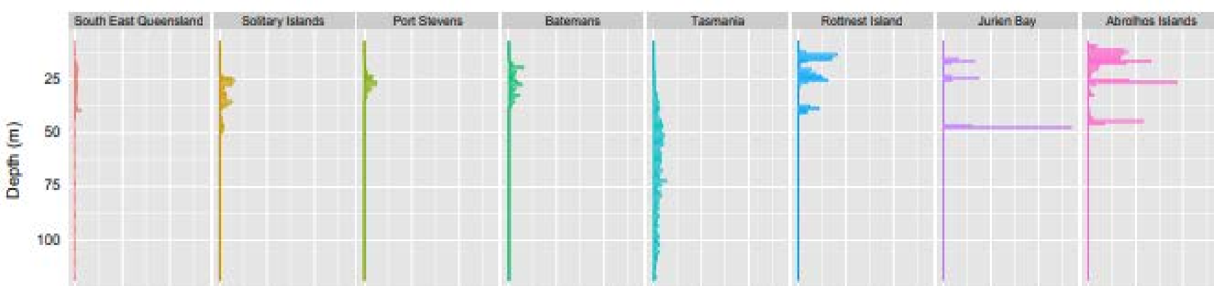


Figure 4. Depth distribution of 9,874 annotated images representing approximately 2% of images collected around Australia between 2008 and 2009 (16).

Both smaller vehicles represent the Facility’s response to this weakness. AUV Holt purchased in 2011 is just 10% the weight of Sirius and can be launched from a small boat. It is a propeller-driven torpedo shaped AUV capable of faster speed over ground than the Sirius but only suited to missions over shallow (100m depth limit) even terrain with few obstacles. While its ability has been tested with a handful of missions over the last decade, AUV Holt has not produced sustained (i.e. repeat) observations from any location.

AUV Nimbus, is a larger torpedo acquired in 2017 with an operational depth range of 300m. Nimbus is capable of hovering operations like Sirius but, at 130kg, is still too large to be deployed easily from small vessels. The ACFR has developed a portable ramp-based launch and recovery system for AUV Nimbus that avoids the need for a crane. This will allow Nimbus to be deployed from smaller vessels than the Sirius.

Since commissioning trials in late 2019, Nimbus has completed 26 transects across three locations (Tasmania, Lord Howe Marine Park, Port Stephens NSW). Because of the disruption to fieldwork caused by the pandemic in 2020, there is little evidence available to evaluate fully the performance of this platform but the ACFR staff are confident that it is a full replacement for AUV Sirius.

In the last 13 years, the IMOS AUVs (primarily AUV Sirius) have collected 85 data sets from 31 locations (covering all coastal States) and deposited 5.5 million images in the AODN (Appendix 2).

AMC

The Australian Maritime College (AMC) is located on the Newnham Campus of the University of Tasmania. AMC has a dedicated AUV Facility, which primarily supports the AUV *nupiri muka*. This AUV was acquired in 2017, as part of the Antarctic Gateway Partnership that aims to provide new insights into the role of Antarctica and the Southern Ocean in the global climate system. The Gateway AUV is 8 metres long, weighs almost 2000 kg, has enough battery for 40 hours of continuous operation. It houses a wide variety of science payloads and sensors.

Although large, the Gateway AUV is mounted on a road trailer and can be launched from a coastal boat ramp. Its first operational mission was to map sand wave and ripple features of the Tamar River bed. Despite its ability to operate in coastal waters, this $5 million AUV is likely to be devoted to demanding missions under the ice shelves of Antarctica.

The AMC AUV Facility also operates a Kongsberg Remus 100 vehicle, with an advanced sensor suite. This is a partnership between AMC, AMC Search, and a commercial partner. It is available for commercial survey and is used regularly in a training partnership with the Australian Navy. The Facility previously operated a Teledyne Gavia of similar type to the IMOS Holt. This AUV has used sonar to map bathymetry (17), clearance under the Tasmania Gas Pipeline, and to map an historic shipwreck for Tasmania Parks and Wildlife Service. It was equipped with a single camera and used in 2015 for surveys to detect seismic impacts on scallops (18). These images were of low quality and used only for broad characterisation of the seafloor habitat, which emphasizes the critical importance of camera quality for useful benthic surveys. This AUV has since been retired.

QUT

Underwater robotics at the Queensland University of Technology began with the recruitment of key staff from the CSIRO Autonomous Systems Laboratory (ASL). In 2009, Professor Peter Corke, who had been the first Research Director of the ASL, left CSIRO to become professor of robotics at QUT. In 2013, he was joined by Professor Matthew Dunbabin who had led the Marine Robotics team at CSIRO. While at CSIRO, both had been involved with the development of a new class of small AUV, known as Starbug, with the Great Barrier Reef as intended target. Starbug was designed to be a low-cost platform that could be deployed in a swarm to improve data collection rates. It was one of the first AUVs in the world designed specifically with vision as the primary sensor for navigation and control (Appendix 5).

In 2014, the Australian Centre for Robotic Vision (ACRV) was funded by the Australian Research Council (ARC) to conduct research in the new field of robotic vision. It was hosted by the Queensland University of Technology and Peter Corke has led the Centre throughout its seven-year life. Dunbabin has been a Chief Investigator in the Centre since 2017. QUT has a significant research program focused on machine vision and machine learning with application to improved image classification, and real-time implementation onboard the autonomous marine platforms to provide interpreted data streams in the field. To validate the various applications to reef conservation, QUT has developed a series of underwater and surface robots at different levels of commercial readiness for government and research agencies. These systems are in use with partners in Australia, Philippines, Tonga and the USA for automated monitoring, real-time surveillance and active intervention tasks in reef and coastal environments.

CSIRO

After the departure of Corke and Dunbabin to QUT, CSIRO Oceans and Atmosphere upgraded the original Starbug Mk III technology to Starbug X, which is described as a robust and reliable field instrument. Marouchos et al. (2015) described the upgrade path, which involved all onboard systems, and compared the specifications of Starbug X against alternative vehicles including the AUV Sirius, Remus 100 and IVER2 (19). Starbug X, which weighs 32 kg and can be deployed from an inflatable boat by a single person, has been validated in coastal estuaries (20), and Ningaloo Reef (21). In the Ningaloo example, the authors had sufficient confidence in the comparability of the Starbug results to pool them with images from two missions by the IMOS AUV Sirius to produce a common mapping product.

Starbug X is the only AUV owned and operated by CSIRO O&A. It is one of 10 image-based technologies available to the organisation (Appendix 6) and its niche is clearly for surveying the seafloor and measuring water quality variables in shallow coastal and inland waters.

AIMS

AIMS has purchased two RangerBots from QUT. These are small AUVs from the Starbug lineage developed separately by QUT since 2013. Both units are being used as training and test platforms for the more complex work that will be undertaken by a future Coral AUV. The latter will a larger version intended to be an agile AUV for image mapping missions in complex environments. The Coral AUV is being developed as a partnership between QUT and AIMS. The AUV will be designed jointly, after which the QUT Centre of Robotics will be responsible for the platform build and AIMS responsible for the science payloads and field testing. The latter will occur in 2021 with the expectation of full operations of the Coral AUV by mid-2022.

Like CSIRO, AIMS owns and operates other underwater imaging systems including ROV and towed systems (Appendix 7).

Australian universities

Leaving aside the two universities hosting Centres for marine robotics (USyd, QUT), my enquiries among all others found none that operate an autonomous underwater vehicle for marine surveys. However, engineering departments (ANU, Flinders, Monash, RMIT, Swinbourne, UNSW, and UWA) have developed prototypes to explore technical aspects of AUV operation and/or for training research students. The focus of these programs is on intrinsic properties of the vehicle like control systems, navigation, and energy systems.

Australian Industries

In the commercial sector, my web searches found no evidence that AUV are a significant part of operations commissioned by heavy industry. Despite this, there are several sub-sea companies capable of supplying AUVs from a global inventory to suit any task. For example, Fugro Australia Marine P/L is a subsidiary company of the international parent Fugro, which owns one of the largest fleets of commercial AUVs in the World. It offers six Kongsberg Hugin 1000 AUVs capable of surveys to 3,000 m including several equipped with digital cameras “to identify seabed features of interest”. DOF Subsea is another global company supplying the same vehicle. It goes without saying that calls to import such high end AUVs could only be justified by the oil and gas industry and are not used for sustained monitoring of marine benthos.

The ACFR has configured a second Iver2, AUV Phoenix, to the same specification as AUV Holt. This vehicle was used in 2015 to survey scallop densities in Bass Strait (18). AUV Phoenix is owned by Australian Maritime Ecology Pty Ltd and is advertised as a partnership with the ACFR. The AMC AUV Facility also operates its small AUV through a commercial partnership. These are the rare exceptions of AUVs that I could find within the community of marine environmental consultants offering benthic surveys. The latter make much greater use of ROVs (reviewed below).

The recently established CRC for the Blue Economy has a project (RP1) led by AMC that promises to combine a review of platform manufacturers with a study of the literature to connect industry users with achievable autonomy at offshore sites in the next five years.

Contributions from the IMOS AUV Facility

In the period 2007-2020, the IMOS AUV Facility has facilitated more than 70 substantive publications and the completion of more than 20 PhD theses (Appendices 8, 9, 10). The published literature is almost equally divided between technical developments and applications.

The technical contributions (Appendix 8) contain a group of studies designed to strengthen navigation, control systems, and sensor performance. This cluster of tasks is also reported in another 45 citable references (not visible in this report) that were based on conference presentations. Most of the student contributions before 2018 are also of a technical and operational nature. While this might not be expected if the AUV had been a fully mature technology in 2007, it is a testament to the high quality of the current observing capability of the IMOS AUV Facility.

The technical contributions include a second sub-group of publications relating to the collection and analysis of images for benthic surveys of marine biodiversity. These include ongoing explorations of optimal survey designs based on the spatial properties of sessile benthic life (2014-2019), annotating, and classifying benthic imagery (2015), and image subsampling (2016). Finally, there is a stream of papers about automated extraction of data from images and machine learning leading to faster image analysis. These papers represent a necessary maturing of the research community to ensure that the data streams collected by the IMOS Facility answer questions about benthic communities that are relevant to implementing agencies and ensuring an efficient path between field operations and the provision of such advice.

The literature on applications (Appendix 10) represents a diverse range of topics with the greatest target audience being researchers. It is inevitable that there are some curiosity driven studies with two examples being day-night changes in cuttlefish camouflage and depth extension of symbiotic associations between fish and anemones on the GBR. Both studies were done during the first five years of IMOS, when the NCRIS mandate emphasised the provision of research infrastructure to the marine community. The IMOS Strategy 2015-25 reorientated the mission of the AUV Facility to sustained observation from a national network of reference sites.

Several publications have described the use of AUV images in conjunction with geophysical sampling methods such as multibeam echosounders (MBES) to find acoustic surrogates for biological features. Once validated, the geophysical surrogates have been used to predict the spatial extent of habitat. This approach has been used in the Great Barrier Reef Marine Park to predict deep habitats dominated by phototrophic and heterotrophic communities (22-24). It has resulted in a large expansion of the known habitat supporting mesophotic communities with significance to the marine park management plans. The same validation of geophysical surrogates has been investigated thoroughly in cool temperate locations along eastern Tasmania (25, 26).

The IMOS mission (as redefined in the IMOS Strategy 2015-25) is to deliver sustained data streams from fixed locations around Australia and the AUV Facility has delivered this with a large-scale design that is suitable for monitoring future changes in the abundance of habitat and sessile marine life below the Tropic of Capricorn (Figure 5). On the west coast, the three locations (Abrolhos, Jurien, Rottnest) were resurveyed annually by AUV Sirius between 2010 and 2013 providing a good basis to investigate short-term variability in these communities. The last surveys from these locations were in 2017. On the east coast, the Henderson location in SE Queensland and two locations on the east coast of Tasmania (Freycinet, Tasman

Peninsula) have each been surveyed seven times between 2010 and 2019. The intermediate locations from NSW (Port Stephens, Batemans Bay) have both been sampled at least three times between 2010 and 2020. In addition, other locations along the NSW Coast have been surveyed in the same time window.

The first surveys across all seven locations have been analysed to provide a snapshot of the distribution and abundance of an important habitat forming kelp, *Ecklonia radiata* (27). In addition to providing a national snapshot for this critical species over its Australian range (it does not occur in the tropics), the 2010 surveys provide the first national baseline for monitoring future change in this species. The lack of locations from South Australia and Victoria represents a large gap that should be filled in future surveys.

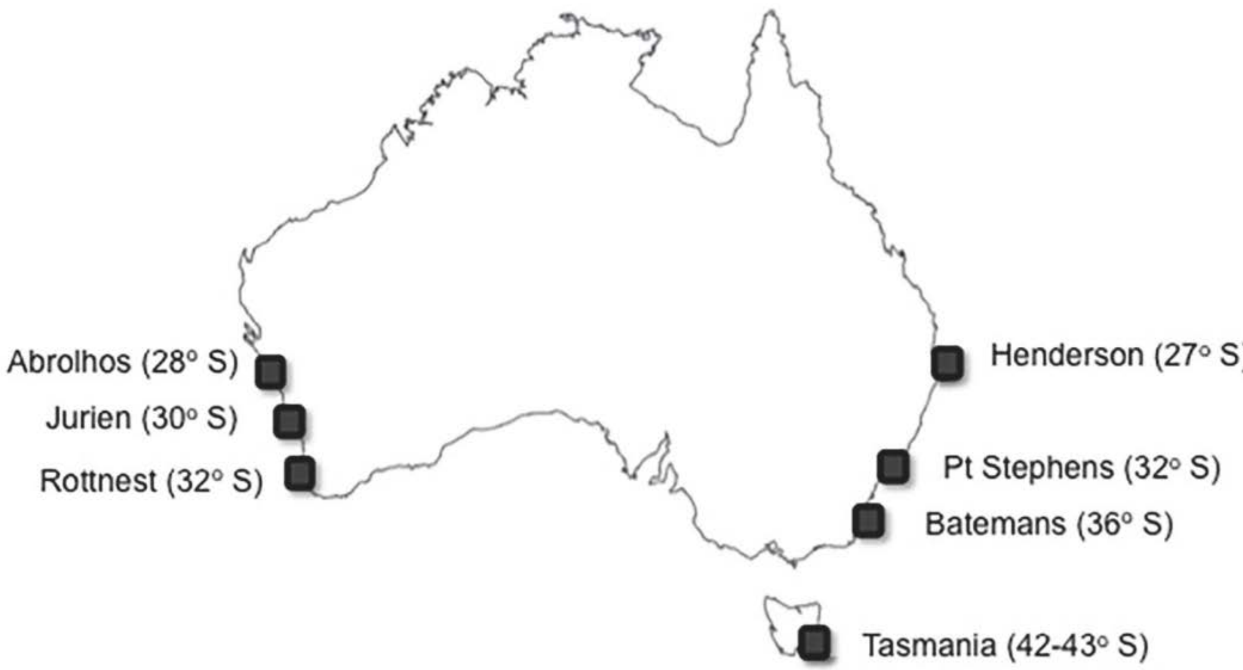


Figure 5. Locations surveyed 30 depth by the IMOS AUV in 2010 to establish a kelp baseline (27).

Both west and east coasts of Australia are influenced by poleward boundary currents (the Leeuwin Current in the West, the East Australian Current in the East) that originate from the tropical waters of the Indian and Pacific Oceans, respectively. Warming of the global oceans has been associated with tropicalisation on both coasts; that is the southern limits of tropical species are moving southwards.

Ridgeway (2007) analysed long-term records from an oceanographic station near Maria Island, Tasmania, that started in 1944 (28). From six decades of data, he detected a warming trend consistent with a 350km poleward advance of the East Australian Current. For this reason. the east coast of Australia has been identified as a hotspot of change in marine climatology.

James et al (2017) analysed the cover of 51 species of invertebrates in 30-90m sampled by AUV Sirius between 2010-2013 from 12 locations between Henderson and Tasmania (additional locations had been sampled on a sporadic basis in NSW and Tasmania). Their analysis was not about change over this short period, but it identified three distinct community types (sub-tropical, warm temperate, cool temperate) along this latitudinal gradient (29).

Marzloff et al (2018) reused the same survey data to predict the probability of presence/absence of 13 functional groups across this domain during the AUV survey period from a rich suite of environmental data (bathymetry, geomorphology, oceanography, geochemistry). Using downscaled projections for the unfixed elements, they predicted presence/absence for 2060. Some species were predicted to move south (Figure 6) but other functional groups were predicted to show different responses. The result was a predicted disruption of current assemblages and a predicted formation of novel ones (30). The potential impact of this reassortment on ecosystem function is unknown.

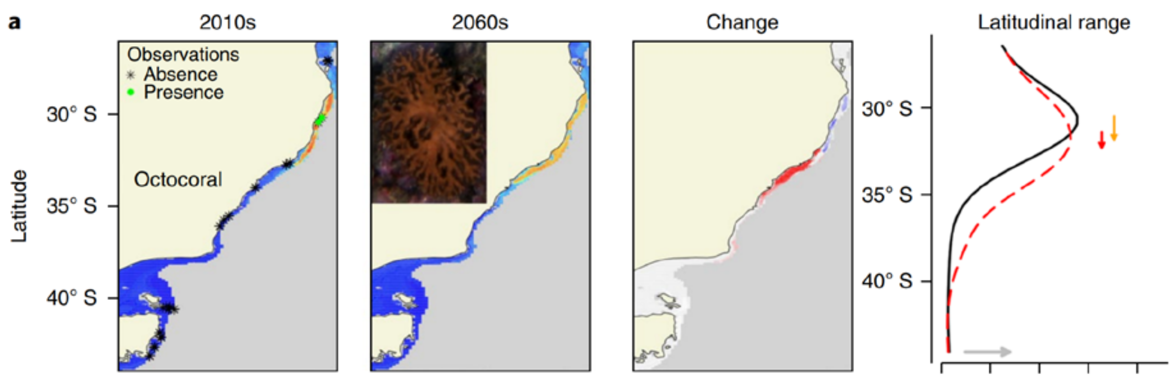


Figure 6. The probability of occurrence of octocorals in the sample period (2010-2013) and 2060 (30).

One of the consequences of ocean warming in NE Tasmania has been the appearance of marine species previously restricted to the mainland. The most documented example is a sea urchin, *Centrostephanus rodgersii*. Throughout its range, this species has shown that it can convert kelp forests to overgrazed barren habitat with collateral impacts on invertebrate and fish communities. This has happened in Tasmania (9).

Comparisons between divers and the AUV have shown that divers are more efficient at counting urchins in kelp beds but nocturnal surveys by the AUV produce similar results to the diurnal surveys of divers in barren ground (31). Surveys by AUV Sirius have shown that urchin barrens are being created at greater depth in Tasmania (20-40m) than in NSW (7-25m) (32). The greater depth range is a challenge for divers and this knowledge would likely have remained hidden without the AUV surveys. Repeated surveys with the AUV on four areas, including one that is a no-take marine reserve, have shown that the reserve is more resilient to the expansion of barren ground than areas open to fishing (33) but with concerning evidence that urchin barrens may be increasing everywhere (Figure 7).

The marine heatwave of 2011 in Western Australia was of strong interest to scientists and marine managers because it resulted in the mortality of many fish and invertebrates. The Department of Fisheries recorded this concern with inclusive workshops soon after the event and two years later (34, 35). The latter documented enduring consequences from the event.

Given that the Abrolhos Islands and Jurien (Figure 5) were near the centre of the heatwave (36), the AUV surveys in 2010 were fortuitous. The response of benthic communities surveyed by the AUV have been described in at least three papers covering different spatial scales. Bridge et al (2014) used the four surveys (2010-2013) to describes changes on three dense grids from a single location at the Houtman Abrolhos Islands (37). Prior to the temperature anomaly, the sites had had high coral cover. Coral bleaching was detected in the 2011 survey and over the four years, hard corals declined in abundance while macroalgal cover doubled. These trends were despite considerable differences among the replicate plots.

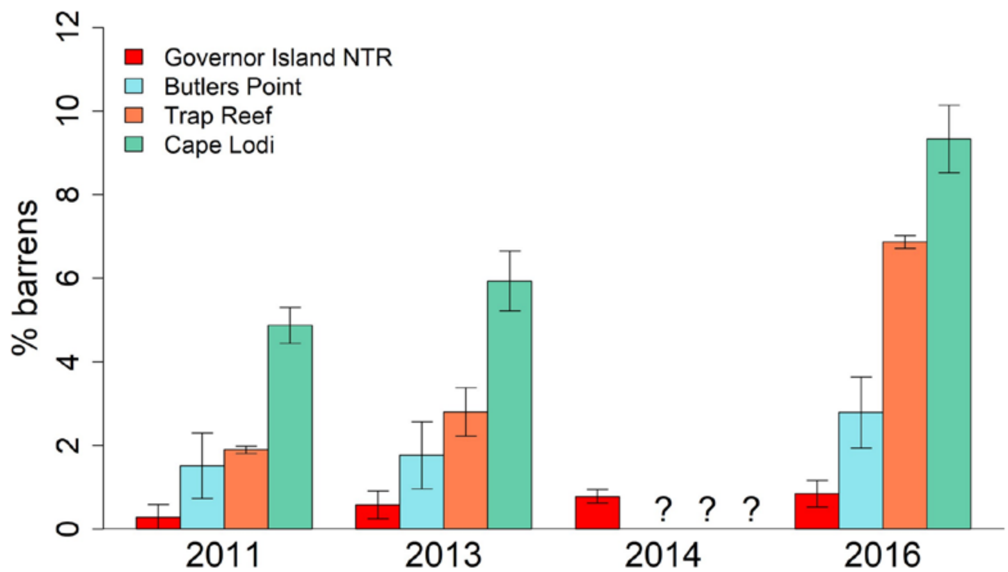


Figure 7. Percent of total AUV images classified as barren ground in one no-take reserve (NTR) and three control areas. The latter were not surveyed in 2014.

Ferrari et al. (2016) reused the same data and exploited the ability of AUV Sirius to relocate the same corals in successive surveys of the dense grids (Figure 8). Using the 2011 surveys, they selected a balanced set of images from sites where corals bleached and did not. They used the precisely aligned orthomosaics to create accurate 3-D reconstructions of the scene. With these finely resolved data, they were able to show that rugosity changed only on sites that bleached and were able to relate this difference to the changing composition of the coral community (38).

Giraldo-Ospina et al (2020) extended the spatial scale of the analysis to a nested design: replicate plots at two sites in each of three depths for each of the three fixed locations shown in Figure 5. They also added additional surveys extending the time series from 2010 to 2017 (39). The key finding was that impact of the marine heatwave on habitat forming seaweeds, including *Ecklonia radiata*, was greatest at the shallowest depths and they proposed that deeper sites could provide refuges to support subsequent recovery.

I could not locate publications describing the impacts of heatwaves on coral communities in tropical Australia measured by the IMOS AUV Facility although data exist for such analysis from Western Australia. Ningaloo Reef (23°S) has been surveyed four times (between 2007-2019) and Scott Reef (14°S), an offshore reef in the tropical Indian Ocean, has been surveyed three times (2009, 2011, 2015). Temporal changes in these three data sets remain unknown). On the east coast, there have been mass bleaching episodes on the Great Barrier Reef in recent years (2016, 2017, 2020) but the last mission of the AUV Sirius to north Queensland was in 2015.

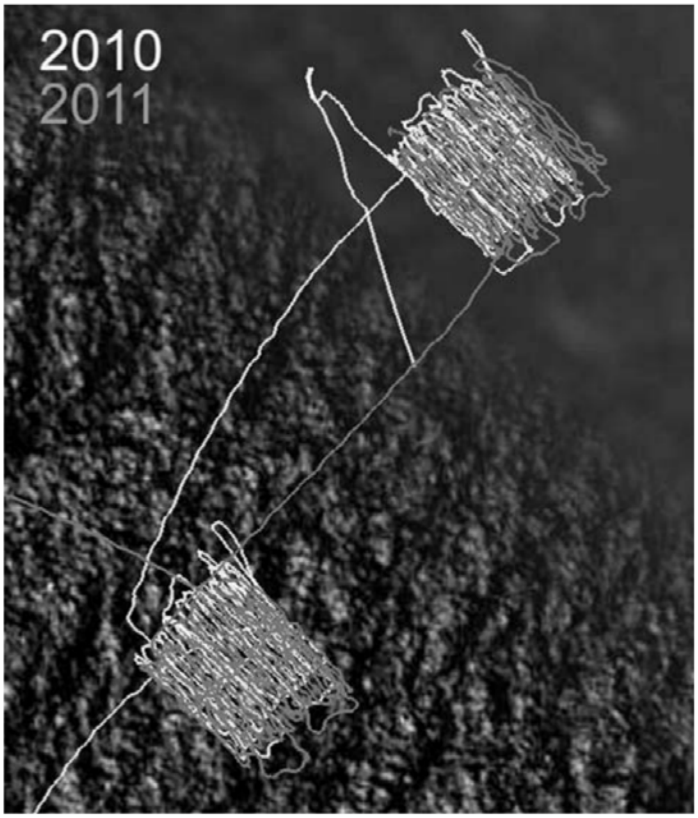


Figure 8. Actual flight paths at a 15m site in the Houtman Abrolhos Islands during the 2010 and 2011 surveys (39). Each dense grid is 25m by 25m, which is 625 m^2 or less than 0.001 km^2.

Relevance to Government agencies

The examples highlighted above show that AUV Sirius has generated multiple data sets since 2007 that have expanded knowledge about marine benthic communities in coastal waters.

Fisheries applications

In Western Australia, staff from the Department of Fisheries WA were authors on a publication declaring AUV surveys at Houtman Abrolhos and Rottnest Island Figure 5) as providing data streams that "will track natural variability in benthic habitat structure, which in turn will facilitate the detection of ecological change and ultimately feed back into the EBFM (ecosystem-based fisheries management) processes (40). The AUV surveys at both locations were based on dense grids and captured effects from the 2011 marine heatwave (35-37) at this scale. Despite the strong relevance of this heat anomaly to the Department (34, 35), WA Fisheries co-invested in the research with vessel support only in 2011.

Discussions with staff in the Department suggested several reasons for their lack of co-investment in AUV surveys over the same locations in Western Australia since 2011. One factor is the competing demands for time on the one vessel (FRV Naturaliste) competent to support operations by the IMOS AUV Sirius. Limited time in the vessel schedule is complicated by a narrow window (April/May) in the regional weather climatology permitting safe launch/retrieval of the AUV (Gary Kendrick, pers. comm.). The same concerns (vessel availability, seasonal sea state climatology) were echoed in discussions with government employees in South Australia. The greatest insight from the discussions with research staff from Fisheries WA committed to EBFM, however, was their realisation that changes observed on the dense grids were too fine to be of use at larger scales. An alternative design is clearly required but this is a sampling challenge for patchy habitats distributed across a broad shelf with low slope.

A greater challenge to more uptake of results from the AUV program to support EBFM in WA comes from frequently heard opinions that other technologies (e.g. towed video, dropped cameras) are cheaper and easier ways to deliver the desired data. A similar sentiment was encountered during discussions with staff from NSW Fisheries. This critical assertion is explored further below, after the description of alternative observing technologies.

In 2012, the NSW Department of Primary Industries used the AUV Sirius to survey three MPAs (Solitary Islands Marine Park, Port Stephens-Great Lakes Marine Park, and Batemans Bay Marine Park) along its coast as the start of a long-term benthic monitoring program. The baseline surveys detected benefits from increased marine protection despite the relatively short life (5-10 year) of most reserves. While the sampling design allowed the effect of protection to be considered over multiple spatial scales, the plots were again based on dense grids (625 m^2).

For a period after 2012, NSW DPI lacked surface vessels suitable for Sirius missions. This forced the fisheries staff to use other observing technologies to continue the program and they became satisfied with the cost effectiveness of the alternative sampling tools. Even so, the Sirius returned to Batemans (2014) and Port Stephens (2015). In 2019, the Department acquired a vessel of size permitting use of the portable ramp-based launch and recovery system for AUV Nimbus and this combination was used in 2020 surveys of the Port Stephens-Great Lakes Marine Park.

In the Solitary Islands, baited underwater cameras were deployed in 2012 to survey fish assemblages on rocky habitats that had been mapped previously by MBES and surveyed by the IMOS AUV. Images collected by the Sirius were converted to 3D terrain maps and estimates of structural complexity. The key finding was that a high proportion of the variance in fish community composition and abundance was explained by the habitat complexity metrics as well as benthic biota and depth. This is an example where the fine scale mapping of the substrate by AUV Sirius provides part of the solution (41).

In another example relevant to fisheries management, AUV Sirius was used at locations along the Tasman Peninsular in Tasmania to measure the size and abundance of an abundant and commercially important rockfish, *Helicolenus percoides*, on rocky habitats inaccessible to trawl gear (42). The survey revealed ontogenetic preferences for different habitats and a general increase in the abundance of this species with depth. The authors of this study were positive about the potential for image-based assessments to provide fishery independent data for EBFM assessments that would be free of biases (size selectivity, gear avoidance) found in traditional sampling methods. They concluded that AUVs are a mature and cost-effective survey platform suitable for fishery-independent assessments of rocky reef species.

In a final example of application, the IMOS AUV Phoenix (jointly operated by Australian Marine Ecology and the ACFR) was found to be a suitable tool for establishing scallop densities on the seafloor (18). With its small form factor allowing easy retrieval and recovery, this might well find favour in other fisheries exploiting sedentary species from soft flat habitats (scallops, sea slugs).

Marine conservation applications

The IMOS AUVs have done more surveys of benefit to marine conservation and produced more outputs on this topic. Most long-term monitoring programs in place today were started by enthusiastic individuals who were able to sustain consistent observations for a decade or more. The Marine Biodiversity Hub has brought together several such champions ensuring the growth of monitoring programs for benthic biodiversity in several states since 2009. Given the Hub's base in Hobart, it is no coincidence that there are more contributions from marine ecosystems around Tasmania.

This island State has just five small marine reserves on its mainland coast along with a dozen marine conservation areas scattered throughout the Bruny Bioregion. In addition, the State territorial waters are surrounded by multiple Commonwealth marine parks. By 2009, in the first phase of the MBH, benthic surveys were completed for temperate reef habitats from seven locations representing both State and Commonwealth waters through a collaboration between Geoscience Australia (GA) and the Tasmanian Aquaculture and Fisheries Institute (TAFI). The purpose of these surveys was to collect co-located data streams for physical and biological variables to model patterns of marine benthic biodiversity. AUV Sirius provided high resolution images of reef habitats and their biota. Years apart, it has shown a valuable capacity to provide data from the same substrata without needing to generate dense grids (Figure 9).

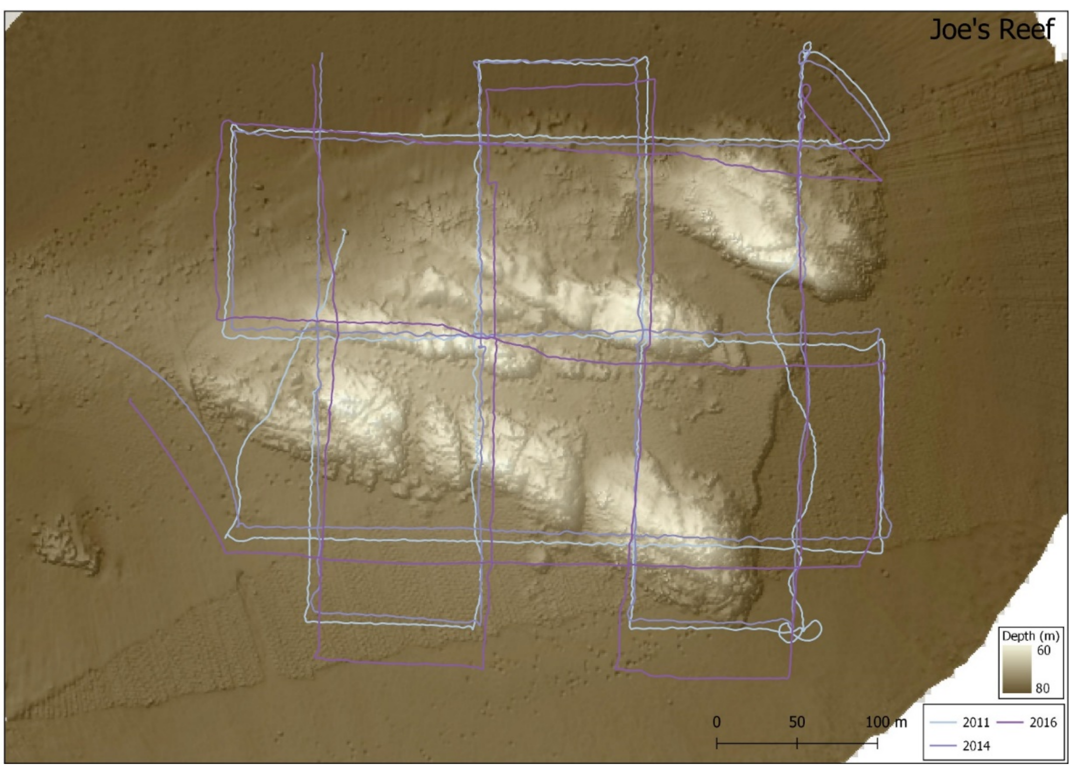


Figure 9. Survey paths from Joe's Reef for AUV Sirius missions in 2011, 2014 and 2016.

These quantitative biological baseline surveys of shelf rocky reef biota were designed from the start to inform monitoring of the newly declared Commonwealth AMPs. While the focus has remained on Tasmania, the same approaches have been expanded to State Parks off the coasts of WA and NSW. In 11 years (2009-2019), the AUV Sirius has made 29 repeat missions to four of the Commonwealth AMPs around Tasmania (Table 1). This represents 40% of all AUV missions in the same period.

The investment in sustained monitoring from the South-east marine parks network has been celebrated on the external website of Parks Australia in anticipation of a pending report from the MBH. I have seen a draft of this report, which represents a very substantial contribution of new knowledge on community patterns and stability in deep-water shelf communities, with the first evidence of temporal change for some morphospecies. The release of this information in early 2021 will be timely because Parks Australia is developing network level science plans for all six of the AMP networks and this task is expected to be done by the end of the calendar year. The South-east network plan will be the first and will set an example for the other five networks.

While the first surveys by the AUV Facility were in tropical waters in 2007 (the first year of IMOS operations), results from the first surveys of temperate Australia were used by MBH researchers to recommend strategies for the best way to collect data with the AUV, analyse AUV imagery, and predict the distribution and abundance of benthic habitats and their associated biota (25-26, 43-50). The purpose of these multiple studies was to provide guidelines for researchers to design evidence-based monitoring programs for Marine Protected Areas (12).

Alongside the provision of a rich stream of advice on design aspects of AUV surveys, the MBH researchers also collated existing mapping in all AMPs. When published in December 2017, they noted that only six AMPs (Beagle, Geographe, Huon, Flinders, Freycinet, and Tasman Fracture) had existing AUV transects, although Hunter and Lord Howe from the East temperate Network have been added in 2018 and 2020, respectively. In the context of informing national State of Environment Reporting, the authors noted the lack of AUV transects in the AMPs along most of the southern and western coastline of mainland Australia as a significant gap in the national AUV monitoring program.

South Australia has 19 marine parks covering 46% of the State's marine waters. Much of this area is within the semi-enclosed waters of the two major Gulfs (Spencer, St Vincent). In 2008, the AUV established 10 baseline transects in the Joseph Banks MP within Spencer Gulf. In 2018, it surveyed four sites in a new area (Western Kangaroo Island Marine Park) and resurveyed two of the 2008 sites. In 2020, the KI sites were resurveyed, and three new baseline sites were established (Gretchen Grammer, pers. comm.) None of the AMPs adjacent to SA waters have been sampled to date by the AUV. Researchers based in Adelaide nominated the limited availability and inflexible schedule of the only research vessel in SA capable of deploying AUV Sirius (RV Ngerin) as reasons for the absence of sampling along the exposed coastline. Even more so than in temperate WA, they cited the brief and unpredictable weather windows as a major impediment to operating in the Great Australian Bight.

Table 1. Repeat AUV missions to four AMPs in the South-east Marine Parks Network

Marine Park	Site Name	Depth (m)	Habitat	When surveyed
Huon	Huon Marine Park site 1	45-71	Extensive rocky reef; sufficient light to support algal communities	2009, 2010, 2014
Huon	Huon Marine Park site 2	47-72	Extensive rocky reef; sufficient light to support algal communities	2009, 2010, 2014
Freycinet	Joe's Reef	59-83	High profile granite reef; beyond or close to the limit of the photic zone.	2011, 2014, 2016
Freycinet	Freycinet MP Site 2	93-100m	Sand dominated, with low relief structure typically covered with a veneer of sand	2010, 2012, 2014, 2016
Flinders	Flinders North West	41-45m	Sand dominated with patchy areas of hard substrate and low relief features	2013, 2017
Flinders	Flinders Outer Patch Reef	75-94m	Sand dominated with patchy areas of hard substrate and prominent ledge features which are often sand inundated	2011, 2013, 2017
Flinders	Flinders Canyon Grids North	112-181m	Flat sandy areas punctuated with high relief rocky walls and boulders	2011, 2013, 2017
Flinders	Flinders Shallow Grids	62-78m	Sand dominated region with areas of hard substrate including underlying shell beds	2011,2013, 2017
Flinders	Flinders West Boundary	43-52m	Low lying rocky reef ledges often covered in a veneer of sand	2011, 2013, 2017
Beagle	Beagle Mid-Shelf 3	57-65	Sand dominated with patchy areas of hard substrate including underlying screwshell and shellhash beds	2017, 2018

Victoria, despite having the shortest mainland coastline of any coastal State, has 13 marine national parks and 11 marine sanctuaries. Most are quite small (compared with SA) as they collectively cover just 6% of the State's marine waters. The IMOS AUV surveyed seven sites around Wilsons Promontory in 2016 in depths from 10 to 75m in a collaboration with Deakin Marine Mapping. The latter has been leading the mapping of seafloor habitats and marine biota within the State. It is led by Daniel Ierodiaconou, who also leads the Victorian Node of IMOS. The systematic surveying of marine habitats in Victoria has led to a Victorian Marine Data Portal sharing a close resemblance with the AODN.

The 2016 AUV data from Wilsons Promontory have been analysed and are included in a Technical Report currently under review within Parks Victoria. The latter has supported monitoring in the network of marine parks and sanctuaries since 2002 but the report will recommend an upgraded monitoring program (Signs of Healthy Parks, SHP) that will focus on at least one park from each of five bioregions (likely to be Discovery Bay MNP, Point Addis MNP, Port Phillip Heads MNP, Wilsons Promontory MNP, and Cape Howe MNP). The release of this Technical Report in 2021 will be accompanied by the release of a MERI Plan (also currently being finalised) for monitoring in the five 'priority' MPAs. AUV surveys are likely to be recommended as appropriate for three of the five (Discovery Bay, Wilsons Promontory, and Cape Howe); however, the capacity to deliver these surveys will depend on whether Parks Victoria can access a vessel capable of deploying AUV Sirius or Nimbus. The portable ramp designed by the ACFR for AUV Nimbus is likely to assist. There are plans also to trial AUV Phoenix in the Point Cooke Marine Sanctuary (in Port Phillip Bay).

The New South Wales mainland coastline is just longer than Victoria. It has six marine parks including one far from the coast (Lord Howe MP). The AUVs Nimbus and Sirius were compared in site surveys from Elizabeth and Middleton Reefs (Lord Howe MP) in early 2020. These are available to be viewed or downloaded from the AODN or Squidle+. The latter also reveals that the IMOS AUV has been deployed in three of the other five marine parks (Solitary Islands MP, Port Stephens-Great Lakes MP, and Batemans MP) plus a campaign around Botany Bay in 2012.

The five marine parks in NSW are oversighted by the Marine Estate Management Authority (MEMA) established in 2013 as a single authority to provide advice to government on management of the NSW marine estate. MEMA released the Marine Estate Management Strategy 2018-2028 (MEMS) in 2018 but this is a high-level statement. Underneath it, however, there is a state-wide kelp/benthos monitoring program using towed video being conducted in NSW as part of climate change monitoring. This program is part of a detailed NSW Marine Integrated Monitoring Program (MIMP) which contains only one reference to monitoring by AUV; reproduced in the following reduced paragraph.

"Sampling at each site consists of replicate transects (~1.5 m wide by 200 m long) conducted using towed video… Additional data may be collected at greater depths (i.e., 20–40 m) using the AUV periodically".

When questioned about the low profile of the IMOS AUV in the MIMP, the feedback mentioned the period when NSW DPI had not had access to a vessel with the capacity to deploy and recover AUV Sirius, and thus the shift to other observing equipment less dependent on vessel size. The experience had convinced staff that these alternative tools were cost-efficient and provided data streams adequate for the purpose. A subsequent cost-benefit analysis involving towed videos and ROVs is instructive (51).

In summary, the IMOS AUV has established the baselines to track change in marine benthic communities from sub-tropical, temperate, and sub-temperate environments. It is well placed to support the monitoring of marine benthos in deeper waters covered by the network of Australian marine parks administered by Commonwealth. An obvious question is what about the northern Australia?

Edyvane and Blanch (2016) state that the Northern Territory ranks last among Australian jurisdictions in creating a comprehensive, adequate, and representative network of marine protected areas. It has only two marine parks (Cobourg, Limmen) and does not have published plans for monitoring either (52).

In Queensland, the greatest marine conservation target on the east coast is the Great Barrier Reef Marine Park declared in 1975. The GBR Marine Park has long had a plethora of champions (from the academic and State sectors) who have established many biological monitoring programs. AIMS institutionalised the monitoring of coral cover in 1985.

The Australian and Queensland governments jointly launched the Reef 2050 Long-Term Sustainability Plan in 2015, and an update in 2018. Public consultation on the draft updated Plan closed in September 2020 and operational plans are now being developed informed by the strategy. A key initiative of the Reef 2050 Plan is the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP). The state of RIMREP is described in its 2020-2021 Business Plan. Appendix 1 of that Plan identifies IMOS as an existing partner already contributing observations through a half dozen Facilities. One the priorities for RIMREP during the 2020-2021 year is to “Finalise a list of prioritised gaps for indicators and information collection”.

Other Benthic Imaging Technologies

The scope here is on imaging techniques that collect a visual record of marine benthos that is later analysed to extract patterns of community structure, species abundance, or evidence of change. These techniques can be subdivided into those directed by humans and unsupervised autonomous systems (excluding AUVs).

Supervised technologies

In shallow water, marine life has been surveyed since the 1980s by divers. In the case of Tasmanian marine reserves, the first decade of change was based on annual surveys across all sites at just 5 m (53). On the Great Barrier Reef, 32 years of systematic monitoring by AIMS SCUBA divers have been done in the upper 10 m. Around the turn of the last Century, AIMS divers switched from pencil and paper recordings along underwater transect lines to underwater video to capture a continuous visual record from the same sites. The use of video required less diving time than the line intercept method and provided a permanent record of the reef benthos at an instant in time; thus, allowing the reuse of tapes in the case of changing analytical methods. A SOP manual describing the use of the diver-held cameras and the analytical interface (AVTAS) was published in 2004 and updated in 2020. The latter shows that video was replaced by digital still cameras in 2006.

During the life of the IMOS AUV Facility, staff from the ACFR have developed diver-held underwater stereo imaging systems. A diver swims with a camera in a spiral pattern, unwinding a line around a drum to ensure even track spacing and a consistent survey footprint. These records are subsequently converted to orthomosaics like the dense grid product produced from the AUV surveys. These very accurate 3-D terrain maps have been used to track changes in individual coral colonies and community attributes (including rugosity) on shallow reef tops following a variety of disturbances including heatwaves and cyclones (54).

Starting in 2012, an international collaborative program (XL Catlin Seaview Surveys) has mapped coral reefs from 23 countries using an innovative camera system propelled by a military grade underwater scooter (Figure 10). At the front of the scooter, three digital still cameras collect images every three seconds. Subsequent processing of the imagery allows the creation of 3-D panoramas with the feel of Google Street Maps, which can be navigated from the Web. The high resolution still images can also be analysed for their information content on the benthic substrate. Like the AUV, this imagery is accurately georeferenced and accompanied by sensor data for depth, temperature, camera inclination, and altitude. In 2020, over a million high-resolution photo-quadrats surveyed between 2012-2018 from five major reef bioregions were analysed at the University of Queensland. This short turnaround from data collection to publication was made possible by using artificial intelligence to automatically estimate the proportional cover of benthic components in the quadrats (55). The result is the first quantitative baseline for global reef condition.

In deeper waters, towed rigs have a long history of use (Figure 11). As tethered systems, forward looking video cameras provide the surface-based operator with a view of the seabed. This is critical for collision avoidance because these towed devices rely on weight to keep them near the seabed and are incapable of autonomously adjusting their altitude above the bottom. This is done typically by the operator having control over the vessel winch to adjust the amount of wire in the water. For the same reason, these rigs experience heave in rough sea states, especially when deployed in shallow water. The video data stream can also be used for real-time data acquisition by a second operator. Most towed-camera systems are also equipped with down-facing digital still cameras that collect a timed series of benthic images for subsequent annotation and scoring.

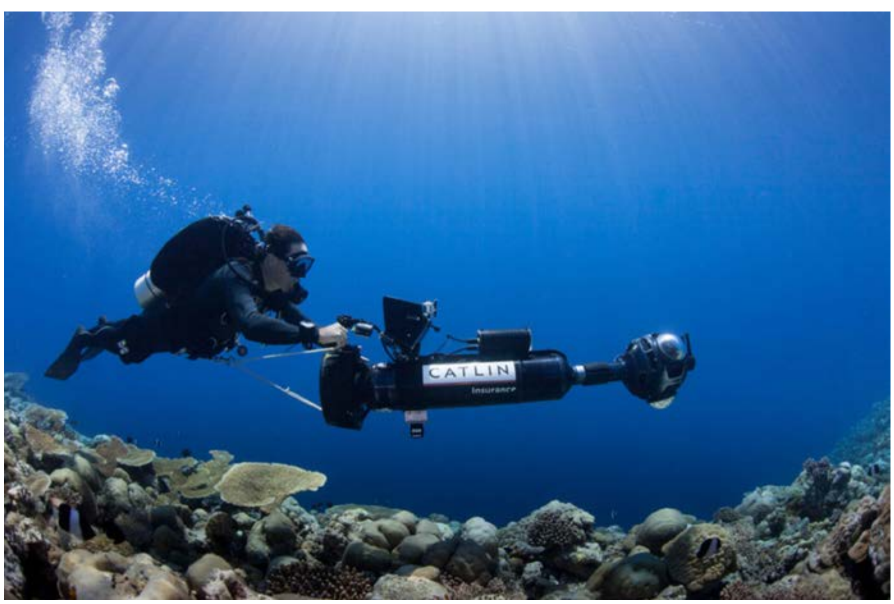


Figure 10. The supervised but self-propelled camera system used by the XL Catlin Seaview Survey team.

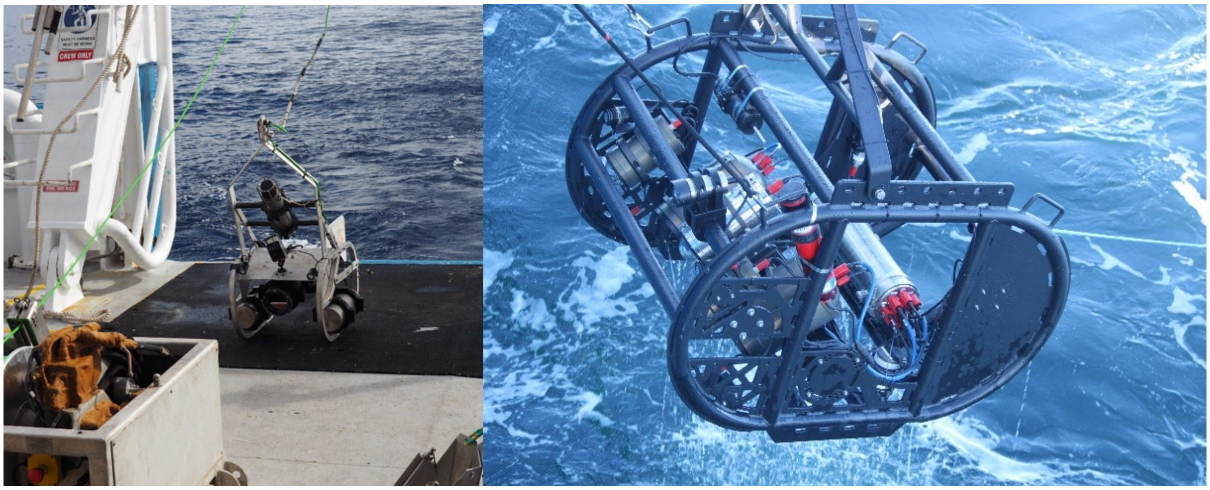


Figure 11. Towed cameras deployed by AIMS (left) and CSIRO (right), designed for different water depths.

The final and most diverse category of supervised observing systems is Remotely Operated Vehicles (ROVs). These are tethered systems capable of movements with six degrees of freedom (Figure 12). Since they are not connected to the surface by rigid wires, they are not subject to the same wave driven heave as most towed camera systems. Because the flexible umbilicus is for two-way communications rather than retrieval, the ROV can be navigated by surface operators and its attitude stabilised by feedback between multiple thrusters and data streams from on board sensors.

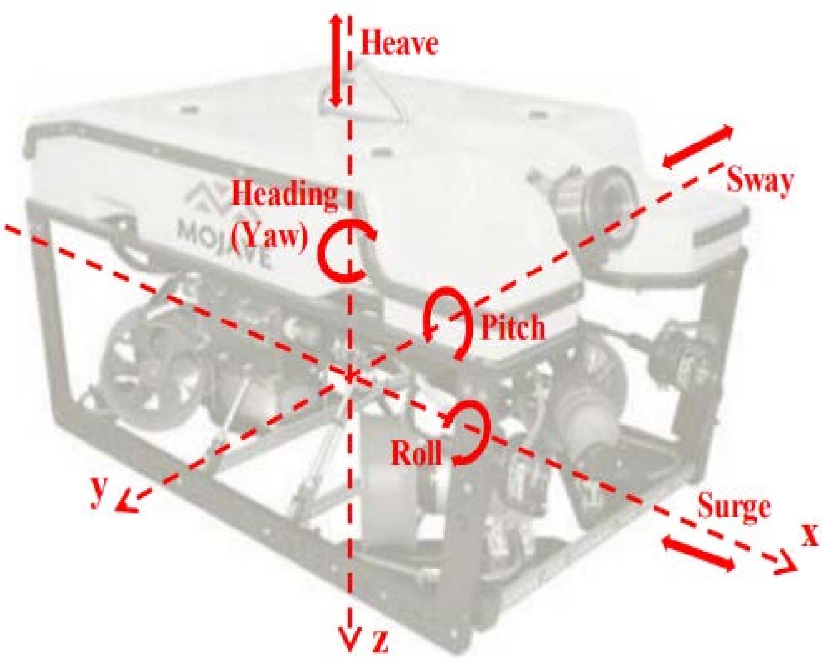


Figure 12: The six degrees of freedom controllable in ROV orientation with a complete set of thrusters (56).

Within the diverse range of designs on the global market, ROVs can be divided into two major classes: (1) Work class (aka Intervention-class) ROVs designed for deep sea operations and/or use by heavy industry, and (2) Inspection-class ROVs designed a variety tasks consistent with much shorter tethers (Figure 13). The smallest devices in the latter can be very compact, such as ROVs designed to provide condition reports from within narrow pipelines.

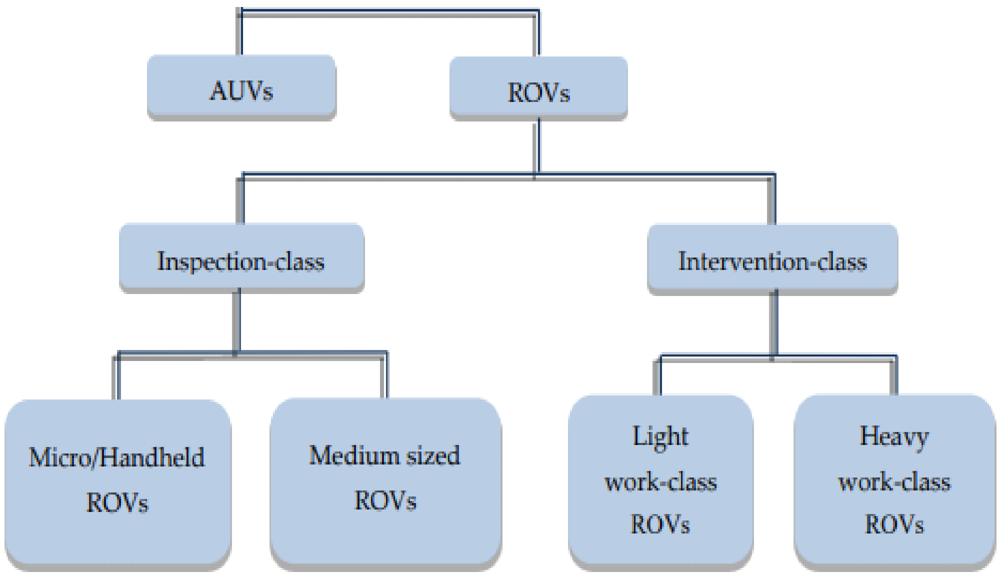


Figure 13. A classification of unmanned underwater vehicles (modified from 56).

Work class ROVs can range from 100 kg to 5000 kg. The largest systems can operate to 6000 m and are usually actuated with hydraulic systems. Their large size usually requires a Launch and Recovery System (LARS) containing a Tether Management System (TMS). Such large systems can be deployed only from very large vessels or from fixed platforms such as those used for oil and gas production. The light work class ROVs are typically electric vehicles capable of operations to a few 1000 m and may be deployed in free-swimming mode (Figure 14). The range of vehicles from medium to large can be seen in the fleet available for hire from the largest Australian owned ROV operator. Even the smallest (called an observation class ROV) is powered through the tether from surface sources.

Figure 14. ROVs from SAAB SeaEye with integrated LARS and TMS (left) or surface TMS (right).

Intervention-class ROVs and their support crew may be committed to lengthy assignments for regular tasks on production platforms. The duration of these work schedules inevitably includes down time. A collaboration between the oil and gas industry and researchers to utilise this down time for science has resulted in SERPENT (**S**cientific and **E**nvironmental **R**ov **P**artnership using **E**xisting i**N**dustrial **T**echnology). SERPENT is a global project hosted by the National Oceanography Centre, Southhampton (UK) but the partnership includes four Australian universities (USyd, UTS, UoW, UWA) as Lead Partners. The partnership has described the program, the application tasks, and some of the benefits achieved to date in multiple publications (57-59). Outcomes include incidental observations on deep life (extending the depth limits for many species, capturing displays of behaviour), and planned studies based on adding instruments and/or collecting samples. The latter include seabed oceanography, marine noise, microbial structure, and the effects of drill spoil on soft-sediment megafauna (60). Figure 15 documents the vertical depth distribution of cold-water corals growing on one production platform in the Gulf of Mexico as measured by ROV.

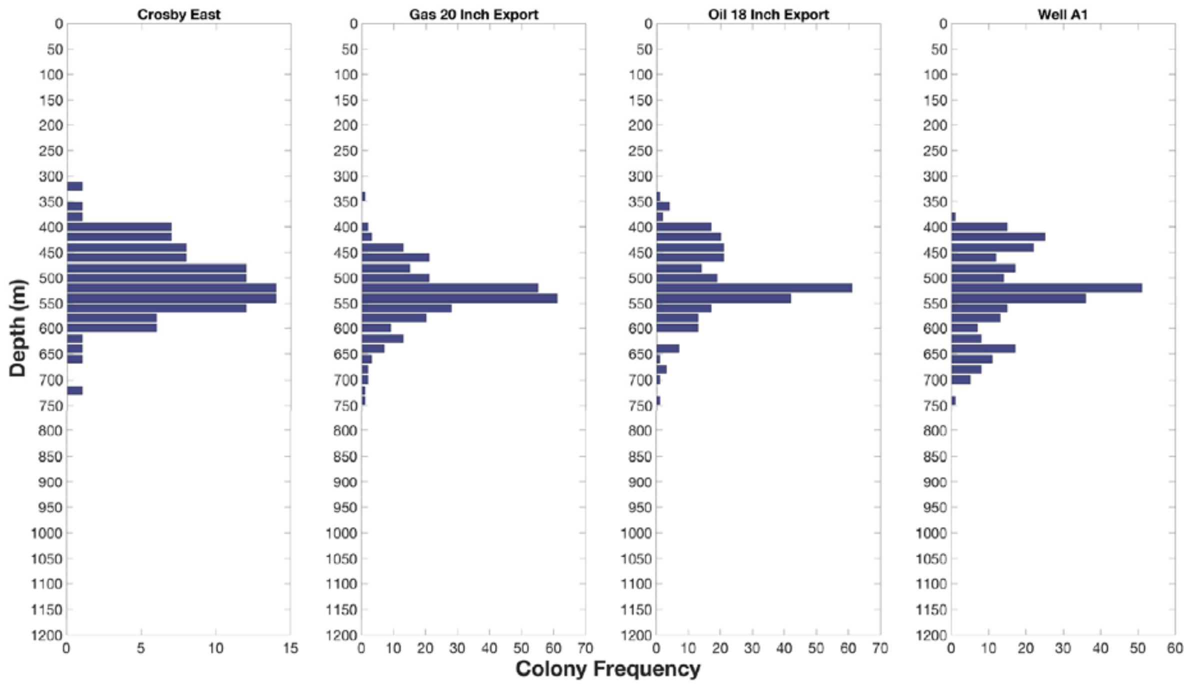


Figure 15. Vertical distributions of *L. pertusa* on separate risers of the Shell Ursa platform (59).

Sward, Monk and Barrett (2019) reviewed 119 publications that reported using ROVs for visual surveys of fish (61). Their global review covered all four classes of ROV from Figure 13 and classified the use cases by purpose, sampling strategy, and sampling metric. Although most of the use cases were from the Northern Hemisphere, the review included studies from north-west Australia where fish have been assessed with ROVs around industry infrastructure including platforms (62), wellheads (63), and pipelines (64). Recent publications have assessed the importance of these data collected with the assistance of industry to the coming era when a lot of oil and gas infrastructure is due to be decommissioned (65-67).

Large ROVs used with the primary purpose being scientific discovery are typically associated with the global fleet of oceanic research vessels. Historically, Australia has been able to benefit from this technology when one of these vessels transits through Australian waters. An example is Thresher et al. (2014) who used the visit of the RV Thomas G Thompson from the UNOLS fleet in 2008/09 to survey sites south of Tasmania down to 4000 m with a combination of gear including the CSIRO deep towed camera system and autonomous vehicles (AUV ABE, ROV Jason2) supplied by the Woods Hole Oceanographic Institution (68). In more recent years, the US-based Schmidt Ocean Institute has brought its flagship, RV Falkor, to Australia on three campaigns: 2012, 2015, and 2020. Among the many missions this vessel has achieved since 2012, most of the Australia cruises have involved the use of two ROVS carried on the ship: ROV SuBastian capable of operations to 4500 m and a SAAB SeaEye Falcon suitable for use in shallow water to 300 m. In the 2015 season, these ROVs were used to provide the first assessment of deep habitats and communities in the Perth Canyon (69). Subsequent cruises in the same year were a co-ordinated robotics cruise to Scott Reef involving the IMOS AUV Facility, and the mapping of submerged and emergent features on the western margin of the Oceanic Shoals bioregion in the Timor Sea. All science communications associated with each cruise is found at the bottom of the appropriate web page, below the final Cruise Report.

In 2020, the RV Falkor spent the whole year in Australia. Operations started with repeat surveys in the Perth Canyon and similar studies of the Bremer Canyon of the Great Australia Bight. During a clockwise navigation of northern Australia, the ship used its ROVs to survey canyons east of the Ningaloo Marine Park, the Coral Sea Marine Park, the northern Great Barrier Reef, and the submerged margins of the continental shelf east of Rockhampton. The ship is currently in the Tasman Sea carrying out bathymetric surveying around the chain of seamounts east of Brisbane. The current schedule ends with a cruise in April 2021 to survey mesophotic communities on the North West Shelf.

ROVs are particularly well suited to locations offering steep relief. In such cases, the surface vessel can be held seaward of the submerged rise using dynamic positioning and the ROV flown up the adjacent slope to reveal zonation patterns in benthic assemblages across a large depth gradient. This pattern was repeated on many occasions by Falkor and SuBastian during 2020 in its explorations of canyons and/or seamounts.

Beaman et al. (2016) used an ROV (Cherokee) loaned from MARUM (University of Bremen, Germany) rated to 1000 m to survey spatial patterns in the distribution of benthic assemblages between 92 and 787 m on the flank of the emergent Osprey Reef in the Coral Sea (70). The same ROV was also used to record the presence and behaviour of live *Nautilus pompilius* between 100-800 m (71). The success of these past and recent missions has no doubt inspired the business planning for the National Marine Facility Vessel, RV Investigator, which has recently upgraded its deep towed camera system and foreshadowed the acquisition of one or more ROVs from the light intervention class (Figure 13) in the next few years.

Large ROVs are required for waters off the continental shelf but there is a very large area of submerged habitat on the continental shelf that can be surveyed by inspection class ROVs capable of operating to shallower depths. The SAAB SeaEye Falcon owned by CSIRO Oceans and Atmosphere is among the largest of the inspection class vehicles and can operate to 300 m. Although the ROV weighs just 60 kg and can be managed by hand, it needs to be powered from the surface and is recommended to be deployed and recovered with a proprietary launch and recovery system.

Between the Falcon and the smallest (mini) ROVS in the inspection class (Figure 13), there is a cluster of battery powered ROVS that are lighter, can be launched by hand from a small boat, require tether management no more complicated that a hand spool, and provide reliable operations to at least 100 m. My enquiries showed that such devices are now owned and operated by a dozen research organisations (Table 2). Although there is more than one supplier of vehicles feeding this market, one brand has become more popular than others. Several dozen BlueRov2 units have been acquired by science agencies and academic researchers in the last five years. These vehicles are manufactured in southern California, but the Company has Australian distributors in Brisbane, Sydney, and Hobart. The ROV is modular allowing upgrade and customisation and supplied with open-source electronics and software. The entry model is priced around $5000 AUD, which no doubt accounts for its rapid penetration of the local market.

Researchers owning these light inspection class ROVs have applied them to multiple tasks. Ironically, those from the centres of innovation for AUV technology (IMOS, AMC, QUT) nominate the main role for their ROVs as back up support for the autonomous vehicles. The ACFR has used its ROV to free the AUV Sirius from entanglement with ghost fishing gear when on assignment in Greece.

Table 2. Inspection class ROVs used for seabed operations by non-industry owners.

Operator	Model	Units	Depth limit	Main tasks
AMC	BlueRov2 Heavy	1	400	AUV rescue
SA DEW	Oceanbotics SVR-8	1	305	Mapping and monitoring
ACFR	Seabotix vLBV 300	1	300	AUV rescue
CSIRO	SeaEye Falcon	1	300	Observing/collecting
AAD	SeaEye Falcon	1	300	Krill assessment
PIRSA	Videoray Pro 3 GTO	1	150	Biosecurity assessments
USC	Openwater Trident	1	100	Observing
AMC	BlueRov2	1	100	AUV rescue
UWA	BlueRov2	1	100	Engineering design
NSW DPI	BlueRov2	1	100	Mapping habitat, observing fish
AAD	BlueRov2	1	100	Under ice observing
Umelb	BlueRov2	1	100	Mapping habitat
UoW	BlueRov2	1	100	Observing/collecting
QUT	BlueRov2	2	100	AUV rescue
AIMS	BlueRov2	2	100	Observing/collecting
UQ	BlueRov2	2	100	Reef monitoring
Newcastle	BlueRov2	2	100	Mapping habitat, observing fish
Curtin	BlueRov2	3	100	Mapping habitat, observing fish

The most common use of inspection class ROVS is naturally observation. Applications include range extensions of known species both geographically and vertically, documentation of unknown behaviours, mapping of habitats and faunal assemblages across spatial gradients, documentation of fish-habitat relationships, inter-comparison with other techniques that are used to generate predictive models, and limited monitoring. The limited use of the inexpensive battery powered AUVs for monitoring is likely to reflect the relatively recent arrival of this class of ROV into the Australian market. The BlueRov2 vehicles, which have become popular, are based on improved thruster technology that was developed following a 2014 Kickstarter campaign.

Some researchers have exploited the manipulative ability of ROVs to collect samples as directed by surface operators. These samples have been used to establish the genetic connectivity of species between depths, to confirm species identifications in visual images, and to find new species. Observations by ROV, supported by collections, have been applied to questions like understanding the impact of local disturbances (e.g. fish farming, vessel anchoring) on marine benthic communities (72-74).

In contrast to AUVs, which currently do not have a high usage among companies supplying or requiring subsea services, ROVs are the traditional marine robotic platforms of choice supporting the heavy industry offshore.

Table 3. ROV services other than those requiring Work-Class vehicles advertised by commercial suppliers. This is a representative rather than exhaustive list of companies supplying such services.

Owner	HQ	ROV Class	Depth	Main tasks
DOF Subsea	Int	Observation	2000	Offshore infrastructure
Fugro	Int	Observation	1500	Offshore infrastructure
ROV Innovations	QLD	Observation	1000	Offshore infrastructure
EGS	Int	Observation	1000	Offshore infrastructure
Geo Oceans	WA	Observation	950	Infrastructure inspection
BlueZone Group	NSW	Inspection	950	Aquaculture inspections
Tamboritha	WA	Observation	600	Infrastructure inspection
AUS ROV	QLD	Observation	500	Infrastructure inspection
MMA Offshore	Int	Inspection	300	Infrastructure inspection
Australian Marine Ecology P/l	VIC	Inspection	300	Marine surveys
Abyss Solutions	NSW	Inspection	300	Asset management
SOSsub	Tas	Inspection	300	Suppliers/distributors
O2M Group	WA	Inspection	300	Marine surveys
Ocean Optics	NSW	Inspection	300	Marine surveys
MSI Seasense	Tas	Inspection	200	Suppliers/distributors
Commercial ROV Australia	WA	Inspection	200	Suppliers/distributors
Southern Commercial Divers	NSW	Inspection	150	Infrastructure inspections
Fathom Pacific	VIC	Inspection	100	Marine surveys
Elgin Associates	Tas	Inspection	100	Marine surveys
Undersea ROV	QLD	Inspection	100	Marine surveys

While this partly reflects the later maturing of autonomous underwater systems (Figure 1), the dexterity of even the large work class ROVs, which are required to operate very precisely among complex and sensitive infrastructure, plus their ability to carry out a wide range tasks under close human supervision provides the combination of essential services required by the offshore industry. In this operating environment, even tasks requiring non-manipulative tasks are done by ROVs from the light work class. In Table 3, these are called Observation Class vehicles to distinguish them from smaller lighter ROVs called Inspection Class where observations are the primary purpose. Even among the smallest companies using ROVs rated to 200 m, the greatest demand for observations comes from infrastructure inspections rather than marine ecological surveys. I found no examples of a commercial firm contracted to supply observations for the purpose of benthic monitoring.

Unsupervised technologies

This category of visual imaging techniques is based on untended cameras, which can be distributed in many ways. In the 1990s, AIMS started dropping water-proofed cameras from rubber boats to sample seabed substrates in north west Australia; both in areas where turbidity (=underwater clarity) precluded mobile apparatus and/or in shallow coastal waters where the presence of estuarine crocodiles precluded divers. The same approach is inherent in landers used to sample the deep sea. In both cases, each launch returns imagery from a fixed location at the bottom of the drop. In shallow water, the camera will be dropped on a tether and triggered when contact is made with the bottom. Although tethered, the surface attendant does not influence the result except by choice of location. This is also the case with landers launched into the deep sea. These free-falling units are untethered and typically return passively to the surface after the timed release of ballast. Given their design and logistics, deep sea landers collect time series data from relatively few positions, whereas the tethered drop cameras used in shallow water typically collect a few images from their landing point before being moved to a new location.

In shelf depths, especially in Australia, the most common form of seabed lander is a weighted frame attached by line to a surface buoy for retrieval. The frame is most often populated by a pair of synchronised digital cameras that provide stereoscopic vision, which allows the size of objects in the field of view to be extracted in subsequent analysis. Battery powered lights are sometimes included but typically used only in the deepest diurnal deployments or those requiring night vision.

The most common class of these landers includes a fish bait in the centre of the field of view. These devices are called a BRUV (Baited Underwater Remote Video) unit. If the same design is unbaited, it is a RUV. While the overwhelming use of these B/RUVs has been for benthic studies, the same designs have been deployed near the surface in oceanic waters to assess pelagic species, especially sharks. These modified applications are distinguished by an appropriate prefix, e.g. p-BRUV. The suite of field manuals developed by the MBH covers the operation of both categories with separate manuals.

BRUVs were designed to attract fish, and they produce data about the local composition, abundance, and size of fish observed during a standardised observation window (typically one hour). Because the camera field of view captures the background habitat as well as the fish attracted by the bait bag (Figure 16), they allow fish habitat relationships to be constructed and these can be powerful when based on many replicates. With instruments on the BRUV frame to measure physicochemical variables, these relationships can be made even more precise.

BRUVs have been used worldwide by many studies to answer questions about fish distribution and abundance within and among different habitats and depths (75-79). The MBH SOP manual for BRUVs includes a supplement that attributes the propose of 259 publications returned by a 2019 literature search. The top three topics were fishing impacts (n=80), spatial and habitat associations (n=79), and behavioural studies (n=63). Although providing point source data from each deployment, BRUVs data can be scaled up to large areas of seabed by models using spatial covariates (e.g. bathymetry, geology, seabed climatology, etc.) with the quality of the result dependent on the granularity of the sampling and the choice of informative covariates.

In 2018, GlobalArchive was developed as a collaborative project supported by the Australian National Data Service (ANDS) to provide an online centralised repository of fish image annotation. The Archive contains data sets from more than a dozen underwater imaging technologies but is dominated by those from benthic stereo-BRUVs (Figure 17). Among the data sets listed, the BRUVs data from the Global FinPrint project has just been published to provide a contemporary view of the conservation status of reef sharks (80).

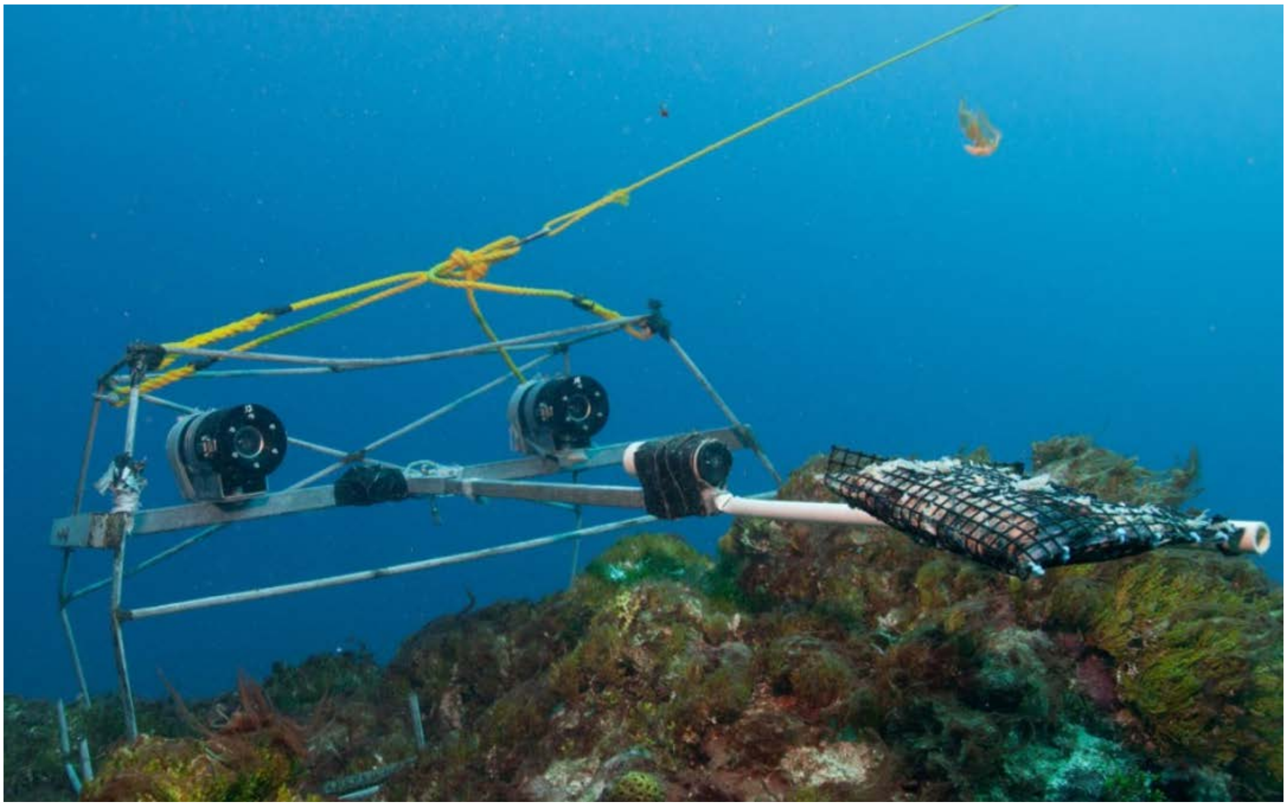


Figure 16. BRUVs record fish attached to the bait bag (foreground) and the local habitat (background).

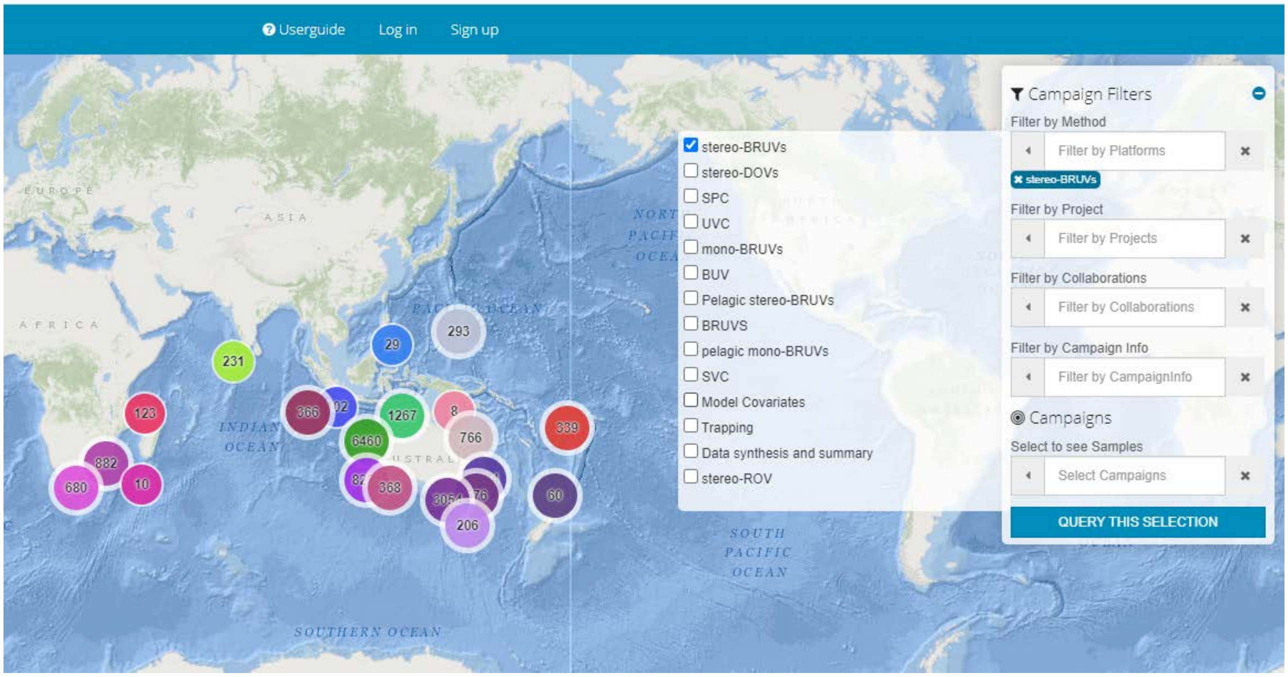


Figure 17. A partial list of data sets from stereo-BRUVs catalogued on the GlobalArchive site. More than a dozen modes of deployment can be selected from the break-out list for "Filter by Method".

Comparison of alternative sampling techniques

In 2018, researchers associated with the production of the MBH SOP manuals also made a comparative assessment of seafloor sampling platforms. Their comparison spanned a broader range of techniques than just those of direct interest to this report. Across the full range from multibeam acoustics to destructive samplers, they described the strengths and limits of each technique as well as assessing its capability to measure EOVs and EBVs. The assessment framework was very appropriate, so I have applied the same questions to the subset of tools and techniques that **generate marine benthic imagery**. Applying this filter, the supervised technologies (ROV, towed video, diver surveys) possess advantages additional to the unsupervised technologies (AUV, BRUV). Within the first group, ROVs comes out ahead of towed video because they can provide continuous coverage at fine spatial scales, while divers come third because they have the smallest safe observing space (81-82). Within the second group, the AUV has advantages over BRUVs, which excel only in observing fish and fish-habitat relationships. The AUV and the ROV are thus the top scoring contenders from the two categories and the latter comes out on top by the single distinction that ROVs can be deployed in a stationary mode suitable for observing behaviour. ROVs equipped with manipulator arms offer an additional advantage through the ability to collect selected targets and return them to the surface. In addition, ROVs are one of only two observing techniques able to survey and/or collect specimens from extremely rugose or high-relief environments (e.g. canyon walls) and the only technique that can do this in depths beyond safe diving limits.

The second analysis shows that four of the five techniques (AUV, towed video, ROV and divers) all have very similar capacity to measure the same suite of EOVs and EBVs. While BRUVs excel at measuring the distribution and abundance of fish, their forward-facing cameras provide imagery that is marginal for assessing the distribution and abundance of benthic invertebrates and the cover of habitat forming biota (corals, macroalgae, and seagrasses). Divers are limited to very shallow depths while towed cameras must maintain a safe altitude buffer when operating over rocky ground or uneven terrain. This weakness is compounded by cable heave when the surface vessel is pitching (common in small vessels). These filters leave the hovering AUV and surface guided ROV as the tools of choice when consistent high-quality imagery is required throughout the observed area. The trade-off for gaining this premium is greater cost.

The conclusion of the MBH analysis was that there is no universal method appropriate for all marine benthic sampling. They suggest that the most complete habitat maps will be based on samples from a diversity of gear types (83-84), whereas the most efficient monitoring surveys should be based on the optimal tool(s) decided by the specific situation (48). Finally, they emphasise that the statistical considerations for monitoring and survey designs are just as important as the choice of tools (another chapter in the suite of SOP Manuals) (85).

Post-script (Hybrid systems)

In 2021, as I was finalising this report, I attended an online seminar to learn of a newly developed platform that can best be described as a towed glider (Figure 18). This device, known as Vertigo3, is a collaboration between a private company (BABEL-sbf), CSIRO (Data61, Oceans and Atmosphere), and QUT. The tether to a surface vehicle provides forward movement, wide bandwidth for two-way communications, and simplifies accurate geolocation. The towed vehicle includes altitude and flight sensors that adjust moveable flight surfaces, so that the vehicle can determine its flight path autonomously from the surface pilot.

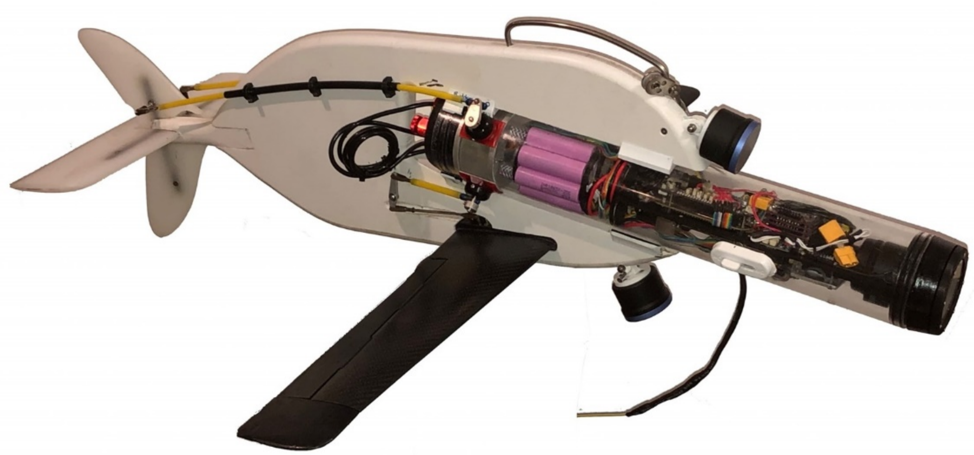


Figure 18. Vertigo3 is a towed autonomous glider being tested on the GBR in 2020-21.

In stabilised flight mode, the glider can be towed across flat terrain at 4.5 knots without any surface intervention while maintaining an altitude of less than 0.5 m. Observations are collected by a 5 MPIX camera with a 90-degree field of view. The camera is tilted below the horizon so that the field of view provides oblique and vertical views from the horizon to a distance behind the glider's position.

The greatest difference from the observing technologies reviewed above is the amount of autonomous processing of imagery done in real time using automated visual classification machine learning algorithms. Vertigo3 was developed for the task of detecting crown of thorns starfish in coral environments. It has been tested against the traditional manta tow surveys and found to be both skilful and more efficient: detecting the same patterns of relative abundance around the perimeter of a reef and in less time. The automated machine surveys detected three time more starfish than the towed observers. Human review of the archived footage confirmed at least twice as many confirming that the traditional method underestimates abundance. In addition, the automated assessments estimated the size frequency distribution of the local starfish population and classified the benthic surface into broad categories including live coral cover. This processing is done in real time by computers in the surface vessel.

The development team is claiming improvement by one or two orders of magnitude in the accuracy of target localisation and in the latency of information flows. While both are important, the latter has overwhelming significance for mapping and monitoring studies.

Vertigo3 illustrates the rapid pace of current development in underwater imaging systems. The towed glider adds another option for marine surveys in the already contested space down to 50-100 m. In principle, the efficient operating space for towed gliders will be determined by their tethers but this new device poses a serious challenge to AUVs operating in shallow water.

Concluding remarks

Niche space for the IMOS AUV Facility

This review has shown that several remote imaging systems have overlapping capabilities fit for the purpose of mapping and monitoring marine benthos. Davis et al. (2020) found that data streams from a BlueROV2 and a simple towed video unit did not differ in quality or quantity, but overheads in the ROV operation led them to recommend the towed video for tasks where large numbers of transects needed to be surveyed (51). Imagery from the IMOS AUV Sirius was acknowledged as better than both (towed video, ROV) in a study that combined photo-quadrats from towed video at 10 sites down the NSW coast with five interleaved sites sampled by the AUV to explain the variability of kelp along the NSW coastline (84). Contrary to the idea that kelp abundance would follow the temperature gradient, the study found that *Ecklonia radiata* is thermally tolerant and that its local abundance is determined by depth and the presence of urchins. The AUV Sirius showed that the kelp-urchin interaction is manifesting at greater depth in north-east Tasmania (32) where the urchin is an invasive native pest.

These examples show that the AUV can provide consistent high-quality data sets along a geographic transect of more than 10 degrees of latitude in the upper 100 m. While able to operate near the surface in a calm sea, the AUV Sirius gains competitive advantage with increasing depth. It is least cost-effective in the upper 50m, simply because of the competition from other cheaper devices. Between 100 and 500 m depth, towed cameras and observation class ROVs are the only practical alternatives to AUVs (Figure 19). Except on very steep relief, where ROVs are the tool of choice, the autonomous navigation, stable attitude, and constant altitude of the AUV gives it an advantage over towed cameras for close benthic observing.

While the 700 m depth limit of AUV Sirius is beyond the requirement for surveys of the photic and mesophotic zones, the AUV Facility has two shallower AUVs and its forward strategy aspires to evaluating a fourth (Appendix 2). This may be healthy growth but the results from the small AUV Holt (100 m depth limit) are invisible. This device has been deployed in Geographe Bay, Port Philip Bay, and Gippsland Lakes. None of these campaigns are recoverable from the Squidle+ site although its twin (AUV Phoenix) owned by Australian Marine Ecology P/L performed well at the task of surveying scallop densities in the Bass Strait (18). The AUV Facility should either demonstrate the utility of AUV Holt for shallow coastal monitoring or abandon it. The CSIRO Starbug-X has been used successfully to map seagrasses in Moreton Bay and Gladstone Harbour.

The IMOS AUV of intermediate size (AUV Nimbus) was developed partially as a response of the limited availability of large vessels capable of supporting the deployment and recovery of the larger AUV Sirius. AUV Nimbus with its customised portable gantry ramp was designed for smaller vessels and should have greater use in coastal waters as a result. Unfortunately, it has had few campaigns since commissioning trials due to the pandemic block on fieldwork, but the Facility staff are confident that AUV Nimbus is a full replacement for AUV Sirius down to its operating depth limit of 300 m.

The “vessel problem” is seen in the activity chart of the AUV Facility between 2009 and 2019 (the last year before the pandemic lockdown). Figure 20 shows that the average number of locations surveyed annually in the last four years was half that of the rate from the previous seven years.

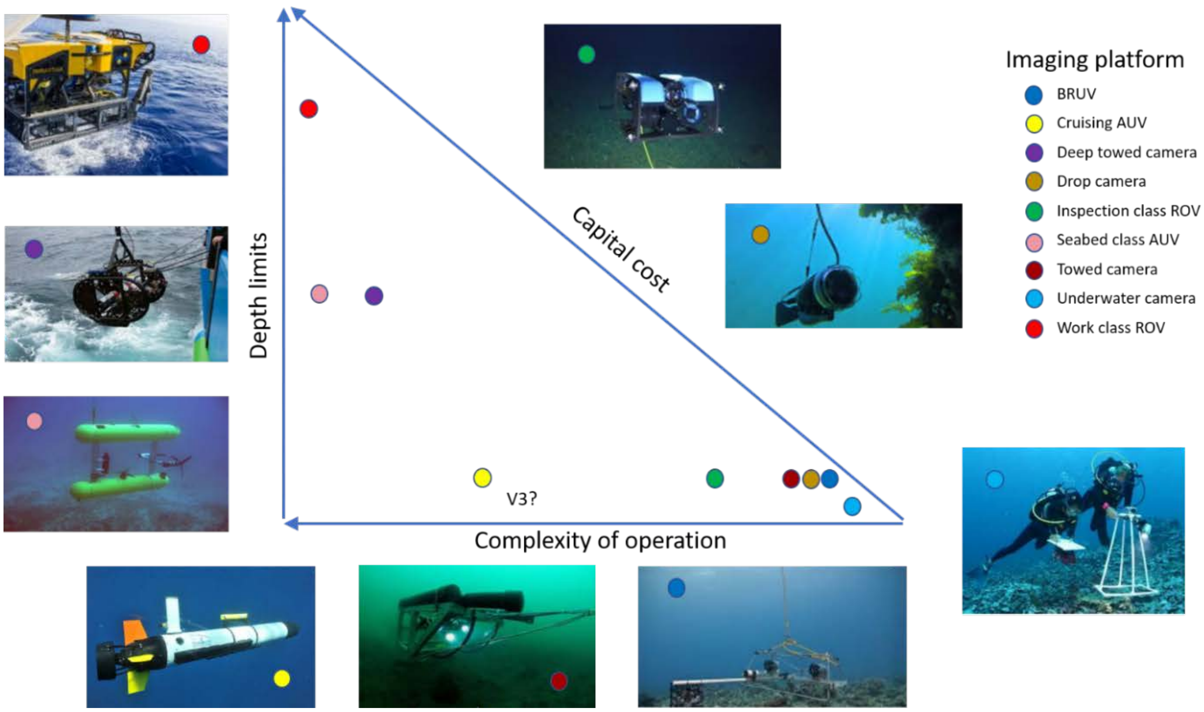


Figure 19. a cost-benefit framework for benthic imaging systems (modified from Monk, pers. comm.). The towed glider (Vertigo3) is placed with some uncertainty given that its cost and depth limits are unknown.

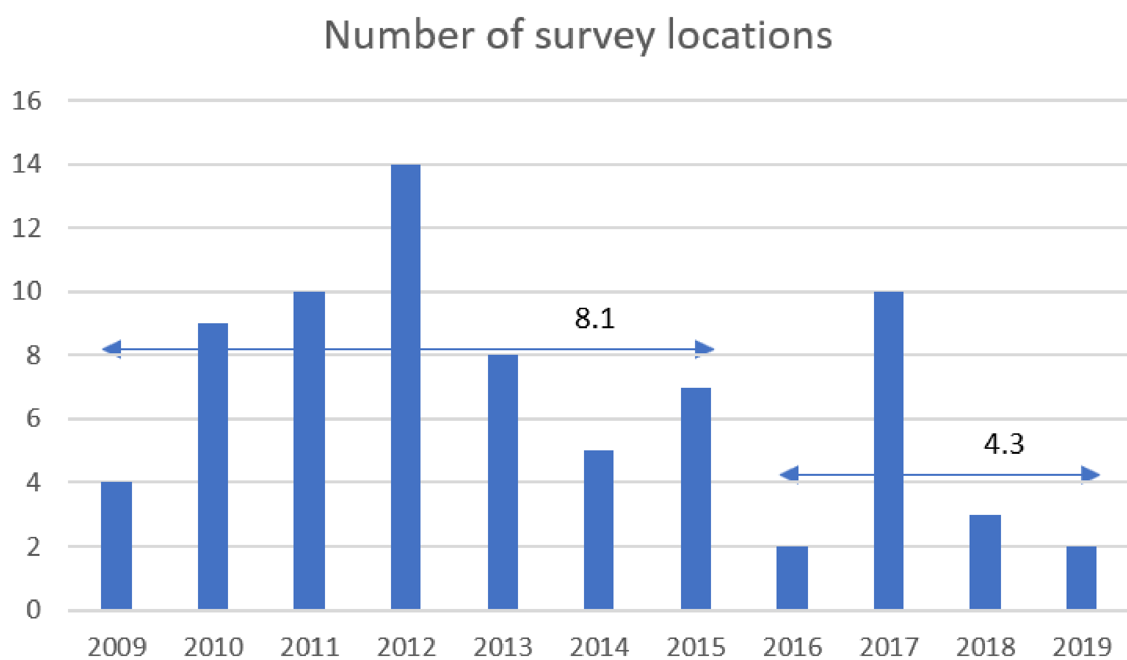


Figure 20. Number of different locations surveyed by the IMOS AUVs between 2009 and 2019. The arrows and numbers show the average annual performance over two periods (2009-15, 2016-19).

While feedback from the Facility and from the user community confirms the increasing difficulty of securing access to the large vessels required by AUV Sirius, the diminished rate of fieldwork after 2015 almost certainly contains an element of reduced demand from the marine community. Some of this is explained by users who simply abandoned efforts to procure time on the large vessels required by AUV Sirius but some of it reflects users who have become accustomed to operating from smaller vessels using alternative methods (discussed above). The ability of the IMOS Facility to survey 10 locations in 2017 shows that the reduced activity over the four-year period lies outside the Facility.

The risk for IMOS is that reduced demand from the historical user base is likely to be permanent. This raises two options for raising future demand.

Option 1 is to endorse the Facility's plan to acquire and test an off-the-shelf 50 kg AUV (Appendix 2), which could be deployed from the smallest class of survey vessel used for coastal observing. The concept of a 50 kg hovering AUV with the capability of AUV Sirius (apart from depth limit) seems attractive to the coastal community interested in monitoring marine benthos down to 100 m within 12 nm of the coast (State territorial limits). It will however be entering a contested space where science and management agencies have already made great use of dropped and towed cameras, and some use of battery powered inspection class ROVs (Figure 19). This was before the arrival of the towed glider (Figure 18), which offers an additional and advanced option for observations in depths to at least 50 m. The competition from these alternative observing technologies is a considerable project risk that must be weighed by IMOS before investing in another platform.

Option 2 is to broaden the market for observations from the larger AUVs (Sirius, Nimbus). This review suggests that such demand will come from organisations with interest in the protection and conservation of marine biodiversity and not from the fisheries management agencies. Priority should be given to engagement in 2021 with Parks Victoria, NSW DPI, Parks Australia, and GBRMPA. The selection of these potential partners for immediate engagement is because each is currently preparing operational plans for monitoring MPAs. All plans are due for finalisation by the end of 2021. It is critical that this demand be assessed within the life of the IMOS Five Year Plan 2017-22.

One of the questions asked in the terms of reference is whether observations from the IMOS AUVs should continue to be delivered by a centralised Facility as opposed to possible distributed models. The situation is that the Facility is likely to operate with just two vehicles for the foreseeable future including a significant period after any decision is taken to invest in a smaller AUV. Under these circumstances, the current centralised model of delivery seems most appropriate.

Reflections on the program design

The IMOS AUV Facility operates autonomous underwater vehicles that collect high quality photographs of habitats and seabed life from downward facing cameras. The main vehicle, AUV Sirius, is a hover capable robot that can map a seabed plot (typically 25 by 25 m) with overlapping images. These can be stitched together later to provide high fidelity orthomosaics within which colonial organisms can be tracked over time as individuals, and temporal changes detected in community composition and habitat rugosity.

While capable of fine scale mapping, the AUV has also applied much longer transect designs at many locations around the Australian coastline between 2007 and 2020 to observe broad scale patterns

(Appendix 2). In terms of sustained observing, however, there are large gaps in the national coverage including most of the tropical coastline and the Great Australian Bight.

A few locations in this selective network have been sampled in seven of the 13 possible years, allowing the detection of change at kilometre scale but only for these locations. More sporadic sampling of multiple locations along the temperate east coast has shown that critical interactions between habitat-forming kelps and sea urchins occur at greater depths in the southern part of the range where only remote observing techniques can provide the necessary observations. Despite these two demonstrations of capability, a weak point of the current observing network is that it did not start with an agreed national sampling plan supported by the Australian marine community. In other words, its present form is the legacy of ad hoc decisions in the early years when the Facility was responsive to unco-ordinated regional demands from the multiple Node Science and Implementation Plans.

The IMOS Strategy 2015-25 document states that after 2015, the AUV Facility will respond to demand for a national capability to cover a national network of reference sites. In February 2016, the Facility undertook an internal review, the results of which were presented to the IMOS Annual Planning Meeting in March. The review group declared three large-scale objectives for the benthic surveys: (1) long-term monitoring of deepwater reefs, (2) long-term monitoring of a major habitat-forming kelp, and (3) interpreting the dynamics of benthic reef systems in the context of biophysical coupling. To date, the Facility has delivered satisfactorily to the first two goals.

In July 2016, the AUV Facility undertook a second review with wider participation than the first meeting. This was presumably in response to some pushback to the March exposure draft of the benthic monitoring program and its three goals. The July workshop acknowledged that the large-scale benthic monitoring program established in 2010 was led by a core group of ecologists studying temperate reef systems who wanted to understand how kelp and deep reef invertebrate assemblages would respond to changes in the eastern and western boundary currents. It acknowledged that there was a need to broaden the goals to a national integrated benthic program that included tropical regions and the southern coast. It further acknowledged the need to service the vision in the National Marine Science Plan of a national integrated monitoring program with a focus on marine protected areas that could be used for SOE reporting.

When analysing the effectiveness of the historical sampling effort, the review panel stated that the original intention had been to sample in and out of MPAs with designs that would untangle climate-related change through time from anthropogenic drivers, within a representative range of kelp and deep reef habitats. While this was the starting vision, the review group acknowledged that this design had not been implemented for a variety of logistical reasons. They suggested that further planning was required for spatial gap filling to move the program towards the ideal model. They proposed that a steering group be established to give the program national representation and to provide a forum for reviewing and revising the program in a timely manner.

After 2016, the AUV historical observations were rebranded with the label of the IMOS AUV "Integrated Benthic Monitoring Program". The review group rebranded itself as the IBMP Working Group (IBMP WG). The WG is an independent group of marine ecologists with an interest in sampling marine benthic systems and willing to offer informal advice about the sampling program to the AUV Facility Director.

At the 2017 Annual Planning Meeting, the AUV Facility was listed as backbone infrastructure that would receive growth funds during the IMOS Five Year Plan 2017-22. It is somewhat surprising therefore to find that the Five Year Plan 2017-22 still attributes the AUV Facility with the same three goals declared by the 2016 Facility review. This may be one reason explaining the lack of any reform of the IBMP in the five years since the formation of the IBMP WG.

The first sign of change was seen at the 2019 Annual Planning Meeting in the joint presentation from the Facility and the IBMP WG under the heading of Engagement and Impact. There is a reference to engagement with the CMR program, government departments from four States, and Geoscience Australia. The statement of impact refers to the potential to deliver to three priorities identified in the National Marine Science Plan. I have not found evidence of further progress on any of these matters.

The IMOS AUV Facility is based in a Centre of Excellence for field robotics within the School of Aerospace, Mechanical and Mechatronic Engineering at Sydney University. Both are led by Professor Stefan Williams, who is a distinguished scientist with an international reputation. While his leadership of the Facility in all aspects from administration to reporting has been exemplary, he is not the right person to design a national marine ecological monitoring network and he would not claim to have done so. When the need became obvious, his solution was to convene the IBMP WG.

While the AUV Facility can point to some ambiguity in the IMOS planning documents (i.e. the intent in the Strategy 2015-25 versus the accountable deliverables in the Five Year Plan 2017-22), the reality is that the IBMP WG has operated too informally and without a sense of urgency to drive effective reform. As a voluntary group, it has not accepted ownership of the need to reform the sampling program. Within the Facility, The IBMP WG is an advisory group to the Facility Director and it is not clear that it has ever been tasked internally with such a direction.

A reconstituted WG could be more effective separated from the Facility and reporting to the IMOS Office rather than the AUV Facility Director, at least until the planning is completed. The IMOS Senior Science Officer seems the most appropriate point of contact within the IMOS Office. Along with a new reporting line, a reconstituted WG should be given fresh terms of reference and clear directions. Commensurate with the ask and the urgency, the IMOS Office should decide whether the WG Chair should be compensated for time with a responsibility allowance. If this was considered appropriate, the position should be filled for a term by competitive application.

The planning for a refreshed program of sampling by the IMOS AUVs must be guided by the outcomes of the national consultations recommended in the previous section. The WG Chair should be included in these discussions. The consultations with potential users should be an early priority for 2021 and should also involve consultations with the leadership of the new Marine and Coastal Hub.

Automated image analysis

The IMOS AUV Facility has deposited 5.5 million images of marine benthos in the AODN (Appendix 2). Although these images have informed numerous publications, most of the images remain in the archive unused. The value of trusted archives (a responsibility devolved increasingly to Cloud servers) is that the imagery will remain discoverable, downloadable, and available for future reuse.

While the storage and record fidelity are not of concern, a small question remains about the ability of the IMOS archives to attract the interest of researchers for potential reuse of the archived material. This could be done by advertising the data sets available but would capture more attention by demonstrating their utility. The quickest path to raising such interest is through greater use of automated analysis using machine-learning routines.

The recent example from the Catlin team (55) demonstrates that automated analysis of identity from visual records is already capable of revealing gross patterns in very large data sets. Several recent papers (86-88) have successfully applied a high level of automated classification to different monitoring sets with one claiming that the automated approach can accelerate the data analysis and reporting by at least 200x for 1% of the cost of traditional approaches (Figure 21). This potential aligns strongly with the IMOS ethos and its imperative to drive down the cost of each observation.

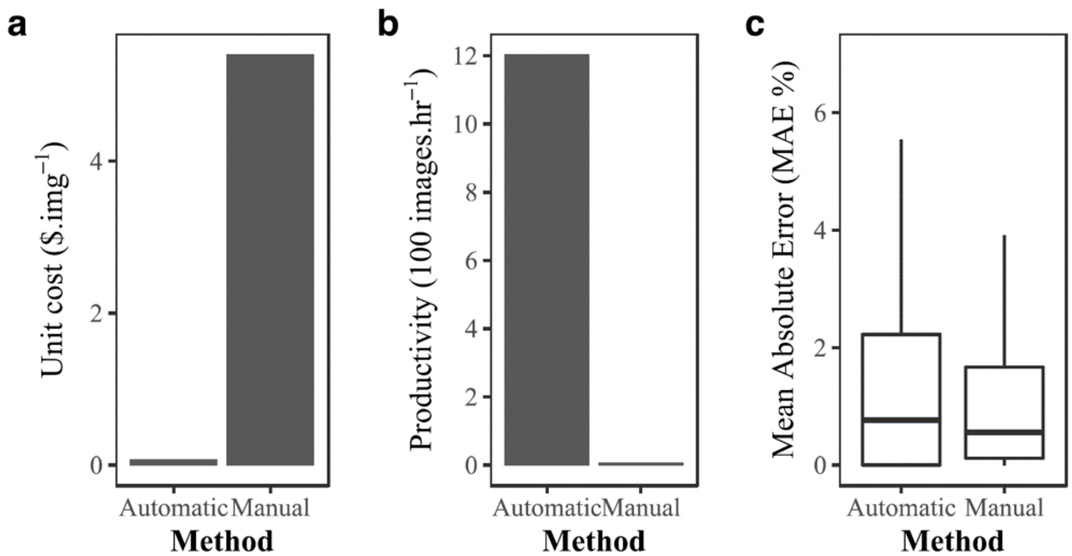


Figure 21. Cost-benefit of implementing automated image analysis in coral reef monitoring: (a) cost per image, (b) relative processing speed, and (c) the error of each method (from 87).

AIMS plans to use this approach to automate its coral reef surveys from 2022. Vertigo3 (Figure 18) shows just how much information can be retrieved in real time by use of automated classifiers and machine learning algorithms. The IMOS AUV Facility must strive to match these ambitions or else risk being left behind. The UMI program (Appendix 4) offers a neutral position on automated automation with the following statement:

“These tools will also be designed to support the integration of automated labelling (although the implementation of automated algorithms is outside of the scope of this project).”

This looks like a large, missed opportunity. Although it would require additional resources, these funds could come from the extra funding given to the AUV Facility recently to subsidise vessels costs. The sum is insufficient to solve the “vessel problem” but it could make a significant difference if invested here.

Co-operative arrangements for national marine benthic imaging

Currently, tropical and temperate researchers in Australia are pursing and developing parallel but independent programs for imaging and analysing marine benthic communities.

In the tropics, AIMS is leading this push with autonomous vehicles built and supported by QUT. These vision actuated AUVs (Appendix 5) navigate differently from the IMOS AUVs but operate well in complex terrain while required to fly within 50 cm of the bottom. They have been designed to recover data on coral cover and other targets. This focus reflects the recent losses of coral cover following mass coral bleaching episodes in 2015, 2016, and 2020 on the Great Barrier Reef. The IMOS AUVs have collected most of their observations from temperate rocky reefs with a focus on habitat forming kelp and encrusting invertebrate communities. The physical context for these observations is no less dynamic than in the tropics. Both communities of practice have a common interest therefore in measuring and understanding the interaction between managed use of the seabed and marine climate variations.

Given the common mission statements, the tropical/temperate divide in remote imaging systems could be cast as healthy competition but from a national perspective there is a greater risk of lost opportunities. This is not to suggest that marine benthic images should be collected with the same equipment nationwide but recognition that every image of similar quality regardless of source represents a common currency. This is not to suggest that all imagery should be stored in a single repository, but the national interest will be served best if Australian marine researchers have effortless access to all repositories using a common set of data harvesting tools. For this to occur, repositories need to maintain common standards and protocols, especially the control of vocabularies. An MBH report showed that this is unlikely to occur without deliberate intention and requires national standards for data served via web feature services.

As part of the national science agency, CSIRO Oceans and Atmosphere is large research group collecting and storing images of the seabed from both tropical and temperate zones. In a collaboration with Data61 and a private company, CSIRO has through its investment in Future Science Platforms recently introduced the first new tool in two decades for benthic imaging (since the widespread adoption of BRUVS) with the towed glider (Figure 18). While the towed glider is an agile towed camera system stabilised by autonomous control, the greatest innovation in this technology platform is its ability to classify imagery in near real time. This is done by fast streaming data from the camera to high performance computers in the surface vessel running automated classifiers within a machine-learning (ML) environment. If this can be done at sea, the same approach must be able to speed up the processing of data archives.

The recent demonstrations of rapid progress with image processing pipelines enhanced by ML algorithms represents a tipping point for all marine benthic mapping and monitoring. There are learning opportunities with national benefits to be gained here from open communication among the innovators. The NESP MBH has funded workshops on marine imagery in 2018 and 2019 attracting seven different partners. IMOS could join with the new Marine and Coastal Hub to co-brand a permanent stream of annual meetings.

Such a forum could have unique exposure to the wider Australian marine science community (beyond ecology) via the IMOS Annual Planning Meetings.

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Appendix 1. – Table of respondents

Alan Jordan	MBH
Alan Kendrick	WA DBCA
Alan Williams	CSIRO
Alberto Rodriguez	UQ
Allison Broad	UoW
Ana Redondo Rodriguez	SA_IMOS
Andrew Heyward	AIMS
Andrew Olds	USC
Andrew Woods	Curtin
Andy Davis	UoW
Ariell Friedman	UMI
Barbara Musso	MNFV
Bill Kirkwood	MBARI
Bonnie Holmes	USC
Brendan Brooke	GA
Brett Muir	CSIRO
Cathy Townsend	USC
Chris Henderson	USC
Daniel Ierodiaconou	Vic_IMOS
Danny Brock	SA DEWNR
David Souter	AIMS
Emma Jackson	CQU
Eric Lawrey	AIMS
Euan Harvey	Curtin
Gary Kendrick	UWA
Greg Jenkins	UMelb
Gretchen Grammer	SARDI
Hamish Malcolm	NSW Fisheries
Indi Hodgson-Johnston	IMOS
Jacqui Pocklington	Vic Parks
John Gunn	IMOS

John Keesing	CSIRO
Jonathon Kool	AAD
Jonny Stark	AAD
Justin Seymour	NSW_IMOS
Karl Forcey	CSIRO
Karl Sammut	Flinders
Kelsey Treloar	SO Sub
Lynda Bellchambers	WA Fisheries
Lyndon Llewellyn	AIMS
Manuel Gonzalez Rivero	AIMS
Mark Shortis	RMIT
Mark Underwood	CSIRO
Mat Wyatt	AIMS
Matt Dunbabbin	QUT
Matt Edmunds	AME
Matt Pember	WAFIC
Matt Sherloch	CSIRO
Mel Olsen	AIMS
Michelle Heupel	IMOS
Mick Keough	UMelb
Mike van Kuelen	Murdoch
Mitchell Lyons	UQ
Natalie Moltschaniwskyj	NSW Fisheries
Neville Barrett	IBMP
Nick Bax	MBH
Nicole Hill	Utas
Oscar Pizarro	AUV Facility
Ove Hoegh-Guldberg	UQ
Paul Lavery	Edith Cowan
Paul van Ruth	IMOS
Peter King	Utas
Peter Steinberg	SIMS
Rachel Przeslawski	GA

Renae Hovey	UWA
Rob Gregor	CSIRO
Robin Beaman	JCU
Rod Connolly	GU
Roger Proctor	IMOS
Roland Pitcher	CSIRO
Ron Thresher	CSIRO
Russ Babcock	Q_IMOS
Sarah Hamylton	UoW
Scott Bainbridge	AIMS
Scott Nicol	GA
Sean Connell	UoA
Stefan Williams	AUV Facility
Steffan Howe	Parks Australia
Steve Smith	SCU
Steve Swearer	UMelb
Stuart Phinn	UQ
Thomas Braunl	UWA
Tim Ingleton	NSW Parks
Tim Langlois	UWA
Tim Lynch	CSIRO
Tim Moltman	IMOS
Tim Stevens	GU
Todd Bond	UWA
Tom Bridge	MTQ
Tony Courtney	QDAF
Troy Gaston	Newcastle
Uwe Zimmer	ANU
Vanessa Lucieer	IBMP
Ziggy Marzinelli	USyd

Appendix 2. The IMOS AUV Facility (by Stefan Williams, USyd)

Introduction

Recent years have seen significant advances in the use of autonomous and remotely operated vehicles for seafloor survey. Work undertaken over the past 15 years at the University of Sydney's Australian Centre for Field Robotics (ACFR) has focused on the development and deployment of numerous vehicles and imaging platforms in support of applications in engineering science, marine ecology, archaeology and geoscience. As part of this work, we have operated an Australia-wide benthic observing program designed to deliver precisely navigated, repeat imagery of the seafloor. This initiative makes extensive use of Autonomous Underwater Vehicles (AUVs) to collect high-resolution stereo imagery, multibeam sonar and water column measurements on an annual or semi-annual basis at sites around Australia, spanning the full latitudinal range of the continent from tropical reefs in the north to temperate regions in the south. We have also contributed to expeditions to document coral bleaching, cyclone recovery, submerged Neolithic settlement sites, ancient shipwrecks, methane seeps and deepwater hydrothermal vents. The IMOS integrated benthic monitoring program, operated by the IMOS AUV Facility, has been effective in collecting high-quality seafloor imagery and associated water column data using AUVs on an on-going basis from sites around the country. This has provided an unprecedented set of precisely repeated data with which to study benthic habitats. Recent reviews of the program recommended that it be continued, with consideration given to the selection and design of the reference sites.

Capability Statement

The following outlines the capabilities of the IMOS AUV Facility, showcasing strengths of the program and the delivery of data in support of long-term monitoring of benthic reference sites around Australia.

Establishment of a coordinated set of reference sites along the east and west coasts of Australia

The IMOS integrated benthic monitoring program has been effective in collecting seafloor imagery and associated water column data from sites around the country on an on-going basis. This has provided an unprecedented set of precisely repeated data with which to study these benthic habitats. We have established an Australia-wide observing program that exploits recent developments in AUV systems to deliver precisely navigated time series benthic imagery at selected reference stations on Australia's shelf. Figure 1 and Table 1 show an overview of the observations collected over the course of this program. These observations are designed to help characterise changes in benthic assemblage composition and benthic cover derived from precisely registered maps collected at regular intervals. This information is providing researchers with the baseline ecological data necessary to make quantitative inferences about the long-term effects of climate change and human activities on the benthos. Incorporating a suite of observations that capitalise on the unique capabilities of AUVs into Australia's Integrated Marine Observing System (IMOS) is providing a critical link between oceanographic and benthic processes. Through this program the activities of the IMOS AUV facility have focused on providing sustained observations at reference sites around the country and making the resulting data streams available to the research community. IMOS scientific end users have defined the location, extent, and frequency of surveying of these sites to be visited by the facility's AUVs through the IMOS Integrated Benthic Monitoring Program

(IBMP, see Appendix 3). Observations collected by the Facility's primary benthic imaging vehicle, the AUV *Sirius*, include detailed, high-resolution benthic imaging, multibeam swath bathymetry, conductivity, temperature, depth (CTD) profiles and fluorometer data measuring chlorophyll-a, coloured dissolved organic matter (CDOM) and turbidity at the benthic reference sites. The new AUV *Nimbus*, which was commissioned in early 2020 carries a similar suite of sensors in a more compact form factor and has been successfully deployed during campaigns in Tasmania and NSW in 2020.

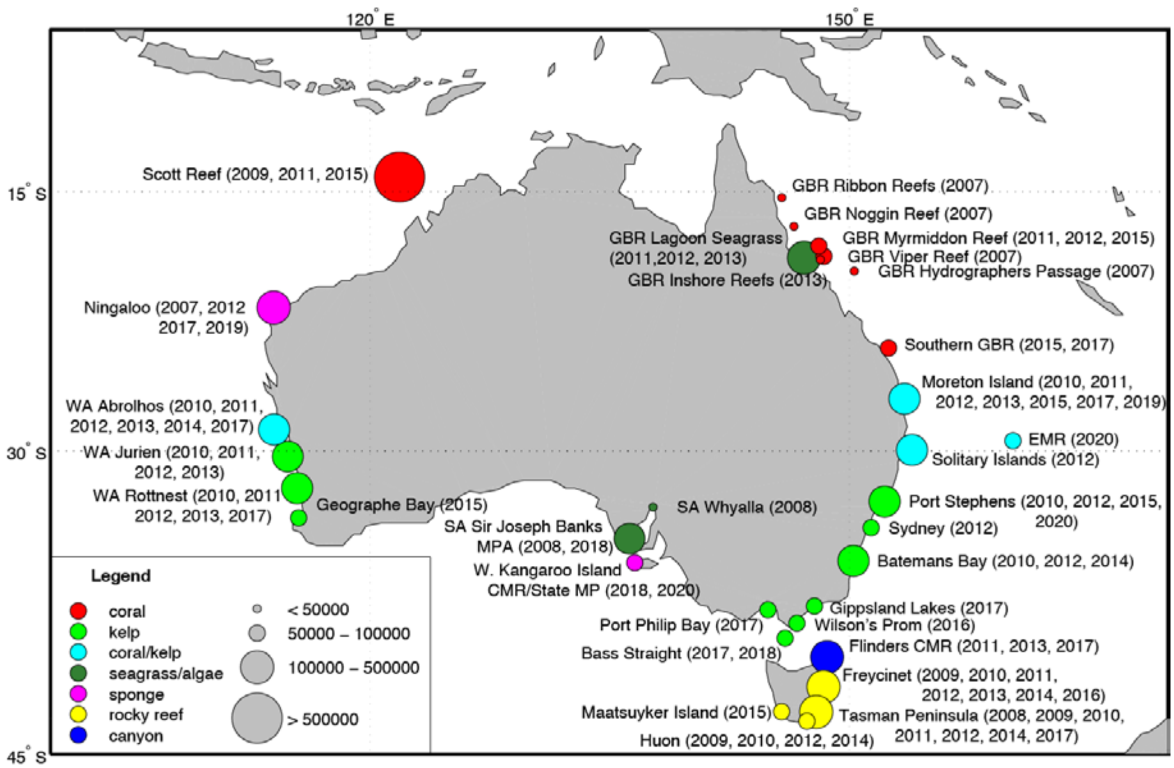


Figure 1 - An overview of the sites surveyed between 2010-2020. The circles are coloured by dominant habitat type and scaled based on the number of images currently available in the IMOS AUV Facility image archive.

Engagement with marine research groups within IMOS nodes around the country

Our scientific steering committee includes representatives from the University of Sydney, the University of Tasmania, the University of Western Australia, the University of New South Wales, the NSW Department of Primary Industries, CSIRO, and the Australian Institute for Marine Science. We rely on this broad range of collaborators to set directions for the facility's observing program and to ensure that the goals are aligned with the node science priorities and the objectives of the Integrated Benthic Monitoring Program.

Table 1 - Overview of data collected by the IMOS AUV Facility over the period 2007-2020. Campaigns are grouped by geographic location.

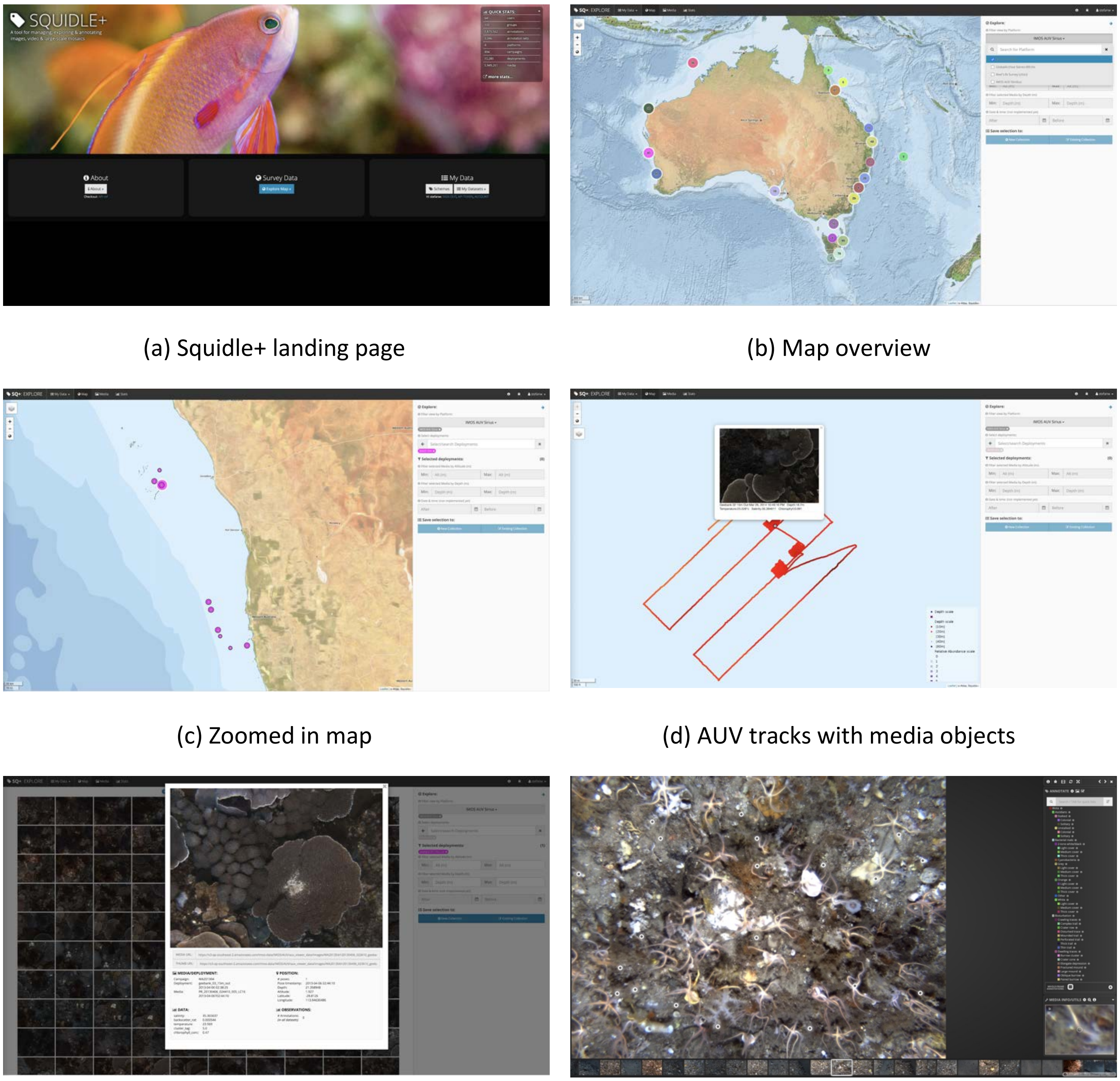
Deployment location	*# campaigns*	*# sites*	*# images*	*Start*	*End*	*# hours of data*
NSW	11	95	865945	17/11/10	18/8/20	207
Queensland	15	169	1321426	28/9/07	11/8/20	314.8
South Australia	2	18	114439	17/6/08	19/5/18	31.2
Tasmania	13	187	1568114	23/3/09	17/1/20	426
Victoria	1	7	16522	17/3/16	19/3/16	4.5
Western Australia	12	230	1681660	26/7/09	5/4/19	556.2
TOTAL	54	706	5568106			1539.7

Collection of seafloor imagery that couples biological response to oceanographic conditions

The record of scientific publication arising from the data collected by the IMOS AUV Facility has demonstrated strong uptake of the data streams being provided by the program. These outputs have focused on both broadscale questions of species distributions as well as more regionally focused studies of processes at relevant scales. Some work has also begun to consider the relationship between the biological distributions and data available from moorings and satellite data. A selection of recent papers is provided in the references at the end of the appendix.

Collecting and Managing data

Over the course of the past decade, the IMOS AUV Facility has conducted hundreds of AUV dives at sites around the country and collected more than 5M stereo pairs of seafloor habitats (Table 1). Managing this volume of data has required the development of tools and processes for collecting, processing, archiving, and providing access to the imagery and associated water column data collected by the vehicles. Squidle+ (http://squidle.org) is an open-source web-based framework that facilitates exploration, management, and annotation of marine imagery. It has been developed through funding by the Australian National Data Service (ANDS) and the Integrated Marine Observing System (IMOS). It provides a streamlined, user-friendly interface that integrates sophisticated map-based data management and query tools with an advanced annotation system (Appendix 4). Figure 2 shows selected screenshots of the interface. Users can quickly select data using search queries and parameters (eg: depth, altitude, date, deployment, or bounding box), which they can then subsample and annotate using a selection of standardised, agreed upon methods. Data can then be exported for further analysis. It is routinely used by marine scientists working with AUV data and has also been adapted by the NESP Biodiversity Hub as the preferred annotation tool for marine imagery.



(a) Squidle+ landing page

(b) Map overview

(c) Zoomed in map

(d) AUV tracks with media objects

(e) Exploring media objects

(f) Annotation Interface

Figure 2 - The Squidle+ online image exploration and analysis tool

The Squidle+ system has been designed to provide access to image data collected by the IMOS AUV Facility. However, it has been recognised that with the proliferation of AUV and ROV platforms, both survey grade and hobby grade (e.g.: BlueROV), there is an ever-increasing mass of high quality georeferenced visual data that needs to be annotated to be scientifically useful. The system has been recently extended to include data from the Reef Life Survey (RLS) project and has also been adopted by the Schmidt Ocean Institute, JAMSTEC and a few other organisations around the world to help them manage their online image archives. This reflects the strong demand for management of marine imagery and is a testament to the quality of the infrastructure developed in collaboration with the IMOS AUV Facility.

The current system can readily ingest data from many online image repositories. One of the motivations for the IMOS Understanding Marine Imagery (UMI) (Appendix 4) was to help capture online annotation data and to create a national repository for this information. Further distributed data storage facilities can also be leveraged to reduce data duplication and inconsistencies and will also mean that data can be made readily available much more quickly. We are in discussions with AODN to help chart a path forward to support closer integration with the AODN portal and to facilitate the inclusion of additional data sources, including a commitment from the CSIRO to make some of their deepwater seafloor imagery available through the portal and to use Squidle+ as an annotation tool feeding into the UMI database.

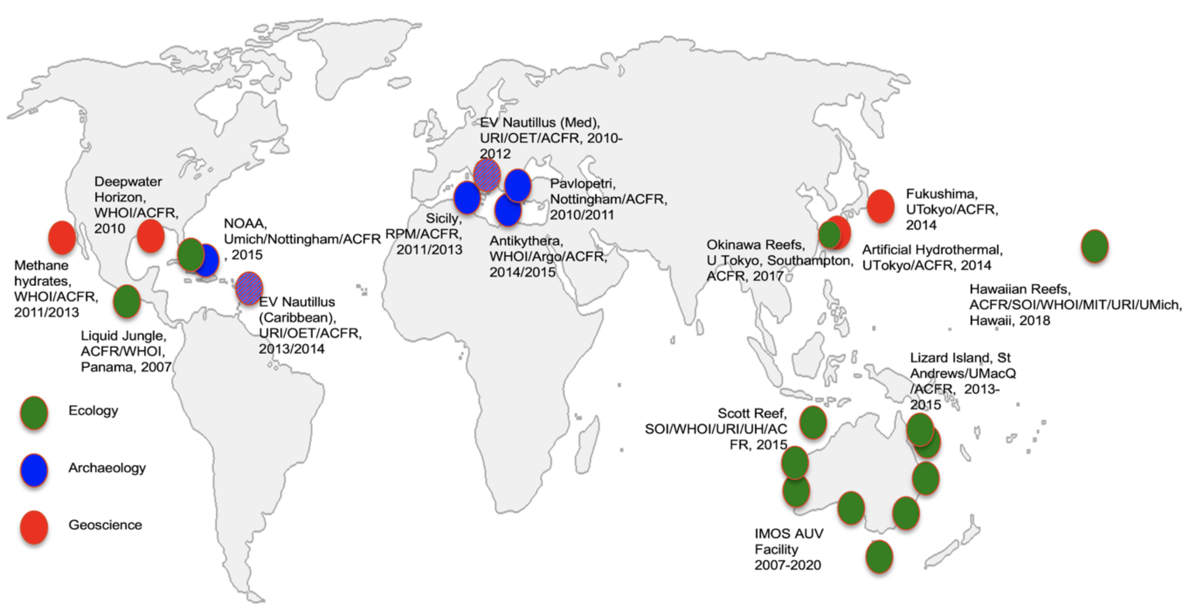


Figure 3 - International engagement. The ACFR has participated in expeditions deploying AUV and ROV based imaging systems at sites around the world. This has included the establishment of benthic reference sites in Japan and Hawaii like those pioneered as part of the IMOS AUV Facility program.

International reputation and engagement

While there are many organisations around the world collecting seafloor imagery, the imagery collected by the IMOS AUV Facility is comparable or superior to that of other world-class infrastructure overseas. Our high-resolution stereo imagery and three-dimensional reconstructions are unparalleled in terms of size (area covered), geo-referencing accuracy, consistency and quality of the imagery and maturity of the data processing pipeline. The IMOS integrated benthic monitoring program also represents a world first in the scale and volume of data collected as part of routine monitoring around Australia. This has led to numerous invitations to participate in international efforts to collect similar data to support a variety of applications, including ecological study, archaeology and deepwater geoscience.

Imaging and software tools

Our ability to process the large volumes of data while at sea provides the scientific party with immediate feedback with which to plan further dives. We have also developed a suite of online tools for browsing, searching, and annotating the imagery collected by the program. These tools could be used more broadly by other programs that require image annotation, including the Reef Life Survey (RLS) program and Baited Remote Underwater Video Systems (BRUVS).

Outstanding technical support and logistical experience

We have managed to attract and retain a talented group of engineers who maintain, operate, and upgrade our suite of vehicles associated with the IMOS AUV Facility program.

Publications output and project support

As outlined previously, many papers have been published using data collected by the AUV at sites around the country. Some of these have focused on regional level questions concerning species distributions while others have examined trends over broader, national scales. We have also seen several papers examining how the distributions of benthic organisms are changing through time and others focused on the tools required to manage the large volumes of data by using automated tools. Refer to the references for a list of recent papers exploiting data collected by the IMOS AUV Facility.

Forward Strategy

Looking forward, the IMOS AUV Facility will focus on continuing to deliver high-resolution, precisely georeferenced seafloor imagery at key benthic reference sites around Australia. Our 2020 review recommended the following actions to help ensure that the facility continues to deliver relevant and timely data for our key stakeholders.

- **Review schedule** - Work with stakeholders to design a revised schedule of deployments for 2020/2021 primarily focused on achieving the key deliverables of the program (i.e. sustained observations at selected reference sites around the country). While this work was begun and priority sites designated for 2020, travel restrictions due to COVID-19 have had a significant impact on our ability to travel within Australia and have resulted in the cancellation of the majority of campaigns through the 2020 calendar year.

- **Contingency planning** - Revise our planning process to explicitly build contingencies into the cruise planning stages to effectively handle weather and ship availability.

- **Governance** - Introduce closer governance oversight and regular reviews by the Facility steering committee to ensure that targets are met and that decisions about prioritising deployments are well documented and accountable.

- **Ship time policy** - Establish a clear policy with respect to accessing ship time funded by IMOS will allow us to work more effectively with stakeholders in planning our deployment schedules and ensuring that our high priority sustained observing objectives are met.

- **Small AUV** - Evaluate an off-the-shelf 50 kg AUV to increase flexibility of operations. If successful, a European Marine Robots proposal will partially support this assessment in mid-2021.

- **Data delivery** - Streamline data processing workflows to ensure that data is delivered in a timely manner to the AODN for dissemination within the stakeholder community. Additional support will be provided through the Understanding Marine Imagery (UMI) Facility.

Conclusions

AUVs present important tools for collecting rich, high resolution, geo-referenced data sets. The IMOS AUV Facility and its Integrated Benthic Monitoring Program are seen as a benchmark in providing sustained observations of key benthic features in a coordinated manner around Australia. Managing the data and transforming it into data products continues to be a key challenge. We are engaging with a number of user communities in exploring the application of these technologies to a variety of application domains. Exciting challenges and novel applications will likely continue to drive developments in these areas. Our future work will focus on the development of novel imaging payloads, sensors and vehicle systems, further improvements in navigation and instrumentation, visualisation, clustering, and classification of large volumes of seafloor data.

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Appendix 3: The IMOS Integrated Benthic Monitoring Program (by Neville Barrett, UTas)

Introduction

The IMOS Integrated Benthic Monitoring Program (IBMP) is a coordinated national collaboration of reef ecologists utilising the IMOS AUV facility to quantitatively observe, monitor and study spatial and temporal variation in benthic reef flora and fauna, in both temperate (rocky) and tropical (coral) reef settings, and spanning reef systems from nearshore coastal to the shelf-break where possible. At the time of its development, the AUV facility provided (and still provides) an outstanding opportunity to study reef systems at depths below those readily accessed by scientific diving, and to do so in a repeatable, spatially precise and quantitative way. In an ideal configuration, the IBMP program aims to provide an adequate national backbone for monitoring programs capable of tracking changes in reef health and benthic reef communities in response to a wide range of natural and anthropogenic pressures, including effects of fishing, coastal runoff, climate change, marine heatwaves, altered ocean currents, and marine pests. Thus, the program provides a range of important information for the research and management communities to be able to assess the causes of change, and management responses to this. Importantly, where possible, the program utilises marine protected areas to contrast responses in no-take zones, for example, with those occurring in adjacent open-access areas, to untangle responses related to fishing or other managed anthropogenic activities from those due to natural variation or unmanaged pressures.

Background:

While the focus of the program and progress has been the subject of several reviews for IMOS (not repeated here), the overall program began around 2007 when a range of initial quantitative reef-based surveys were initiated around Australia and supported by a wide group of key stakeholders/researchers. This then developed into the IBMP following the establishment of a steering committee to guide national deployments and develop an agreed standard protocol. The committee was essentially composed of ecologists representing State/National agencies and universities (primarily those either actively engaging with the facility as part of IMOS regional nodes or expressing an interest to do so), along with representatives from IMOS and the AUV Facility itself. Initial stages of the program established a network of coastal to shelf transects around the Australian coastline where possible, typically with bioregional scale separation between main transects, and multiple replication within these, at a range of depths typical of coast to shelf habitats. Individual transect designs were of two types, a "broad grid" where multiple 500m to 1km length legs were completed with 100 m (approx.) spacing between legs to give "broad" representation of individual reef systems and their depth range, and a "dense grid" where a full seabed photomosaic of approx. 25 x 25 m was undertaken at each site. The former approach provides a good estimate of reef-wide variability in individual species, whereas the latter approach gives the ability to track annual variability in individual plants/corals etc, and in the target patch, but less ability to infer change at a reef-wide scale.

A subsequent review of the program after several years of trials resulted in a reappraisal of the broad grid vs dense grid approach, deciding that the broad grid approach was preferential where possible due to greater regional inference, but that in some instances, such as patch reefs in WA, a dense grid was more appropriately matched with the spatial extent of each reef patch.

Likewise, while the initial aim was to sample at a range of depths across the shelf where possible, in many locations this was not possible due to the varying width of the shelf and accessing suitable vessels to undertake this task. Hence the program had a more pragmatic approach of at least maintaining a time-series of core sites where possible, and expanding these into spatial gaps in the network, and seeking opportunities for more offshore surveys as they arose, such as surveys within the developing AMP network with Parks Australia and/or the NERP/NESP Marine Hub. In the last two years of the program, overall deployments were reduced relative to earlier years due to reduced access to appropriate coastal vessels capable of cost-effectively deploying the AUV *Sirius*. Most researchers and agencies were awaiting successful development of the new, smaller and lighter AUV *Nimbus*, that is now in operation and will allow use of smaller vessels for deployment, greatly enhancing vessel availability and regional access.

Forward Strategy

The IBMP has evolved significantly since its inception and will continue to do so in response to facility availability, funding opportunities, researcher interest (regional/agency champions), research agency interest, management agency needs and national drivers. Despite this, the need for a nationally integrated monitoring program has been clearly articulated by the National Marine Science Council and the current IBMP is a very good fit to that model, providing a national network, national collaboration across commonwealth/state and university groups, open access imagery and open access data (via UMI, see Appendix 4).

As discussed above, the recent availability of the smaller, but still reef-capable AUV *Nimbus*, will be a game-changer in this space due to greatly increased vessel flexibility. Another game-changer, at least in commonwealth waters, is the establishment of the AMP network and the need for inventory and monitoring of key biodiversity assets within that network. This will provide increased funding support to survey deeper shelf waters than traditionally covered by state/university programs, hence both expanding depth coverage and overall spatial coverage. A central focus of NERP/NESP Hub research has been to demonstrate the effectiveness of AUV-based approaches in this space across a range of case-studies, as well as development of agreed SOPs for AUV deployments and data generation. Following from this work, it appears highly likely that AUV-based surveys will be an integral component of many future AMP inventory and monitoring programs. As demands for facility time increase over the next few years there will be an increasing need for the IBMP steering group to be more actively engaged in prioritising the overall balance between temporal replication of existing survey locations, the need for spatial gap-filling surveys (improve spatial predictions and species distribution models) and surveys in the new AMP network. Despite this, we are likely to be several years away from such a limitation arising, particularly as there is currently the capability of operating both *Sirius* and *Nimbus* simultaneously at times to meet demand in situations where larger vessels are available.

As outlined above, the last review of the program in 2016 by the steering group revised the design to primarily utilise a broad grid approach wherever possible, at least as part of the national program, as this gives greater generality from observations and greater compatibility of datasets generated by regional surveys. Despite this, there is certainly a need for more process-based studies to follow the annual trajectories of individual plants/sessile invertebrates etc, to examine growth rates and responses to disturbance and the AUV facility offers a capacity to undertake this approach at depth that is yet to be matched by other tools. Importantly, such approaches rely on annual repeat surveys of the dense grid patches over multiple years, and this level of repetition has yet to be supported by research agencies.

Given the importance of process-based studies to understanding responses to disturbance, no doubt these should be an important consideration for future AUV-based work by the facility but guided by the IBMP steering group to ensure their relevance and that temporal consistency can be maintained.

Conclusions

Arising from an opportunity to explore a new emerging technology as a seabed imaging platform in 2007, the IBMP has emerged and evolved to be a major component of the IMOS engagement in biological monitoring, and a truly national-scale integrated monitoring program focussed on the benthic biota of temperate to tropical reefs. While constantly evolving and responding to changing needs and opportunities, the focus of the IBMP steering group on establishing and maintaining a nationally standard approach to transect design ensures data compatibility as well as extensive collaboration and interest in uptake by a wide range of management and research agencies. The initial decade of adaptation in response to learning appropriate use of this new technology has resulted in what is now a fairly standard SOP-based approach adopted by the AUV-based community, a sound demonstration of the capability of the program and the AUV itself, significantly increased spatial coverage (e.g. in 2020, despite COVID restrictions this extended to the Coral Sea and Elizabeth and Middleton reefs and new sites in NSW), and strong demand for future access to the facility through 2021 and onwards. With the concurrent development of the UMI facility, data generated from the platform is becoming increasingly available, compatible and available for open access, leading to enhanced data uptake, increased publication opportunities, and greatly improved ability for end users to visualise acquired imagery and the data arising. Despite this, there are a number of challenges for the IBMP steering group and the facility to address in the coming year, including managing and prioritising demand and accommodating possible travel restrictions and contingencies associated with weather and other scheduling constraints, encouraging all researcher annotations to follow a standard approach, including using a shared morphospecies library to ensure maximum data inter-comparability, and ensuring all annotations are available on the UMI platform for open-access as soon as possible. With the advent of automation of image annotation, a reinvigorated IBMP should be well positioned to contribute strong quantitative data into the next SOE reporting period, particularly for key elements such as kelp cover, sponge cover and coral cover/health, and this should be a real target for the steering group to strive for. However, to meet this aim at the fully national scale, increased effort is needed to find regional champions in leading research agencies in regions where the uptake is still inadequate, particularly in tropical settings.

Appendix 4. The IMOS UMI sub-Facility (by Ariell Friedman, Greybits Engineering)

1. History

Understanding Marine Imagery (UMI) is a new sub facility of the IMOS AUV Facility. Software development under the UMI facility commenced in July 2020 (~6 months ago) and the project is still in the development phase. A pre-existing codebase that has been built and maintained by Greybits Engineering (also the UMI-contracted software lead) forms the foundation for the design of UMI's national annotation repository. The frontend, Squidle+[1] provides a web-based user interface to the data contained in the national repository and has tools for creating, viewing, validating, sharing, and managing annotation data. Before UMI, the development of the open source codebase has been supported by various stakeholders (including the Schmidt Ocean Institute, IMOS, Japan Agency for Marine-Earth Science and Technology and the Australian Research Data Commons). Prior to the project commencement, Squidle+ was marked as the recommended annotation tool by the NESP Marine Biodiversity Hub for both Towed Video and AUV imagery field manuals [2,3].

1.1. Background / Objectives

There is an ongoing need to extract quantitative information (such as benthic cover and substrate composition) from large and growing collections of marine imagery and to provide the means to share this information amongst a broad range of users and stakeholders. The Australian Ocean Data Network (AODN) already stores and provides access to millions of images from the AUV-based Integrated Benthic Monitoring Program (IBMP) but there currently is no national repository for annotations of visual datasets from the IMOS AUV and other sources, which is where a substantial amount of the value of this data lies.

The objectives of the UMI project are 1) to develop the fundamental open source infrastructure required to establish a national repository for annotations of marine imagery, discoverable and accessible through the AODN and 2) to refine and extend tools and interfaces required to support annotation, exploration, validation, sharing and exporting of this data. This will include establishing an online annotation repository linked to the existing AODN data storage infrastructure and portal, providing software tools and Application Programming Interfaces (APIs) for ingesting existing and new data streams, managing projects

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[1] The codebase of "Squidle+" supersedes the original ACFR-based "Squidle", which was a fork of the Catami project. The projects are not related in any way (except for their names and part of the development team). "Squidle+" has been developed from the ground up and is in no way tethered to/affiliated with Catami.

[2] Monk J, Barrett N, Bridge T, Carroll A, Friedman A, Ierodiaconou D, Jordan A, Kendrick G, Lucieer V. 2018. Marine sampling field manual for autonomous underwater vehicles (AUVs). In Field Manuals for Marine Sampling to Monitor Australian Waters, Version 2. Przeslawski R, Foster S (Eds). National Environmental Science Program (NESP).

[3] Carroll A, Althaus F, Beaman R, Friedman A, Ierodiaconou D, Ingleton T, Jordan A, Linklater M, Monk J, Post A, Przeslawski R, Smith J, Stowar M, Tran M, Tyndall A. 2020. Marine sampling field manual for towed underwater camera systems. In Field Manuals for Marine Sampling to Monitor Australian Waters, Version 2. Przeslawski R, Foster S (Eds). National Environmental Science Programme (NESP).

with multiple annotators and users, tracking data provenance, establishing flexible annotation schemes and generating a morphospecies library to encourage consistency in annotated labelling, and providing tools for summarising and reporting on the resulting data streams related to species and habitat distributions around Australia.

These tools will also be designed to support the integration of automated labelling (although the implementation of automated algorithms is outside of the scope of this project).

2. Capability / priorities

2.1. Planned activities:

Fig 1 shows an overview of the UMI components. The specific planned activities being supported by UMI include:

1. **Remote repository and data source integration:** develop the tools required to allow access to remote repositories of marine imagery including syncing of uploaded survey and associated annotation data. This will be demonstrated through the integration of the RLS repositories and maintenance and refinement of the AODN repository integration for IMOS IBMP. These tools will be designed to facilitate the import of other data sources from a variety of data storage platforms such as AWS S3, Google Cloud Storage, Thredds, Geoserver, and TPAC.
2. **Annotation framework:** extend the existing annotation framework supporting the open source MarineDB/Squidle+ codebase to define and manage multiple classification schemes, including the ability to: (a) translate between classification schemes, (b) aggregate annotations in a manner consistent with classification hierarchies, and (c) share and manage national visual reference libraries of morphospecies. Some of the schemes already available include CATAMI 1.4, and preliminary implementations of CBiCS, the RLS catalogue and the Australian Morphospecies Catalogue (as an extension of CATAMI). A goal is to develop a system to manage and develop standardised schemes that can be leveraged elsewhere in other tools.
3. **Data sharing, collaboration and release policies:** the framework will be extended to support sharing of annotation data between users and user groups including the granular sharing of datasets (with optional user agreements), permissions to modify and validate annotations collaboratively (with traceable authorship, see below) and mechanisms for timed public release of data (embargos). The specific sharing protocols, agreements around file completion and public release, rules and requirements will ultimately be decided by the UMI steering group and/or funding bodies, but the framework will be designed to support a variety of flexible data sharing modes.
4. **Quality assurance/control tools:** integrate a framework for QA/QC, including cross validation between annotators. This software tooling will be applicable to both human-human and human-algorithm cross-checking and validation.
5. **Data export and summaries:** basic reporting and visualisation capabilities including data export, data visualisation, QC state, map-based summaries, and science communication.

6. **Interoperability through secure API:** for flexible data ingestion/export, enabling scriptable interfaces to the annotation database. This will facilitate integration with the AODN portal and will be built with a forward-looking view to streamline future integration and interoperability with third party annotation tools (eg: Benthobox/Reef Cloud, CoralNet).
7. **Data provenance trace-route:** develop a mechanism for tracing attributions and authorship of all resources from the underlying survey data / campaigns during data collection through to annotated data products. All exported data should maintain a "trace-route" of data provenance to enable the correct handling of attributions and authorship of data products.
8. **User activity tracking and reporting:** implement system for tracking user activity and generating usage reports for IMOS to assist in assessing impact and tracking outputs.
9. **Ongoing user support, project management, user features and user engagement:** to assist with data stewardship, facilitate uptake, implement feature requests, and react to user support queries, bug reports and feature requests.

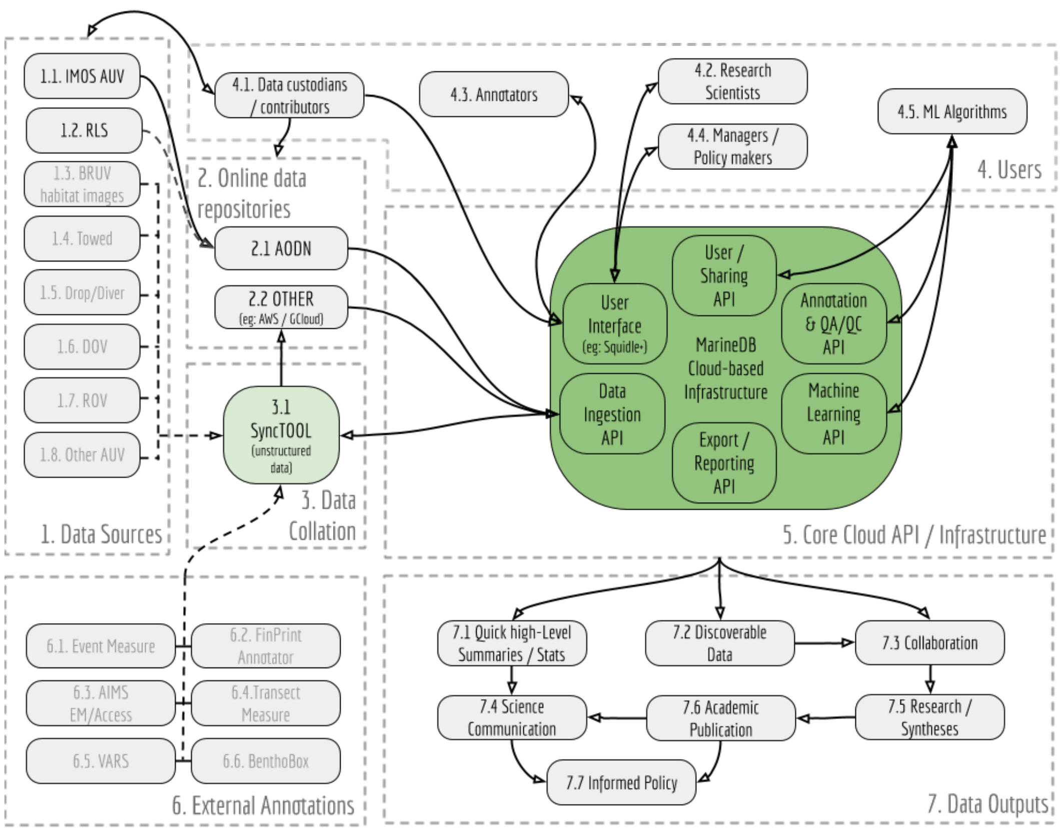
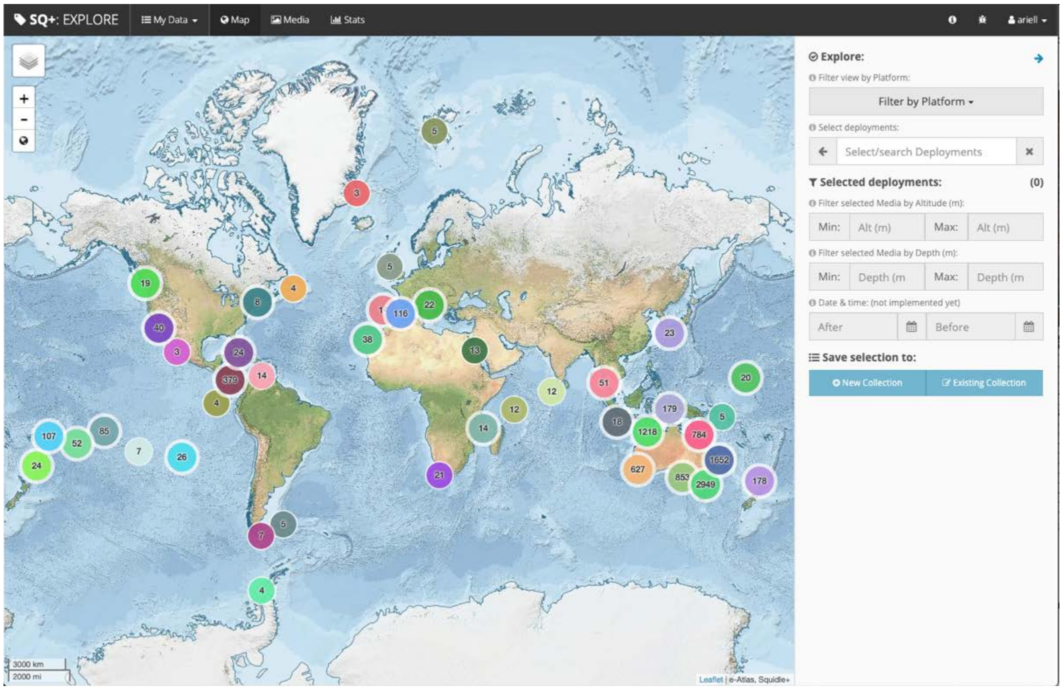


Fig 1 Context of the Understanding of Marine Imagery (UMI) facility. Major UMI components are in green. The subcomponents that will be initially interfaced with UMI are in dark grey. The light grey components are not in the scope of this project but have been included to show possible future integrations.

2.2. Approach

- **Open access and open source:** provide a suite of open access tools for end-to-end data delivery, discovery, analysis, validation and sharing of annotation data (maintaining links to the underlying survey data).
- **Leverage existing repositories of survey data:** Most established marine image data collection programs are already mandated to put collected data online in a supported repository. UMI is designed to automatically harvest structured survey data that is uploaded to pre-existing distributed repositories (eg: S3/AODN for IMOS AUV, TPAC for RLS, Thredds, GeoserverWFS, GoogleCloud).
- **Maintaining links to originating survey data:** historically, there has been little to no downstream support of derived analysed data products. Historically users had to download, offline-process and then manually manipulate / process / shift survey data around to conduct their analysis on a third-party platform. There is little to no control on the offline processing methods used, which subsequently breaks links to the original survey data repositories.
- **Integrated exploration, discovery, analysis and validation tools:** the survey data from each supporting platform repository is exposed through an explore interface in a way that makes it discoverable, accessible and filterable for further detailed analysis. While UMI does provide an in-built annotation workflow (i.e. through Squidle+), which is designed to streamline the annotation process by having all the survey data ready to go, it is also designed to support the importing of annotation data created using external annotation tools, provided UMI can establish the links back to the originating survey data. In that case the in-built UMI annotation tools can be used for validation, exploration, and discovery of imported/catalogued annotations from other tools. Fig 2 to Fig 5 show examples of the tools and interfaces that have been built.
- **Flexibility of supported annotation modes:** Squidle+ supports a wide variety of annotation modes (eg: whole-frame, points, polygons, bounding boxes, multiple labels per annotation with tags & comments, see Fig 4) and is designed to be media-type agnostic, i.e. the same annotation framework can be used for images, videos, large scale mosaics, etc... (although support for some of these is yet to be built).
- **Standardisation through translation:** Perhaps one of the most important problems that UMI aims to solve is standardisation of the raw annotation data products. One of the major challenges when working with annotation data from disparate groups and projects is that there is little to no standardisation between the annotation schemes/vocabularies used for annotation and these can sometimes vary within groups from project to project. This poses a barrier to data reuse, syntheses between projects and large-scale training of ML algorithms. It is also not realistic to impose a single vocab upon scientists as their needs and projects are different. From past experiences, enforcing a single standardised vocabulary is too restrictive for many scenarios, and tends to inadvertently drive users towards a splintered/bespoke approach to data analysis using other tools that provide the flexibility they want. UMI aims to offer flexibility by supporting multiple annotation schemes (vocabularies) and analysis workflows that can be managed and standardised from within UMI by crosswalking between schemes using semantic translation tools. This makes it possible to analyse data in a manner that suits your needs, and then export it in a translated target format of your choosing (federated query/search).

- **Integration with external services and databases:** UMI is designed to be a centralised national repository for standardised annotation products and provides a data sharing framework, which can



be used to share/release datasets with users and to publish it to external data services (eg: ALA, OBIS, SeamapAustralia, AODN).

- **Flexible integration of external algorithms[4]:** there is a substantial API backing UMI and supporting libraries are being built which will facilitate interaction with the data using a user's API authentication token. In a similar way that data can be shared, collaborated on and validated between human users, algorithms can be set up as "users" of the system and can assist human users in their analysis on datasets that they have been granted access to through the same sharing framework. This architecture makes it possible to offer a variety of different externally (or internally) developed automated processing pipelines. It opens up the possibility of connecting independent machine learning (ML) researchers to real-world ML problems with validated training data, and conversely provides the marine science user community with access to algorithms that can help bootstrap their analyses. Other annotation tools that offer automation, are most often wedded to a particular internal ML pipeline. In theory, it could be possible to offer the automated processes from these other platforms within UMI (assuming the algorithms can be made available and the services can be set up). In this architecture each ML researcher or ML service provider can administer their ML integrations with UMI.

[4] This round of IMOS-funded UMI development is focused on the infrastructure rather than ML algorithm development, but through demand and natural progression of available tools, we've already been able to demonstrate the ease of integration of ML services with this architecture.

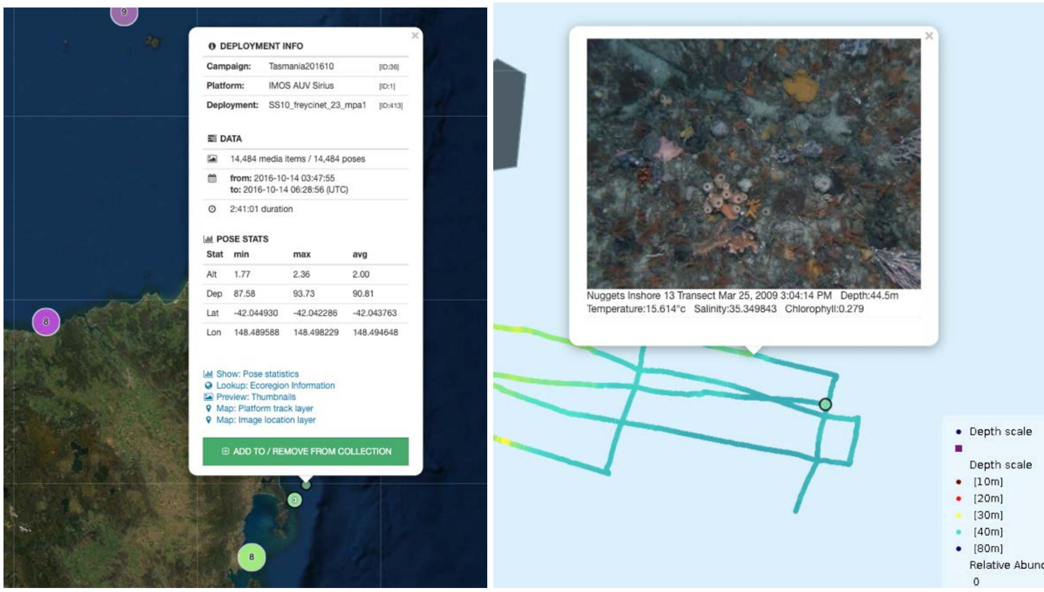


Fig 2 TOP: Explore interface showing campaigns and deployments from multiple platforms. Datasets are searchable by applying filters on the right pane, BOT LEFT: deployment metadata popups, BOT RIGHT: queryable WMS map layer plugin integrated from AODN-managed geoserver instance.

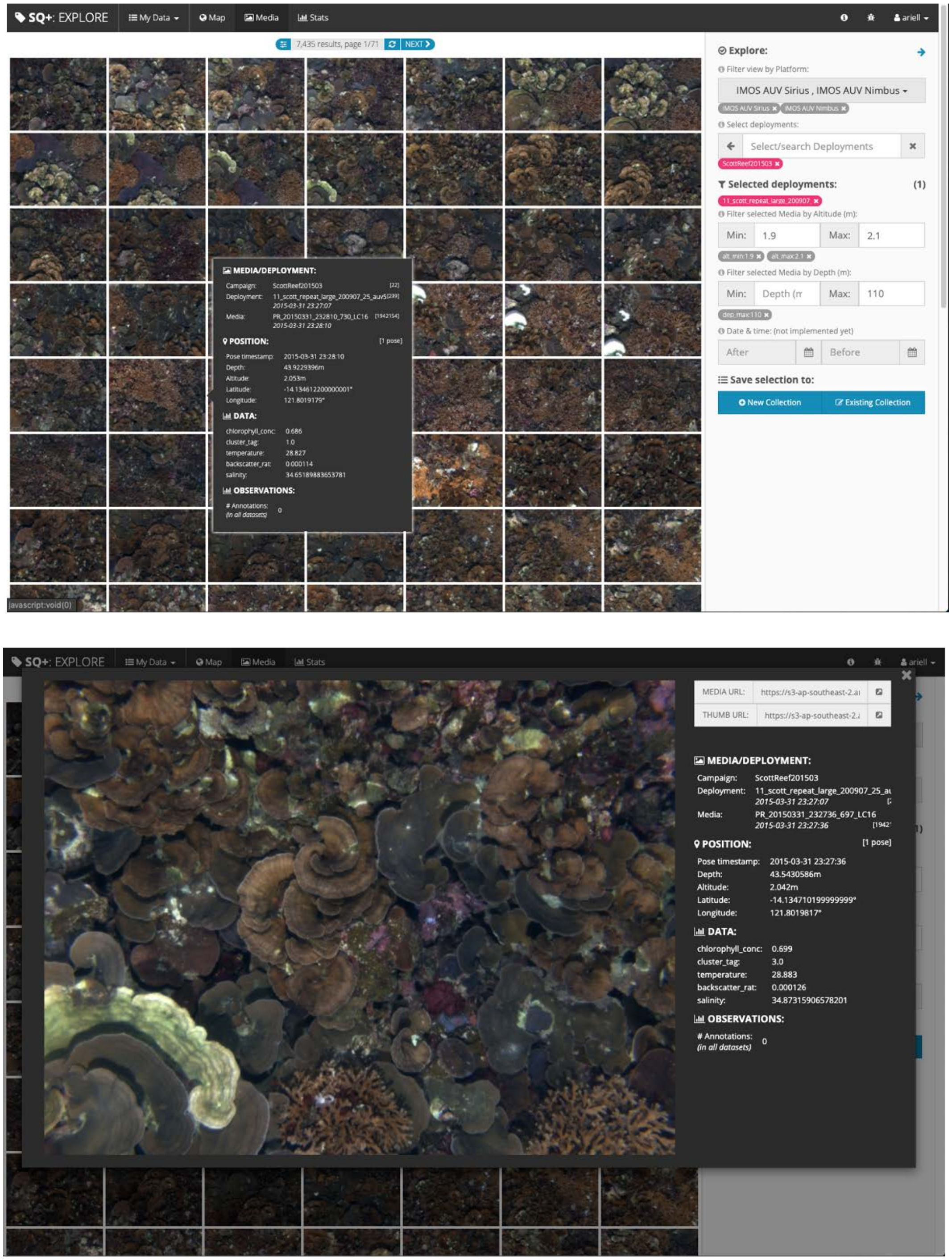


Fig 3 Explore interface showing thumbnails (TOP) and full resolution image (BOT), both with associated pose and sensor data.

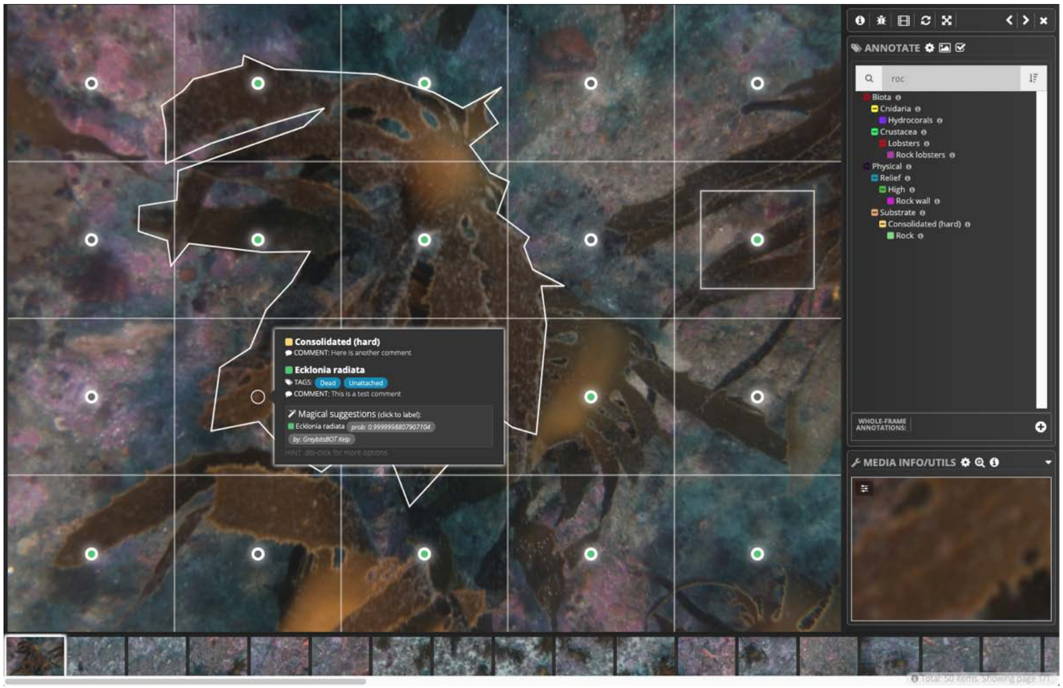


Fig 4 Annotation interface showing annotation framework supporting polygons, bounding boxes, tags, comments, and searchable annotation schemes. Selected annotation shows multiple labels per point, including two manually defined labels and a "magical suggestion" from an automated algorithm.

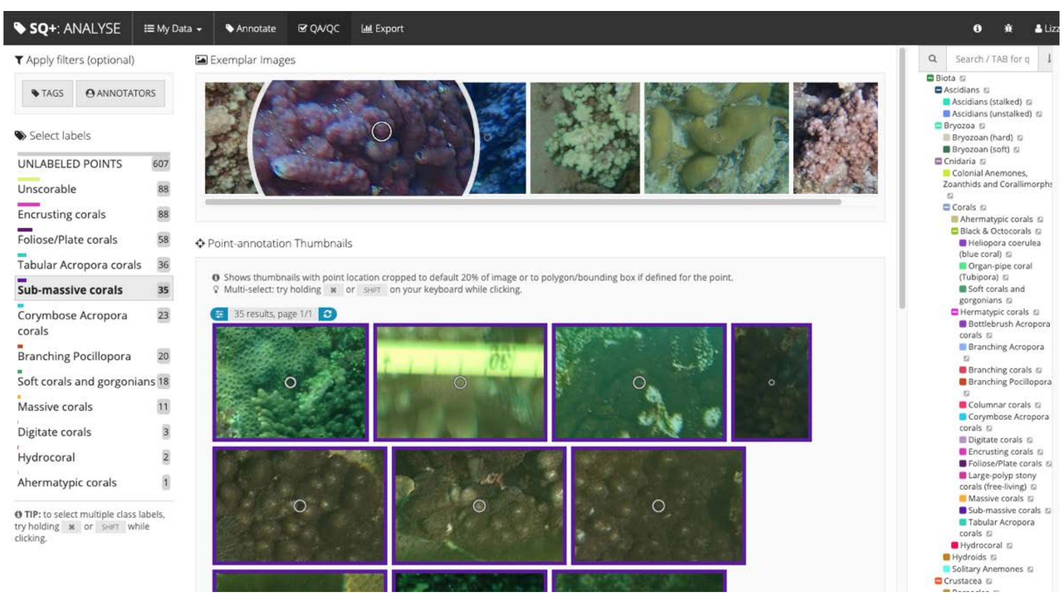


Fig 5 Initial implementation of QA/QC framework, with a clickable list of labels showing thumbnails for each annotated point, polygon, or bounding box along with exemplar images at top row. This makes it easier to quickly check/correct and batch change labels without needing to view each image separately.

3. Progress / Uptake

Software development has been progressing well. All critical-path deliverables are on schedule. Some deliverables are ahead of schedule and others slightly behind, but overall development is on track:

- Established public instance of Squidle+ including database underpinning UMI infrastructure based on open-source software stack. It includes tools for exploration, annotation, validation and sharing of benthic imagery and associated annotation data. It automatically harvests data from supported online repositories (AODN, TPAC) and provides mechanisms for rapid delivery of collected survey imagery for online analyses.
- Squidle+ (UMI) has become the dominant annotation tool for IMOS AUV and RLS photo quadrat annotation, where the underlying survey datasets are all readily available. As at 18/12/2020 UMI has:
    - 5,709,547 media items imported from 10,266 deployments across 492 campaigns from the RLS and IMOS AUV data sources (see Fig 2 for locations of imported datasets).
    - 640 registered users
    - 1,849,129 manually labelled annotations with 505,961 of these created in the last two months, with an increasing rate of growth.
- A technical coordination group between UMI, AODN and AIMS (ReefCloud) has been established to consider the alignment between these platforms. Early meetings indicate that there is a clear commitment from all parties to identify synergies, interoperability, and distinctions between UMI and ReefCloud offerings. The pathway for integration with ReefCloud, best practices and data standards have been discussed and scoped.
- Started drafting AODN-UMI integration specification document in collaboration with AODN. Partial implementation of some necessary functionality to facilitate the integration on the UMI side (pending integration from the AODN side).
- Implemented various user requested annotation workflow optimisations (annotation counts / frequent/recent labels)
- Integrated new IMOS AUV data source for AUV Nimbus (Sirius was already imported)
- Integrated RLS photo quadrats data source imported from TPAC API.
- Implemented annotation scheme management which has allowed users to build and manage their annotation label schemes collaboratively more easily.
- Enabled the creation of extended annotation schemes to help standardise the building of annotation schemes and prevent reinventing of the wheel with each scheme.
- Implemented exemplar image management for annotation schemes enabling the creation of visual reference libraries helping with training and improving label consistency between annotators.
- Partial implementation of QA/QC validation workflows to enable quicker checking of label consistency and batch labelling / corrections (See Fig 5)

- Partially implemented data sharing and collaboration framework allowing for granular dataset sharing and collaboration, enabling public sharing (sharing policies or enforcement of these policies still to come).
- Added API documentation and built an auto-documentation pipeline to ensure it is always up to date, based on the code structure of available endpoints.
- Facilitated API integrations for managers of annotation projects who are generating custom reports using annotation data shared with them through UMI from different annotators.
- Ongoing user support and management of feature requests and extensions.

4. Limitations / Challenges

- UMI is not designed to be an "annotation tool" for one-off data collection projects. It is built to support established data collection programs with supported online repositories and does not currently support the upload of bespoke datasets. This reflects project scope and the requirement of maintaining QA/QC links to survey data, rather than being a technical limitation of the architecture. In the future, it may be possible to build in a public data repository that enables the annotation and management of one-off projects, but this is not currently a priority for IMOS. This has been a consistent request from members of the user community.
- Encouraging uptake for pre-existing offline workflows can be a challenge. Different platform user communities tend to use different annotation tools based on what is familiar, tried & tested, and what tools they have at their disposal. There are also technical challenges that encourage decentralised/offline annotation workflows. For example, EventMeasure, which is routinely used by the BRUVS community, is an offline annotation tool for stereo videos. To the best of our knowledge, there are currently no existing online platforms that support *stereo* video annotation. Video annotation is something that is intended to be supported through UMI eventually, but annotation of high-resolution stereo video through an online interface will likely be pushing the technological limits of what is currently possible due to bandwidth constraints. While it is still possible to import these annotation data products into a national database, provided there are compatible repositories for hosting the underlying survey data, the lack of standardisation of offline workflows makes it more challenging. Importing data from offline workflows will likely require user support from UMI or the development of tools that streamline the process[5].
- There have been some delays relating to integration with the AODN due to resourcing constraints on their end. This has not affected the ability to integrate with existing AODN services but has created some development delays for new proposed features and derived data products that require input from the AODN development team. We envision that this will commence in early 2021.

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[5] The Synctool project (component 3.1 in Fig 1) was conceived and developed (by Greybits Engineering) to fulfil this purpose, however the project requires further development and support before it can be put into production. The project is not currently in active development.

Appendix 5. Capability statement on marine imaging: QUT (by Matthew Dunbabin)

1. What equipment is available?

QUT has an extensive array of Autonomous Underwater Vehicles (AUV), Remotely Operated Vehicles (ROV) and Autonomous Surface Vehicles (ASV) used for underwater image collection, image-based surveillance and autonomous active intervention and restoration tasks. These are a mix of custom developed and off-the-shelf systems as listed in Table 1.

All these systems are used for underwater image collection. The ASVs are also used as benthic imaging and classification platforms either in shallow water with rigidly mounted cameras or with towed imaging systems (both passive and active systems with autonomous depth and altitude control).

Table 1: QUT's Imaging Autonomous Maritime Systems

System	Qty
RangerBot AUV	6
Autonomous Terrain Following Tow-Cameras	4
BlueROV	2
EcoMapper AUV	1
Custom Surfbee ASV with payload moon-pool	5
WAM-V ASV (Customised)	1

RangerBot AUV

The RangerBot AUV is a small vision-based autonomous system developed specifically to address a technology gap for coastal environments. It has real-time onboard image processing capabilities for active intervention (e.g. COTS injection, coral larvae release) as well as seagrass and benthic cover assessments. Each AUV has an NVIDIA GPU allowing different machine learning models to be added. A benefit of the RangerBot AUV compared to most other AUVs is its ability to manoeuvre at very low altitudes above the seafloor (minimum 0.5m) in complex coral reef environments with a single charge operational time of up to 6 hours. This allows high-resolution imagery as well as operation in severely limited visibility conditions. These are used operationally through collaborators and support a range of research programs both in Australia and around the world. Summary papers of some applications are listed below.

BlueROV

QUT has two commercial Blue-ROV platforms. Payloads include imaging systems including stereoscopic cameras, light-field cameras, oceanographic sensors and custom sampling equipment and two customised Blue-Robotics gripper arms. These are operational and have been used down to 130m and operated by researchers and field rangers with less than 30 minutes training. Recent applications include imaging and sampling subsea volcanos (Tonga), vessel grounding site assessment, and sample collection and imaging Halimeda bioherms.

EcoMapper AUV

The EcoMapper AUV is a commercial platform with an integrated YSI Sonde measuring Turbidity, pH, CTD, Blue Green Algae and an integrated side-scan sonar and upward and downward looking ADCP. A number of externally mounted cameras can be attached to the underside of the pressure hull. As it is a torpedo shape, it is more suited to long transects with less vertical obstacles. It can also travel at speeds up to 6 knots.

Autonomous Terrain Following Tow-Cameras

QUT has developed a small autonomous terrain following tow-camera which interfaces to a top-side GPU for real-time classification. These are typically towed by a surface vessel (e.g. QUTs custom Surfbees) along predefined transects. Their active control system allows the camera to maintain a fixed height above the seabed especially in complex reef environments. Applications to date include video transect data collection and coral larvae reseeding on degraded reef systems.

Custom Surfbee ASV with payload moon-pool

QUT has a series of custom made Surfbee ASVs which have imaging payloads which are either fixed to the hull (above and below the waterline) and/or towed behind the ASV using a custom winching system for deeper water applications. Up to three Autonomous Terrain Following Tow-Cameras can be towed behind each custom Surfbee ASV to increase image swath-width. The ASVs are inflatable and fit into backpacks for transport around the world. Applications currently include autonomous coral larvae reseeding, seagrass and reef flat image surveys, drop camera surveys. These platforms have been used in seastates > 1.2m and winds greater than 30knots with an endurance up to 3 hours on a single battery.

WAM-V ASV (Customised)

This is a large (5m long) ASV originally developed and used as part of the Maritime RobotX Challenge. Its size and low draft are beneficial for larger payloads (up to 150 kg) and over shallow reef (down to 0.6m water depth). Since 2018, custom imaging payloads have been developed and tested by QUT and collaborators such as AIMS and UQ. These include fixed and towed cameras systems, and winched drop cameras as well as an integrated ROV attached to the autonomous platform and can be remotely observed and controlled.

2. What are the applications?

Most autonomous underwater robotic systems are subject to the Defence Strategic Goods List and details of the systems are becoming increasingly export controlled. As such, many of the details particularly around operational and use cases of QUT developed systems are not formally published. Additionally, several of the compliance-based applications through QUTs collaborators do not produce publicly available reports. Recent applications of these systems by QUT and our research collaborators are:

- Image transects of coral reefs from surface to 35m (altitudes down to 0.5m from seabed)
- Seagrass mapping in embayment's and canal systems
- Side-scan and image-based mapping of subsea pipe infrastructure
- Surveillance of marine pests (e.g. COTS) including the ability to perform population control
- Reef restoration through precision coral larvae placement onto degraded reef.
- Autonomous physical water and substate sample collection.

3. What annotation system is used for images?

QUT collected imagery is primarily used for Machine Learning and algorithm development purposes. Therefore, we have custom annotation systems for labelling images which depend on the machine learning framework being evaluated or developed. These labelled images are stored on an internally managed cloud storage system. Imagery collected by research partners/collaborators using QUT hardware is annotated using their respective systems.

4. What degree of automated classification is used with images?

The research focus of QUT's Centre of Robotics and the Australian Centre for Robotic Vision is fundamentally machine learning and automated classification (both real-time and post processing). Therefore, most classification and analysis is automated with only manual labelling of images for training purposes. Any manual classification that is performed can be as simple as CPPC to full semantic labelling of images and is project/task dependent.

5. Where will the imagery be stored?

QUT collected imagery is typically only retained for training and system development purposes and is stored on a Centre accessible cloud storage site with local copies taken for machine learning and post processing requirements. Note that as QUT has access to system level information on the platforms, these data files are also retained in addition to the images and includes point-clouds, environmental information, vehicle and mission information. This data is used to augment and increase performance of the onboard AI classification systems.

Most scientific data (typically images) collected by the platforms through collaborative projects or supplied hardware is stored and maintained by the research partners using their protocols and hardware (e.g. local or clouds storage) often with a local copy kept at QUT on its cloud storage as backup.

6. What will be the access arrangements?

The majority of QUT's underwater data is held internally and shared on request with strategic partners/collaborators. Data collected by collaborators/research partners for marine science and compliance activities is maintained by the respective partner and access is either restricted or open access depending on their processes and protocols.

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Appendix 6. Capability statement on marine imaging: CSIRO (by Alan Williams)

What type of equipment is available?

The list below includes major CSIRO-owned imaging platforms in current and recent use. Equipment items 1 to 8 are bespoke systems designed and fabricated by CSIRO. Items 9 and 10 are, respectively, a commonly used baited video system also used by CSIRO, and a commercial device. Third-party equipment is also used for specialist applications, e.g. work-class ROVs for sample collection in the deep sea; the IMOS Sirius AUV for biodiversity mapping on the Ningaloo tropical shelf. Image data are also routinely captured by self-contained cameras (e.g. Go-Pros) mounted on other sampling gear (e.g. traps, moorings).

1. **Deep Towed Camera System** (Sherlock et al. 2016)
2. **Shallow or sled-integrated towed camera systems** (several, e.g. Marouchos et al. 2016)
3. **Compact self-contained camera systems for trawls** (Sherlock et al. 2018)
4. **Instrumented coring platform** (ICP) (Sherlock et al. 2014)
5. **Acoustic Optical System** (AOS) (https://www.youtube.com/watch?v=NYLCW90R8YE)
6. **Profiling Lagrangian Acoustic Optical System** (PLAOS) (Marouchos et al. 2016)
7. **Starbug AUV** (miniature AUV), https://research.csiro.au/robotics/starbug-underwater-vehicle-collecting-data-sea/
8. **DeepBRUVS** (Marouchos et al. 2011)
9. **Standard BRUVs** (e.g. Harvey et al. 2014)
10. **Seaeye Falcon ROV** (http://tamboritha.com.au/tbwp/wp-content/uploads/2020/07/Falcon-R2.pdf)

What are the applications (e.g. survey, monitoring, collection)? (by gear type, if different)

Visual imaging is part of a broad range of data collected for a variety of marine science applications; most tools generate quantitative image data because this is fundamental for comparing data between surveys, areas and through time. For example, the equipment item #1 (Deep Tow Camera) uses calibrated paired ('stereo') cameras to produce imagery in which the field-of-view can be estimated with high accuracy and known error. A range of applications in CSIRO projects is summarised here under a set of convenient headings (this is illustrative, not comprehensive). Applications are often overlapping, e.g. quantitative biodiversity assessment may simultaneously be a fishery management and marine park application. Each application is show with equipment items from the above list in parentheses [item].

Marine parks: biodiversity and habitat mapping and assessment

Imagery has played a key role in designing, characterising and monitoring marine parks — including those in commonwealth water that are predominantly in the deep sea (depths > 200 m) (e.g. Schlacher et al. 2010; Williams et al. 2015; Williams et al. 2020a). Sampling with cameras is important in sensitive habitats and where repeated sampling (for monitoring) is required.

- Biodiversity discovery and inventory [1, 2, 3]
- Monitoring status of ecosystem health indicators [1, 2, 3]
- Determining community structure of fishes [8, 9]

Extractive industries: impact /recovery assessments

Imagery provides an effective means of establishing baseline conditions, assessing impacts, and monitoring – including recovery of impacted communities — associated with the historical, current and future environmental footprints of fishing, oil and gas, and seabed mining industries (e.g. see Williams et al. 2020b, 2020c; Williams et al. 2018; Clark et al. 2016).

- Bottom trawl impacts / recovery of cold-water corals (continental slope / seamounts) [1]
- Fishing impacts and recovery of tropical shelf benthos [2, 3]
- Baseline environmental status for oil/gas exploratory drilling [1, 2, 4]
- Assessment of oil/gas environmental permit applications [2, 9]
- Decommissioning oil and gas infrastructure [8, 9, 10]
- Carbon sequestration [9, 10]

Fishery management

Imagery contributes information to a wide range of fishery management applications. Prominently these inform risk assessments and management measures to reduce impacts on benthos (e.g. Pitcher et al. 2020; 2016), and to validate species identification in acoustic biomass surveys (e.g. Ryan et al. 2009). Image data is a core component of commercial fishing vessel e-monitoring to verify catch reporting (species, numbers, sizes) and quantify bycatch of threatened, endangered and protected seabirds, cetaceans and fishes.

- Ecological risk assessments (ERA) [1, 2]
- Informing specific management/policy measures, e.g. avoiding impacts on vulnerable marine ecosystems [1]
- Biomass estimation [5]
- Determining community structure of fishes [8, 9]
- E-monitoring aboard fishing vessels [deck mounted cameras]

Environmental monitoring/characterisation

Among many applications, two examples are using small, portable, easy-to-launch AUs for environmental monitoring with imagery and sensor suites, and estimating biomass of micronekton communities (including gelatinous zooplankton) using integrated acoustics and imagery (e.g. Kloser et al. 2016).

- Shallow embayment/ estuarine monitoring [7]
- Biomass estimation of deep scattering layers [6]

What annotation system is used for images? (by gear type, if different)

Annotation systems (data post-processing workflows, classification schema, databases) vary between gear types and applications. Both video and still images are used to generate data; these are used separately and sometimes cross-referenced to maximise the strength of each format, e.g. identifying detail in the higher resolution of stills vs detecting change or pattern with the moving perspective of video. Data acquisition may occur at sea in real time, at sea following initial post-processing, or back in the lab, or in combination. Data are stored and managed in different databases and there is not yet organisational convergence on data formats and structures. One example for towed cameras is provided here:

- Video: 'point of change' annotation of substratum types and habitat forming biota are recorded at 1 sec-intervals for continuous distributional mapping overlays. Data are acquired, stored and managed in the Video Annotation and Reference System (VARS) (Schlining and Jacobsen Stout, 2006) developed by the Monterey Bay Aquarium and Research Institute (MBARI).
- Paired still images: quadrats of known size are generated and random point clouds of standard density (no. per m2) are generated and embedded in images using commercially available SEAGIS EventMeasure and SEAGIS TransectMeasure; counts of individual biota in quadrats (densities), percent cover of encrusting, spreading biota and substratum/habitat types, and sizes of selected fauna are recorded in VARS. Prior to post-processing, subsampling of the very large image datasets are implemented using statistically robust procedures.
- Annotation classification systems for all imagery: (a) CSIRO classifications for habitats and biota have been developed and evolved over an ~25-year period of survey during which physical collections and image data were collected together; biota categories are primarily taxonomically-based 'phototaxa' – the lowest possible resolution in imagery for known taxonomic entities; (b) these have contributed to, and are now cross-walked, with the CATAMI scheme (Althaus et al. 2015) which provides a standardised vocabulary for habitats and biota, but which is based more

strongly on morphologically defined 'morphotypes'. It is anticipated that continued evolution of the CATAMI classification scheme (which is increasingly adopted internationally and has independent research groups refining different faunal elements) will be coordinated through the Understanding Marine Imagery (UMI) initiative (UMI 2020) or within the Marine Biodiversity Hub.

The UMI initiative is an important linkage for CSIRO as it will refine and extend tools and interfaces required to support annotation, exploration, validation, sharing and exporting of data through Squidle+ (squidle.org). This will include providing software tools and Application Programming Interfaces (APIs) for ingesting existing and new data streams, managing projects with multiple annotators and users, tracking data provenance, establishing flexible annotation schemes, generating a morphospecies library to encourage consistency in annotated labelling, providing tools for annotation QAQC, data summarizing and basic reporting, and defining/generating species catalogs from classification schemes.

What degree of automated classification is used with images? (by gear type, if different)

Automated annotation of habitat features, biota categories and abundance metrics is under development. Until recently there were no sufficiently large and/or routinely collected datasets to warrant the investment in machine learning (ML) approaches – including because a continuing need for substantial human intervention made it uneconomic and because identification error rates for the biota of interest (e.g. mixed complex benthos) were too high. Investments in new cross-disciplinary ML projects and needs for emerging image-focussed projects will see a rapid acceleration of automated approaches. Four examples relevant to imagery are:

- E-monitoring of fishery catch aboard commercial vessels using deck-based cameras: subsamples from large volumes of AFMA-collected image data will be analysed to verify catch reporting (species, numbers, sizes) and the bycatch of threatened, endangered and protected seabirds, cetaceans and fishes. ML approaches for long-line caught species are well-advanced; trawl-catches (more complex) are being worked on.
- Deep-sea coral reefs: minimising impacts on vulnerable marine ecosystems (VME) during commercial bottom trawling will be achieved by screening for the presence of stony corals and other VME indicator taxa in large volumes of data captured in situ by cameras mounted in trawl nets. Pilot studies completed in 2020 provided proof-of-concept in terms of image quality and validated success rate of identifications (true and false).
- Biomass assessment: improved estimates of biomass will be made by processing large volumes of AOS data to tighten the relationships between acoustic target strength and fish species, size and orientation.

- Harmful algae species: ML techniques will be used to screen large numbers of routinely collected water samples that monitor aquaculture and other environments for the presence of harmful algal species.

Where will the imagery be stored?

Results from a recent (2020) questionnaire found that imagery and image-derived data are collected by many marine projects within CSIRO, and are stored and managed in many different ways and in different data repositories. The methods ranged from highly organised structures in the VARS database and ORACLE with linkage to the CSIRO Bowen cloud storage, though to 'informal' storage on local hard drives. This finding has prompted a more formal audit to drive a process in 2021 to determine what level of organisational convergence is possible for data formats and structures. A large component of future planning for storing data and annotations is linked to the UMI initiative —cloud storage with external accessibility through APIs. CSIRO has a technical and coordination project that links its assortment of image-related projects to the integration/ingestion system that synchronises CSIRO (e.g. VARS) annotations with the UMI national repository.

What will be the access arrangements?

CSIRO is committed to following the FAIR principles for access to image and annotation data to the extent possible. At the present time, well-organised data (e.g. from deep-sea surveys in VARS/ORACLE) are findable and accessible because metadata records at dataset level are published in MARLIN, datasets have DOI identifiers attached to the metadata, and these are available via the CSIRO Data Access Portal (DAP) and findable via several registries. The present 'individual arrangement' for data sharing will be replaced by a standard web service API (CSIRO DataTrawler conforming to OGC standards). Ensuring FAIRness for some projects may be limited by the way in which the data have been post-processed and stored historically (e.g. data not in structured databases), or in some cases because there are issues of confidentiality (e.g. industry-derived data), or because all data are not stored indefinitely (e.g. commercial e-monitoring data). In the future, a key element of ensuring data meet FAIR expectations is the UMI initiative that will develop the open source infrastructure to establish a national repository for annotations from marine imagery, making them discoverable and accessible through the AODN. This will include imagery and data from CSIRO towed-camera platforms housed in VARS and other CSIRO archives.

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Appendix 7. Capability statement on marine imaging: AIMS (by Melanie Olsen, Scott Bainbridge, Lyndon Lewellyn)

1. What equipment is available?

AIMS has purchased several off the shelf systems for technology evaluation to support the development of our own bespoke solutions. As such we have a range of equipment that spans the range of fully developed and operational through to systems currently in development.

Blue-ROV (Operational - 2 units):

AIMS has two commercial Blue-ROV platforms that have been modified with field-safety compliant power systems and increased capacity payload bays. Payload include several imaging systems including DSLR cameras, a hyperspectral camera, oceanographic equipment, and a Blue-Robotics gripper arm. These are operational (typically <60m, 2 hours battery duration with quick-swap batteries) and typically are operated by engineers & technicians over science leads.

RangerBots (Operational - 2 units):

The RangerBot is small AUV developed by QUT. AIMS has purchased two units as a precursor to the development of a larger Coral AUV which is a joint AIMS-QUT development for use by AIMS. The RangerBots are primarily used as training and test platforms for the more complex work that will be undertaken by the Coral AUV. These are operational but with limitations depending on mission requirements (typically diver depth, 30 min duration and relatively calm conditions where they can be visually tracked). Typical operational performance of the RangerBots is up to 0.5m/s descent rate, horizontal movement rate kept to under 0.45m/s to avoid image blur, typically up to 30m mission depth and up to several hours mission duration (estimated).

Coral AUV (In Field Testing - 2 Units):

AIMS is undertaking field testing of the Coral AUV, a custom developed agile AUV for undertaking complex underwater image mapping missions, jointly designed but solely built by the QUT Centre of Robotics with AIMS responsible for developing the science payloads. This is an AIMS platform that will enter coral reef monitoring operations at an initial operational capability in 2021, with full operations expected mid-2022.

The Coral AUV is unique in that is uses robotic visual perception to navigate safely in close proximity to high value, shallow, complex environments such as coral reefs. The system is designed and built with cost effectiveness in mind for at-scale operations in shallow (<100m and potentially <200m) regions. Operating speeds will be limited by image blur on the camera payloads and mission duration will be several hours. AIMS has invested in operations research modelling to optimise our AUV investment to ensure data is collected efficiently through simultaneous deployments.

ReefScan (Field Testing Q1 2021, # units made to order):

ReefScan is the name for a series of shallow underwater imaging systems, including transom mounted, towed and ASV mounted systems, designed to increase the efficiency of coral reef and seagrass surveys. The first operational system is transom mounted and will be available for external users from mid-2021, with the towed and ASV based configurations available next financial year. The towed system has active control for depth hold and terrain following capabilities. The ReefScan platforms interface with a cloud-based data workflow with machine learning overlays for benthic classification. The target end user group is non-technical personnel, so it is robust and cost effective.

The ReefScan work is a joint development between AIMS, GBRMPA, Queensland Parks and Wildlife Service and the Torres Strait Regional Authority.

Drones (operational, various units):

While not AUV's, AIMS has a number of aerial drones for marine operational mapping including one with a hyperspectral camera suitable for detailed spectral mapping. AIMS has two larger DJI M600 drones (6 kg payload capacity) and a waterproof drone for training purposes. AIMS is also working with the TERN sponsored Australian Scalable Drone Cloud initiative to establish a scalable drone image processing workflow for marine end users.

2. What are the applications?

Synoptic Benthic Surveys [ReefScan, Drones]:

A large driver behind the ReefScan series of platforms, including the ASV's, is the need to undertake large area benthic surveys efficiently and by non-technical personnel. This includes large scale image-based surveys of reefs, seagrass areas and other coastal habitats. The platforms effectively replace synoptic surveys, such as is currently done for coral reefs by Manta Tow survey method.

Drones have been deployed for mapping intertidal areas, mangroves, sand cays and shallow reef habitats. Drones have also been deployed to assist the IMOS Moorings team in rapidly locating subsurface moorings.

High resolution images are typically stitched together into large scale ortho-image mosaics or used in machine learning models to get estimates of benthic habitat type (precent cover). Under one science program, the data is used to map change in coral colony structure at fixed sites along the Great Barrier Reef.

Detailed Benthic Surveys / Pest detection [CoralAUV, Blue-ROV,RangerBot]:

Fine-scale monitoring of complex benthic habitats, such as coral reefs, requires more sophisticated guidance, navigation and control techniques to safely and reliably position imaging systems close to the benthos. The Coral AUV was designed specifically for this mission and is seen as an alternative to diver-based surveys. As a precursor, the Blue-ROV has been used for this type of mapping both in a tethered mode and as a fixed-depth towed platform.

These platforms have also been used in other applications such as night-surveys, beyond diver-depth surveys, visually detecting Crown of Thorns Starfish (CoTS), identifying CoTS feeding scars and coral bleaching.

High-resolution imagery is the core dataset, but the platforms are payload agnostic and can interface with other sensors where required, such as hyperspectral imaging systems, multi- beam sonar and oceanographic sensors. The datasets are quality controlled such that they are suitable for the production of image mosaics or suitable for machine learning based analysis. The dataset to be acquired is closely tied into the platform mission planning.

3. What annotation system is used for images?

The annotation schema used depends on the area being surveyed, the habitat type, the survey method and the information needs of the client. A number of schemas are under development but there is the intent to make these hierarchical so that the same schema can be used for differing survey types or information requirements by defining a level in the hierarchy to do the analysis at. This allows more detailed analysis to be simplified to a generic set of higher- level categories.

The main annotation system used to date are the LTMP classification codes (see: https://www.aims.gov.au/sites/default/files/2020-11/AIMS_LTMP_SOP10v2_Benthic- surveys-photography_2020_DOI.pdf).

For synoptic surveys where the camera is some distance away from the substrate the higher- level categories are used (e.g., abiotic, hard coral, soft coral) more following the codes used by the Manta Tow method (see SOP Number 9 2019 on the AIMS web site: https://www.aims.gov.au/docs/research/monitoring/reef/sops.html).

As much of our work is done in conjunction with clients the final resolution of the annotations is based on client needs. AIMS is part of the IMOS-UMI project looking to develop a common annotation schema for benthic imagery.

The annotations are undertaken by a mix of Machine Learning and manual checking using Machine Learning models developed in-house and custom software, also developed in-house. The software is web based and runs off our cloud-based software systems. These systems can be made available for external users and AIMS is developing a series of externally available web-based systems, using the cloud-based software, to support client projects that require annotation services.

4. What degree of automated classification is used with images?

The platforms/payloads and data workflows are designed to work together to collect data appropriate for the mission. Whether the platform is a diver or an AUV, some missions are designed for automated classification, others for human-assisted classification and other are bespoke. Data collection missions must collect data of sufficient quality to meet AIMS QA/QC requirements, and when this is met, the processing workflows are platform independent.

AIMS currently has operational automated classification models for high resolution shallow coral reef environments, developmental automated classification models for Baited Remote Underwater Video Stations, developmental deep reef habitat classification and developmental synoptic survey models (for the Manta Tow Survey use case). Through ReefCloud, AIMS is also integrating machine learning techniques to analyse images from Pacific Nation partners and Traditional Owners which require models that operate across a wider environment variation.

For AIMS published science, currently only towed video collected imagery and LTMP imagery is analysed in a routine operational manner with assisted automated classification using machine learning techniques. In-house systems are used for annotation.

The accuracy of the annotation is dependant on the benthic form as some forms are better resolved by the Machine Learning models than others. For the detailed coral classification, the 30 years of AIMS annotated images and video were used to train the models giving accuracies in the low 90% for most taxa (at the genus level). For other areas, especially where you get mixed assemblages, the accuracy is lower – typically in the high 80% range. An example is sand and algal assemblages that are hard to characterise by humans and so also resolve to a lower level of accuracy by the models.

The current model for use of automated annotations is that all annotations are manually checked by an experienced scientist with corrections being fed into the model development cycle to ensure the models reflect the latest data. As many benthic forms are well resolved by the models the hybrid method of doing initial annotations by the Machine Learning system followed by manual QC is faster than just doing human based analysis.

5. Where will the imagery be stored?

Autonomous & unmanned systems and next generation sensors (e.g., acoustic and hyperspectral sensors) create orders of magnitude increases in "imagery" storage requirements. To be sustainably used in routine operations, a staged storage workflow is required. This includes portable local mass storage at sea, collocated compute/storage for QA/QC and complex dataset processing on-site, cloud-based storage for fast-tracked processing workflows (or machine to cloud), and traditional long-term storage for Archives Act compliance. The key is having a workflow that effectively moves data through the storage pipeline such that no staging/processing storage area is overwhelmed by incoming data.

AIMS is still developing strategies as to where it stores the final image data and the annotations noting that moving images between systems is time and resource intensive and so aligning work-flow systems and storage systems is a key efficiency and may determine ultimately where images are stored.

As a publicly funded research organisation, AIMS must comply with stringent sovereign data security and integrity requirements remembering that much of the data we collect is done so under specific arrangements and agreements. As more unmanned systems come online, AIMS' data pipeline will continue to evolve and integrate with national initiatives. Broadly, AIMS is adopting the FAIR (findable, accessible, interoperable and re-usable) data principles as a design rule and will be considering how best we approach these same principles regards code.

6. What will be the access arrangements?

The majority of AIMS collected information is publicly available. Access to the underlying imagery and annotations is available on request. IMOS and the AODN is a logical pathway to development more open access data reserves in the future.

The development of Machine Learning models requires "gold-standard" training data, and we see that this is one area where we would like to see a collaborative effort to developed quality- controlled training data. This is one area where data sharing and access would have a huge impact.

7. Other Capacity / Future Development:

ReefWorks:

AIMS Cape Cleveland is home to ReefWorks, Australia's tropical marine technology test range (see attached brochure). AIMS has invested heavily over the last five years in marine robotics, autonomous and AI-driven technologies to transform its own operations.

ReefWorks provides a test range to safely and routinely mature these systems from concept through to operational service. It is designed to demonstrate systems as:

- fit-for-purpose,
- safe to operate, and
- environmentally compliant.

Operations Research:

A prerequisite for introducing autonomous systems to routine operations is the ability to efficiently achieve their mission from and end-to-end system perspective. AIMS has worked with QUT to conduct operational modelling on routine AUV deployment for coral reef surveys so that AIMS can optimise its number of AUVs and mission configurations to ensure cost effective performance. This modelling is an important way of understanding how AUV's can be used effectively to ensure that we meet the design goals including financial goals.

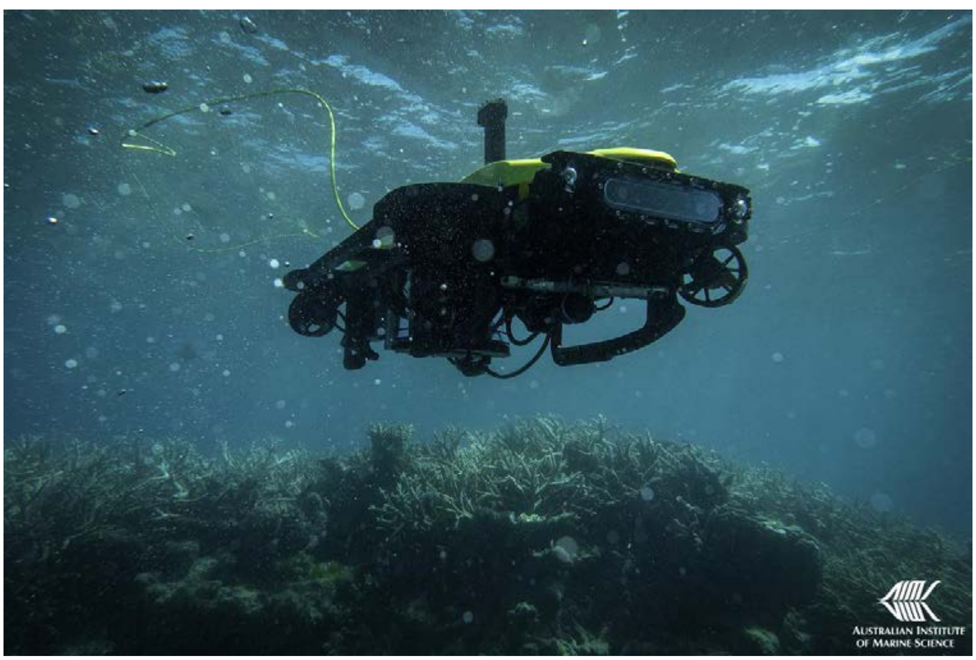
Development/application priorities for the next 3-5 years:

The key challenge to AIMS is to scale the monitoring and observation work it does in a cost- effective manner to meet the needs of an increasingly changeable environment. The need to survey more areas more often and to deliver the resulting information in a timely manner to decision makes are Traditional Owners requires a re-think in how we monitor. This includes developing and trialling new platforms, new data analysis methods and new models for how we deploy the limited resources we have including the collaborative use of other resources.Part of this strategy is the use of AUV's and so AIMS has commissioned the development and delivery of a be-spoke shallow water agile AUV, the Coral AUV. In tandem AIMS is developing data workflow systems and Machine Learning Model to support the increased data that this platform will generate along with the Operational Modelling required to understand how best to apply the new capability.

The current set of work priorities to achieve this over the next few years includes:

- bedding in and fully operationalising the LTMP system with a move to the cloud
- validation and publication of the models so that we can use them in reports and publications (still to work out how versions of models are identified and curated)
- development of models for synoptic manta tow level data and for particular habitats to support work in the Pacific and work with northern rangers in the Torres Strait and the top of WA
- development of 'gold-standard' training data for set environments and for target species such as COTS, Tritons and so on
- move to on-node detection and analysis so that images are analysed as they are collected – we have this in prototype but not operational yet
- development of platforms for data collection including towed systems and so on.

The overall goal in 3-5 years is to have operational ML models that give a level of reliability that users are happy with first level results from the models and that the human component is to QC the results and to resolve areas where the ML is known to perform poorly. This will be a capability we can integrate into our cloud-based data processing systems and move down to the data collection node so that as data is collected it is analysed.



Coral AUV being tested at John Brewer Reef, image G. Page, AIMS.

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Appendix 9. Student theses supported by the IMOS AUV Facility

Title	Name	Type	Completion	Affiliation
Large-scale multi-sensor 3D reconstructions and visualisations of unstructured underwater environments	Matthew Johnson-Robertson	PhD	2009	USYD
Habitats and sessile benthic megafaunal communities in the mesophotic zone of the Great Barrier Reef world heritage area, Australia	Thomas Bridge	PhD	2011	JCU
Non-extractive monitoring of biodiversity on temperate Australian deepwater reefs: using advanced vision-processing techniques to develop and test reliable biodiversity metrics	Jan Seiler	PhD	2011	UTAS
Water column current profile aided localisation for Autonomous Underwater Vehicles	Lashika Medagoda	PhD	2012	DFKI (Germany)
Seeking abiotic surrogates for temperate reef invertebrate assemblages using an Autonomous Underwater Vehicle (AUV)	Jessica Rugge	MSc	2012	UOW
Active learning using a variational Dirichlet process model for pre-clustering and classification of underwater stereo imagery	Ariell Friedman	PhD	2013	USYD
Plenoptic signal processing for robust vision in field robotics	Donald Dansereau	PhD	2014	Stanford (USA)
Full history cooperative localisation with complete information sharing	Lachlan Toohey	PhD	2014	USYD
Hyperspectral benthic mapping from underwater robotic platforms	Daniel Bongiorno	PhD	2015	USYD
Multimodal learning from visual and remotely sensed data	Dushyant Rao	PhD	2015	USYD
Hierarchical classification of scientific taxonomics with Autonomous Underwater Vehicles	Michael Bewley	PhD	2015	USYD
The application of benthic imagery from an Autonomous Underwater Vehicle to broad-scale ecological monitoring	Nicholas Perkins	PhD	2015	UTAS
Efficient and featureless approaches to bathymetric simultaneous localisation and mapping	Stephen Barkby	PhD	2015	USYD
Bayesian non-parametric benthic habitat mapping	Asher Bender	PhD	2017	USYD
Dirichlet process mixture models for autonomous habitat classification.	Daniel Steinberg	PhD	2017	USYD

Title	Name	Type	Completion	Affiliation
Combining exploration and exploitation in active learning	Nasir Ahsan	PhD	2017	USYD
Response of Rottnest Island kelp habitats to the marine heatwave of 2010/2011	Tim Ward	MSc	2017	SARDI
Deep learning for underwater scene classifications	Ammar Mahmood	PhD	2018	UWA
Spatial ecology of the mesophotic benthic communities of the Ningaloo Marine Park	Joseph Turner	PhD	2019	UWA
Autonomous underwater vehicles: a platform for investigating biophysical relationships in cross self-benthic communities	Lainey James	PhD	2019	UTAS
Evaluating the role of inertial and tidal internal wave dynamics on a narrow continental shelf: an assessment of the dominant physical dynamics influencing the nutrient energy budget	Tamara Schlosser	PhD	2019	UWA
Understanding the role of mid-shelf reefs in coastal ecology: can they act as refugia for shallow marine communities in an extreme climatic event?	Ana Giraldo-Ospina	PhD	2020	UWA
Demersal fish surveys from small form factor AUVs	Nader Boutrous	PhD	2020	USYD
Heterogeneous marine robot teams	Jackson Shields	PhD	2021	UNSW
Multiscale and hierarchical classification for benthic habitat mapping	Peter Porskamp	PhD	2021	Deakin
Subsea optical scanners for navigation of AUVs and mapping of subsea environments	Thomas Hitchcox	PhD	2022	McGill (Canada)

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The Development of Autonomous Underwater Vehicles (AUV); A Brief Summary

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Introduction

The concept of a submersible vehicle is not a new idea. The first American submarine was called "Turtle." It was built at Saybrook, Connecticut in 1775 by David Bushnell and his brother, Ezra. The Turtle was a little egg-shaped wooden submarine held together by iron straps. Turtle bobbed like a cork in rough surface winds and seas even though she was lead weighted at the bottom. In this hand and foot-operated contraption, one person could descend by operating a valve to admit water into the ballast tank and ascend with the use of pumps to eject the water. Two flap-type air vents at the top opened when the hatch was clear of water and closed when it was as not. The air supply lasted only 30 minutes. The Turtle's first engagement, which took place in New York Harbor in 1776, was also the first naval battle in history involving a submarine. [Pararas]

In November of 1879, the Reverend George W. Garrett designed, what was considered by some to be the world's first practical powered submarine, the "Resurgam." It was built at the Britannia Engine Works and Foundry of J. B. Cochran in Birkenhead, England and was powered by a Lamm 'fireless' steam engine and could travel for some ten hours on power stored in an insulated tank.

After these historic underwater vehicles, there have been many more submersibles developed and used operationally for a number of different tasks. With these submarines, came the development of torpedoes. Torpedoes are truly the first (AUVs) Autonomous Underwater Vehicles. Although there are a number of AUV-like systems that were considered prior to the 1970s, most never were used for extended periods of time or discussed in open literature. Since that time a great deal of development has occurred.

There are different types of underwater vehicles. One method of categorizing these vehicles is to identify them as members one of two classes of vehicles; manned and unmanned systems. We are all familiar with the manned systems. They can be described simply as falling into two sub-classes; military submarines and non-military submersibles such as those operated to support underwater investigations and assessment. The navies of the world utilize a number of different classes of submarines to conduct their missions. On the other hand, Alvin (USA), Epaulard (France), Mir (Russia) and Shinkai 6500 (Japan) are all familiar names of small submarines that allow a few individuals to descend into the ocean to gather data and information from observations of the water column and ocean bottom.

Figure 1 Autonomous Benthic Explorer (ABE), Woods Hole Oceanographic Institution (WHOI)

Unmanned submersibles also fall into a number of different sub-classes. The simplest and most easily described are those submersibles that are towed behind a ship. They act as platforms for various sensor suites attached to the vehicle frame. A second type of submersible system is called a Remotely Operated Vehicle (ROV). An ROV is a tethered vehicle. The tether supplies power and communication to the ROV and is controlled directly by a remote operator.

Figure 2 AUTOSUB, Southampton Oceanography Center (SOC)

A third type of unmanned submersible is an Unmanned Untethered Vehicle (UUV). This untethered vehicle contains its own onboard power but is controlled by a remote operator via some type of a communications link. An AUV is an undersea system containing its own power and controlling itself while accomplishing a pre-defined task. A further distinction between the AUV and UUV is that the AUV requires no communication during its mission whereas the UUV requires some level of communication for it to complete its assigned mission.[1]

A Brief Chronological History of AUV Development

It is informative to understand what has happed over the past few decades relative to the development of AUVs. It is clear that the process has led to a technology whose time has arrived.

Prior to 1970 - Special Applications of AUVs

Initial investigations into the utility of AUV systems.

AUV development began in the 1960s. A few AUVs vehicles are built mostly to focused on very specific applications / data gathering. There are not a great amount of published papers that describe these efforts.

1970 - 1980 - Explore the Potential of AUVs

Technology development: some testbeds built.

During the 1970s, a number of testbeds were developed. The University of Washington APL developed the UARS and SPURV vehicles to gather data from the Arctic regions. The

[1] **Another difference between the AUV and the UUV is in the genesis of the acronyms. AUV was a term coined by the AUV development community. When the US Navy got involved, with AUV technology development they coined the acronym of UUV. This became an all-encompassing term to include both ROVs and AUVs.**

University of New Hampshire's Marine Systems Engineering Laboratory (now the Autonomous Undersea Systems Institute) developed the EAVE vehicle (an open space-frame AUV) in conjunction with a complementary effort undertaken at the US Navy's facility in San Diego. Also at this time the Institute of Marine Technology Problems, Russian Academy of Sciences (IMTP, RAS) began their AUV program with the development of the SKAT vehicles, as well as the first deep diving AUVs L1 & L2. Other AUV testbeds were also fabricated. This was a time of experimentation with technology in hopes of defining the potential of these autonomous systems. There were some successes and many failures. The vision shared by the development community far exceeded the technology available to implement that vision. None the less, there was significant advancement in AUV development.

1980 - 1990 - Experiment with Prototypes

Advances in technology reinforce development efforts.

Proof of Concept (POC) prototypes are developed/tested/used.

In the 1980s there were a number of technological advances outside of the AUV community that greatly affected AUV development. Small, low power computers and memory offered the potential of implementing complex guidance and control algorithms on autonomous platforms. Advances in software systems and engineering made it possible to develop complex software systems able to implement the vision of the system developers. Even with these technological advances, it became quite clear that a number of technology development problems had to be solved if AUVs were to become operational systems.

In 1980, the first "International Symposium on Unmanned Untethered Submersible Technology" (UUST) was held in Durham New Hampshire, USA Twenty-four technologist attended this meeting. By 1987, the attendance had grown to more than 320 people representing more than 100 companies, 20 Universities and 20 Federal agencies.

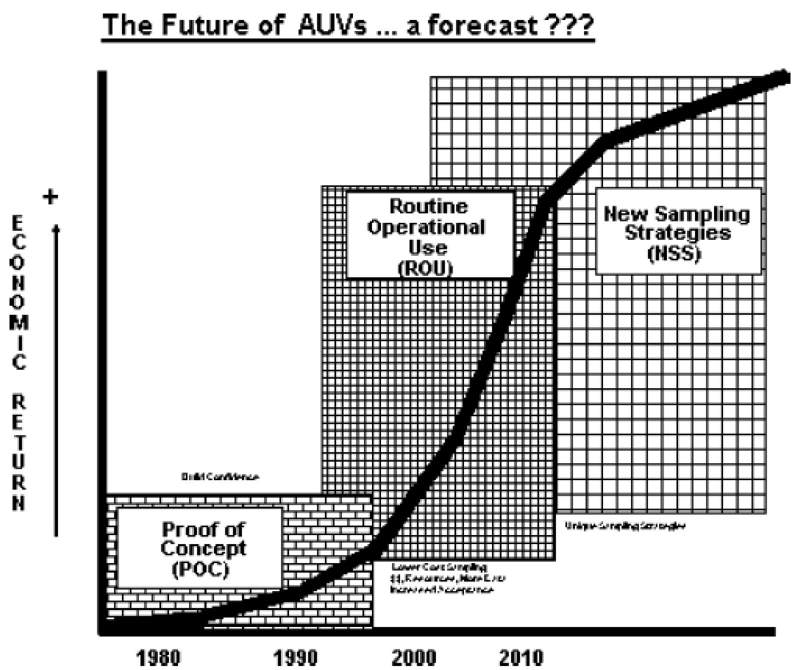

Figure 3 A possible timetable for the transition of AUV technology from prototype systems to operational vehicle systems is described by the characteristic "S" curve associated with the introduction of new technology into the marketplace. The year 2000 should see this technology expand into operational use and produce an economic return for developers.

Nine countries were represented at the meeting.

Most importantly in the USA, research programs were begun which provided significant funding to develop proof of concept prototypes. The most published program was the effort at Draper Labs that led to the development of two Large AUVs to be used as testbeds for a number of Navy programs. This decade was indeed the turning point for AUV technology. It was clear that the technology would evolve into operational systems, but not as clear as to the tasks that those systems would perform.

1990 - 2000 - Goal Driven Tech. Development

Broader based funding of technology development.

Many AUVs developed internationally. Users awake.

During this decade, AUVs grew from proof of concept testbeds into first generation operational systems able to be tasked to accomplish defined objectives. A number of organizations around the world undertook development efforts focused on various operational tasks. Potential users surfaced and helped to define mission systems necessary to accomplish the objectives of their data gathering programs. This decade also identified new paradigms for AUV utilization such as the Autonomous Oceanographic Sampling System (AOSN) [Curtin] and provided the resources necessary to move the technology closer to commercialization.

2000 - 2010 - Commercial markets grow

First truly commercial products

As this decade begins, the utilization of AUV technology for a number of commercial tasks is obvious. Programs are underway to build, operate and make money using AUVs. Markets have been defined and are being assessed as to viability. This will be the decade that sees AUV technology move from the academic and research environment into the commercial mainstream of the ocean industry. There are still technological problems to be solved. The economic viability of the technology has still to be proven. The AUV must be proven in an operational regime in order for the technology to continue its advance and for industry to embrace its potential.

Figure 4 Maridan 600, Maridan A/S, Denmark

AUV Technology

Over the years, the focus of technology development has changed as new ideas surfaced to address technology problems. Some of the problems have been solved, others remain that must be addressed, and other, previously unrecognized problems, have surfaced. It is hard to list those technologies that are needed for AUV systems. Any list that is developed will be incomplete. It could be suggested, however, that the following list represents many of the technologies that have been addressed over the past three decades.

- Autonomy
- Energy
- Navigation
- Sensors
- Communications

The interesting aspect of this list is that although there have been advances in these technical areas, a number of these technologies still remain the "technology long poles" associated with AUV systems. Limits in these technologies limit the capability of AUV systems.

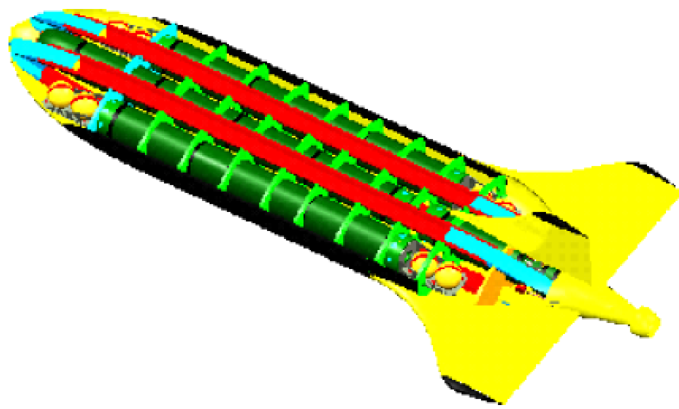

Figure 5 STDV (Manta AUV, NUWC Newport)

Technology "Long Poles"

- Autonomy / Cooperation / Intelligent Systems and Technologies
- Energy Systems / Energy management
- Navigation
- Sensor Systems and Processing
- 3D Imaging
- Communications.

<u>Autonomy / Cooperation / Intelligent Systems and Technologies:</u> In the 1980s there was a considerable effort placed into understanding how to give an AUV a level of intelligence necessary to accomplish assigned tasks. Issues such as intelligent systems architectures design, mission planning, perception and situation assessment were investigated. These are all hard problems and there were few successes that led to in-water evaluation. As the capabilities required by the first generation AUVs became clear, the tasks the AUVs were to perform seemed not to demand a high level of intelligent behavior. In fact, many of the tasks being assigned to today's AUVs required only a list of preprogrammed instructions to accomplish a task. For this reason, there has not been a significant level of development, recently, that is focused on AUV autonomy.

The problem of autonomy still remains unsolved. There have been some successes with other autonomous systems, but those advances have not been brought into the AUV community. There are very few programs funded to address these issues and the problem remains. As AUV operations increase, it will become apparent that more investigation is needed. This will again emphasize the need for more development along the lines of making AUV systems more intelligent and better able to adapt to the environment within which they exist.

The use of multiple cooperating AUVs was first considered in the 1980s. Some work was undertaken, but not completed. Since that time, there has been little funded work on this technological issue. In the past few years, there has been increased recognition of the potential of multiple cooperating AUVs. Currently some work is underway to investigate cooperating AUVs tasked to meet some of the needs of mine clearance. Many more investigations are required as the problem is a significant problem and far from being solved.

Energy Systems / Energy management: Endurance of AUVs has increased from a few hours to 10s of hours. Some systems now contemplate missions of days and, a very few, of years. This extended endurance, however, is at the expense of sensing capability, as well as very limited transit speeds. In the majority of early AUV systems, Lead Acid batteries were the workhorse for energy systems. Some AUV designs included Silver Zinc batteries, but, for the most part, the cost was prohibitive. Some applications, such as the ABE vehicle, utilized Lithium primary batteries. A number of other chemistries were tried for different applications. Recent advances in NiMH batteries have provided new opportunities for AUV and this technology is being used in many of the current AUV systems. In 1987 the use of an Aluminum / Oxygen "semi-cell" was proposed to DARPA for use in an AUV. A number of years later a similar system development was funded and dramatically increased the endurance of the DARPA UUV. Currently the ALTEX [altex] program is underway to utilize similar technology to allow an AUV to transit under the Arctic ice.

Solar Energy is now being used to power an AUV [AUSI]. This system demands a detailed design of onboard energy management; both during the acquisition phase, as well as the utilization phase of operations. It is an inexhaustible energy source but requires an AUV to surface while recharging. The Glider AUVs [Simonetti] utilize heat energy to vary the buoyancy of an AUV that can glide up and down in the water column. The potential endurance of such a system is measured in years.

Figure 6 The Solar Powered AUV (SAUV), AUSI & IMTP, RAS, FEB

Navigation: Early AUV systems relied on dead reckoning for their navigation. Acoustic transponder navigation systems provided greater accuracy but at a significant logistics cost. Inertial navigation systems were available for more expensive AUVs, but costs were prohibitive for the non-military user. With advances in inertial platform technology, the cost has dropped significantly to a point where it is possible to utilize these systems for lower cost AUVs. Navigation systems continue to improve in accuracy as well as precision. In the past few years, many AUVs have taken advantage of Global Positioning Systems (GPS). When the vehicle surfaces, it is possible to obtain an accurate position and update onboard inertial systems. Still, there is strong interest in being able to navigate relative to the environment within which the system exists. This environment referenced navigation utilizing bottom features, gravimetric variations or other similar characteristics is an objective to be attained. A successful system will provide a significant increase in AUV capability.

Sensor Systems and Processing / 3D Imaging: An AUV is simply a platform on which to mount sensors and sensing systems. Initial efforts to develop AUV technology was more concerned about the basic technologies required to allow reliable vehicle operation. As that reliability was achieved, sensors were added to the vehicle system to acquire data from the ocean environment. Most of these efforts to date have been to integrate existing sensors and sensor processing to the sometimes-unique constraints of the AUV. This paradigm has proven to work reasonably well. Recently it has been recognized that we must develop entirely new sensors based on the constraints imposed by an AUV. This would change the paradigm of sensor integration. It would encourage the development of sensors specifically for AUVs; smarter, lower power, highly reliable, smaller in size, etc. It is also becoming clear that AUVs can be used in groups to act cooperatively to acquired needed data. By maintaining a common spatial and temporal reference, data acquired by multiple AUVs can be aggregated and processed to obtain synoptic, high resolution data describing a process of interest.

Much work continues on the development of higher and higher resolution imaging systems, both optical and acoustic. With the new processors it has been possible to obtain very high-resolution images over longer and longer ranges [LENS]. The roadblock to much of this work is the ability to analyze the acquired data autonomously such that the AUV can utilize this data for guidance and control decisions. This perception ability is still beyond the current capabilities of AUVs.

Communications: In the underwater environment acoustic communications is probably the most viable communication system available to the system designer. Some development programs have investigated and evaluated other technologies such as laser communication at short range and relatively noise free communications over larger ranges using RF current field density techniques. In the past 10 years there has been significant advances in acoustic communications such that relatively low error rate communications is possible over ranges of kMs at bit rate of a few kbps [Comms]. This remains an active area of investigation.

Another aspect of communication is the issue of connecting multiple vehicles and/or bottom mounted instrument platforms via a networked-based communication infrastructure. This subsea network can then be connected to a surface vehicle that will act as a gateway to the terrestrial based communication infrastructure such as the internet [Welsh]. Efforts are underway to investigate how to implement such a network and be able to have effective communications among and between multiple underwater systems.

Other technologies have been investigated over the years such as those below. There have been a number of significant advances in these areas and, although there is still much to be learned, they do not represent major stumbling blocks to the further advancement of AUV technology at this time. These technologies continue to be investigated and refined in the development of operational systems. There remain some important advances to be made such as in the area of autonomous manipulation but the emphasis of current activities are not along these lines.

- Guidance /Low Level Control
- Hydrodynamics and Control Systems
- Autonomous Manipulation / Work Systems
- User Interface / Development Tools / Emulation / Modeling

There are also issues associated with the basic system design. It is clear that the system design must result from an understanding of the mission to be undertaken by the system. Over the past few decades, there has been an increased effort to standardize such that advances in system design can be shared by the community. This move toward standardization has increased dramatically over the past few years as AUV systems move closer and closer to operational systems.

Another aspect of the system design that has become commonplace is the tendency to think in terms of modularity. This is seen in current efforts to design distributed control systems architecture both in terms of software and hardware. The concept of "plug & play" is becoming a buzz word for AUV developers as well as PC users. In an environment where new sensors are added to AUV systems on a regular basis, it is obvious that a simple method for managing the impact on the vehicle software system is important.

As AUV systems mature to a point where they are being commercialized, the importance of cost reliability and robustness are gaining increased importance. These are the characteristics that are best optimized by industry. The next few years will undoubtedly see AUVs undergo a strong systems design process to optimize these features. This will benefit the community as a whole and should be well received by the potential user community of the future.

- Software System Architecture / Distributed Control
- Hardware System Architecture / Standardization
- Platform Design
- Cost / Reliability / Robustness

Current Activities/Players

At one point in time it was relatively easy to identify all of the ongoing efforts related to the development of AUV technology. The players were few and, more than not, professional acquaintances and friends. Some of the more advertised efforts can, however, be summarized. The community though international in scope, was well aware of each other's work. In the late 80s the number of individuals and organizations increased significantly. Since then, the number of players has continued to increase. It is now quite impossible to understand the full breadth of ongoing technology development or, even more impossible, to assess progress in the area of commercialization.

Figure 7 DORADO, ISE, Canada

Current activities fall into two categories. First there is a significant amount of research underway to investigate enabling technologies pacing further development of AUV systems. Secondly, there is considerable effort to design, fabricate and evaluate AUV systems under operational conditions. This development activity is being driven somewhat by the evolving markets for AUV technology.

Research & Development: Current AUV development programs are, in many cases, being supported by funding that results from the political process as opposed to market need or technical merit. This, however, is a current reality within which development of AUV technology advances.

Although these programs are very visible due to the level of activity, it is short sited to over emphasize some of these activities over smaller, less advertised work. There are a number of organizations in the USA, and elsewhere, actively working on important research problems. As mentioned above, there is much to be understood regarding technologies such as Autonomy, Energy, Navigation, Sensors, and Communications. These are very much open research topics.

Evolving markets: At this point in time we are seeing a number of markets beginning to form. Although not clearly defined the level of enthusiasm of a number of individuals and organizations suggests that we will see many opportunities for commercializing AUV technology over the next few years.

Individual companies, as well as teams of organizations, have begun efforts to make operational AUVs part of the oil & gas industry toolkit. Missions have been defined, contracts let, vehicle systems designed, and fabrication of the operational systems begun. The next few years will provide insight into the real capability of the commercial AUV [Hasan].

In the area of Ocean Science, the potential for AUV systems is clearly recognized by most researchers. Successes of ABE, AUTOSUB [GRIF97] and other vehicles in gathering scientifically significant data has made a positive impact on the community. New sensors, uniquely suited for AUVs, are being developed. Indeed, the worry is that too much is expected from this evolving technology. Clearly the success and failures of the next few years will help adjust system capabilities and user expectations. This is sign of a maturing technology. It is generally agreed that AUV technology has an important role to play in the future ocean science data acquisition programs.

The US Navy is encouraging and supporting a coordinated effort sometimes referred to as the AOSN [Curtin]. This effort suggests that multiple AUVs can be networked together to acquire oceanographic data and information in spatial and temporal resolution far exceeding current capabilities. It emphasizes coastal areas but, conceptually, a long-term view would envision a similar system obtaining required information throughout the oceans of the world.

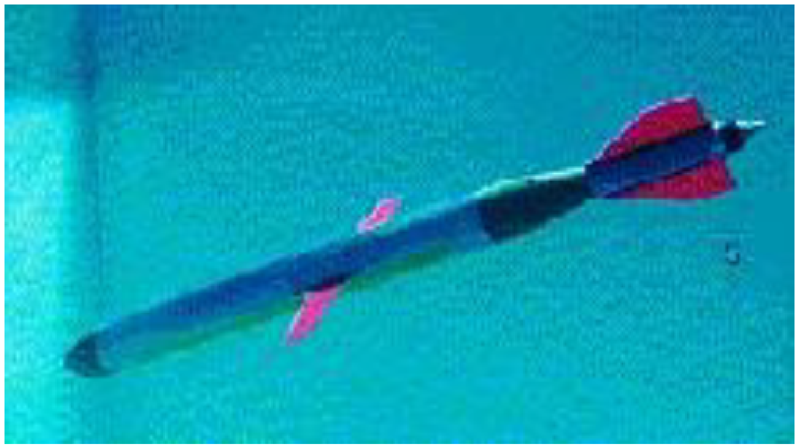

Figure 8 The Slocum AUV Webb Research Inc

International efforts are perhaps further along the path to truly operational systems. Almost from the start, AUV development has encouraged collaboration among academic, industrial and government partners. This has focused development to address real market needs. Again, it will be interesting to see where many of these efforts will provide an economic impact.

AUVs: a Culture Issue

The use of autonomous systems is a revolutionary concept in that the user has very little, if any control over the system as it performs its task. Even space-based satellites can be reached by high data rate communications. The user never really loses control of the system except for very small periods of time. AUVs, on the other hand, by definition, will control themselves over extended periods of time. How soon the user will accept the idea of giving up real time control is unknown. In the short term, that control will be implemented over low data rate communication links. If AUV technology is to truly prove its value, that near real time control function must be eliminated or, at least, minimized. Applications requiring higher levels of autonomy will pace this evolution.

Over the years it has become reasonably clear that there will be no single AUV concept that meets all user needs. A number of workshops have suggested a number of different types of AUVs (size, complexity, and capability). In the 1970s it was possible to count the number of

AUV systems on the fingers of your hands. A recent effort to catalogue AUV systems lists 145 different types of AUV. In the final analysis, an AUV system design must be driven by a specific mission. ISE has taken this philosophy one step further by constructing a web-based tool that allows a potential user to design a specific AUV to meet his/her needs. As operational experience increases, preferred types of AUVs will undoubtedly be identified. The only trend that can be seen now is the two paths that the marketplace has established. The first is the development of small, low cost AUVs. It is envisioned that these systems can eventually be used in groups of cooperating vehicles. The second type of AUVs are much larger systems containing complex sensor suites configured to meet specific user needs. These are not low-cost systems but they are able to undertake tasks that, if done in other ways, would be far more expensive to accomplish. It will be interesting to watch the evolution of these two trends in AUV development.

As clearly as AUV development will be driven by the marketplace, it will be further impacted by the decisions made as to how the businesses that provide AUVs will be structured. Many business models are surfacing. Individual companies spun off from academic efforts have formed. Other models suggest that the appropriate structure is to form a consortium approach that teams multiple academic organizations in some fashion with a commercial organization. Still another model teams large corporations to focus on a specific market. Some individuals state that since AUV technology is so expensive requiring diverse expertise, only a large company or group of organizations can compete. Others suggest that since technology changes so quickly only small organization have the flexibility to adapt quickly. In this final analysis, both models may be right for difference markets. The next few years will tell.

AUV systems are at a transition point. They are moving from the Science and Technology communities into the commercial marketplace. They must now show a return on the dollars invested over the last 30 years.

The Future of AUV Technology

AUV technology has followed a path not unlike other technologies. It has gone through stages where academic curiosity was followed by research investigation and prototype development. Applications have recently surfaced that seem to have sufficient financial backing to develop operational systems. Certainly the timing of AUV technology was good. It has been able to leverage its development by utilizing many technologies developed for other markets. The next five years will see the expansion of AUV technology into the commercial marketplace. The size of that market is unclear but the move into the marketplace has begun.

There are still many important research investigations to be undertaken. Autonomy is probably the most important issue to be addressed but others, such as those described above, certainly must be addressed. It is clear that the limit to the capability of any AUV is the amount of energy it has onboard. There have been many discussions that suggest that fuel cell technology has reached a point where it may well be possible to use this technology in AUV systems. The increase in endurance will be substantial. Is this the "silver bullet" for AUVs? I would suggest that there is no "silver bullet," but rather a continuum of activity that spans a wide spectrum. Basic research into some of the enabling technologies must be supported. The development of operationally reliable systems must be undertaken. Unique markets where AUV technology can make a significant impact must be identified. Most important, the AUV community must educate the user community of the future about AUV systems capabilities and operational reliability

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