Benthic monitoring with robotic platforms - the experience of Australia

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***Abstract*—Australias Integrated Marine Observing System (IMOS) has a strategic focus on the impact of major boundary currents on continental shelf environments, ecosystems and biodiversity. To improve our understanding of natural, climate change, and human-induced variability in shelf environments, the IMOS Autonomous Underwater Vehicle (AUV) facility has been charged with generating physical and biological observations of benthic variables that cannot be cost-effectively obtained by other means. Starting in 2010, the IMOS AUV facility began collecting precisely navigated benthic imagery using AUVs at selected reference sites on Australias shelf. This observing program capitalizes on the unique capabilities of AUVs that have allowed repeated visits to the reference sites, providing a critical observational link between oceanographic and benthic processes. This paper provides a brief overview of the relevant capabilities of the AUV facility, the design of the IMOS benthic sampling program, and some preliminary results. We also report on some of the challenges and potential benefits to be realized from a benthic observation system that collects several TB of geo-referenced stereo imagery a year. This includes collaborative semi-automated image analysis, clustering and classification, large scale visualization and data mining, and lighting correction for change detection and characterization. We also mention some of the lessons from operating an AUV-based monitoring program and future work in this area.**

I. Introduction

Autonomous Underwater Vehicles (AUVs) are playing an increasingly important role in modern oceanographic research. Tasks for which AUVs are suited range from deep water exploration [1], [2] and monitoring of oceanographic phenomena to high-resolution optical imaging [3], [4], [5], [6] and multibeam surveying in deepwater applications [7], [8]. Their ability to operate at close sensing ranges to the seafloor, decoupled from surface motions and with reduced ship requirements (compared to ROVs) make them well-suited platforms for high-resolution mapping.

Australias Integrated Marine Observing System (IMOS) has a strategic focus on the impact of major boundary currents on continental shelf environments, ecosystems and biodiversity. To improve our understanding of natural, climate change, and human-induced variability in shelf environments, the IMOS Autonomous Underwater Vehicle facility has been charged with generating physical and biological observations of benthic variables that cannot be cost-effectively obtained by other means. Starting in 2010, the IMOS AUV facility began collecting precisely navigated benthic imagery using AUVs at selected reference sites on Australias shelf. This observing program capitalizes on the unique capabilities of AUVs that have allowed repeated visits to the reference sites, providing a critical observational link between oceanographic and benthic processes. This is arguably the world's first benthic observing program to make extensive use of AUV systems for the purposes of monitoring benthic habitats on the scale described by this work.

This paper provides a brief overview of the relevant capabilities of the AUV facility, the design of the IMOS benthic sampling program, and some preliminary results. We also report on some of the challenges and potential benefits to be realized from a benthic observation system that collects several TB of geo-referenced stereo imagery a year. This includes collaborative semi-automated image analysis, clustering and classification, large scale visualization and data mining, and lighting correction for change detection and characterization. We also mention some of the lessons from operating an AUV-based monitoring program and future work in this area.

The remainder of this paper is organized as follows. Section II presents the core operational capabilities of the IMOS AUV Facility. Section III outlines the design of the benthic monitoring program and sample results. Section IV presents lessons and current and future research challenges. Section V presents concluding remarks.

II. IMOS AUV Facility

The IMOS AUV Facility is operated by the marine robotics group at the Australian Centre for Field Robotics (ACFR). Mature robotics research and vehicles form the basis of the facility.

A. Core Capabilities

The three main capabilities on which our program relies are briefly described below.

1) Simultaneous Localisation and Mapping: The estimated vehicle trajectory must be self-consistent with respect to the data being collected during each survey for accurate 3D reconstructions. We employ visual Simultaneous Localisation and Mapping (SLAM) to fuse uncertain navigation estimates and visual observations [9] [10]. This allows us to further refine the estimated vehicle trajectory using the environmental

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data such as the high-resolution imagery collected during the survey. Overlapping views of the seafloor are used to determine relative pose information between cameras and these constraints are fused into the vehicle's navigation solution. Example loop closures identified in a dense survey are shown in Figure 2 (a).

2) Seafloor 3D Reconstruction and Visualization: While useful in themselves, single images do not easily convey spatial features and patterns at larger scales so we have developed a suite of tools to combine the SLAM trajectory estimates with the stereo image pairs to generate 3D meshes and place them in a common reference frame [11]. These meshes are generated once the vehicle is recovered and take on the order of the same amount of time to compute as the length of the dive allowing dive outcomes to be examined while still at a site. The resulting composite mesh allows a user to quickly and easily interact with the data while choosing the scale and viewpoint. In contrast to more conventional photo-mosaicking approaches [12], [13], the full three dimensional spatial relationships within the data are preserved and users can move from a high level view of the environment down to very detailed investigation of individual images and features of interest within them.

3) Image-based 'Habitat' Clustering: While the visualization of 3D reconstructions improves our ability to understand the spatial layout of seafloor features, further analysis and interpretation is required to address tasks such as habitat characterization and monitoring. This analysis stage is typically performed by human experts which limits the amount and speed of data processing [14]. It is unlikely that machines will match humans at fine-scale classification any time soon but machines can now perform preliminary, coarse classification to provide timely and relevant feedback to assist human interpretation. We are developing image-based habitat classification and clustering systems to facilitate the analysis of the large volumes of image data collected by the AUV [15], [16], [17].

TABLE I
SUMMARY OF THE *Sirius* AUV SPECIFICATIONS.

Vehicle	
Depth rating	800 m
Size	2.0 m (L) × 1.5 m (H) × 1.5 m (W)
Mass	250 kg
Maximum Speed	1.0 m/s
Batteries	2.28 kWh Li-ion pack
Propulsion	Three 150 W brushless DC thrusters
Navigation	
Attitude+Heading	TCM2 Compass/Tilt Sensor
Depth	Digiquartz press. sensor
Velocity	RDI 1200 kHz Navigator ADCP
Altitude	RDI Navigator
USBL	TrackLink 1500 HA
GPS receiver	U-Blox receiver
Optical Imaging	
Camera	Prosilica 12bit 1360×1024 CCD stereo
Lighting	Two LED pucks, 30,000 lm each
Separation	0.75 m between camera and strobes
Acoustic	
Multibeam sonar	Imagenex DeltaT 260 kHz
Obstacle avoidance	Imagenex 852 675 kHz
Tracking and comms	
Radio	Freewave RF Modem / Ethernet
Acoustic Modem	Linkquest 1500 HA Integrated Modem
Other Sensors	
Conductivity and Temperature	Seabird 37SBI
Clorophyll-A and Turbidity	Wetlabs FLNTU Ecopuck

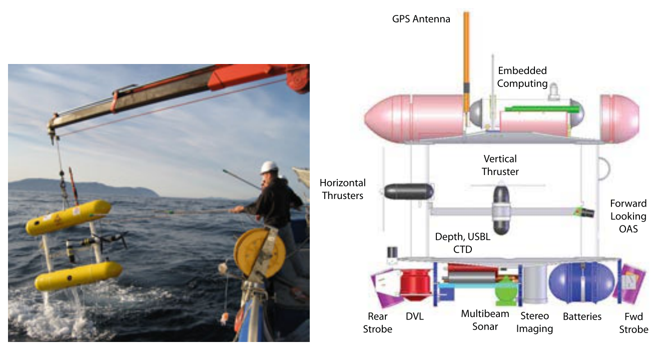


Fig. 1. The AUV *Sirius* being retrieved aboard the RV *Challenger* following a mission in SE Tasmania.

B. Main monitoring AUV

We operate *Sirius*, an ocean going AUV capable of undertaking the high-resolution, geo-referenced survey work [18], [19]. This platform is a modified version of a mid-size robotic vehicle SeaBED built at the Woods Hole Oceanographic Institution [20]. This class of AUV has been designed specifically for relatively low speed, high resolution imaging and is passively stable in pitch and roll. The submersible is equipped with a full suite of oceanographic sensors (see Table I).

For real-time navigation the observations of velocity provided by the DVL, attitude and depth are fused using an Extended Kalman Filter [19]. The USBL observations, consisting of range and bearing between the vessel and the vehicle, are collected on the surface and are sent together with the ship's position and attitude to the vehicle using the acoustic modem. These observations are received by the vehicle and fused into its onboard navigation filter. The heading reference used is sensitive to the magnetic signature of the rest of the vehicle, which can introduce distortions of several degrees into the heading estimate. Even when soft and hard iron calibration are performed, persistent heading-dependent errors of 1 deg are possible. While adequate to perform linear transects or broader acoustic surveys (particularly when aided by acoustic positioning from LBL or USBL), the magnitude of these errors makes an dense 'mow the lawn' pattern with reciprocal, closely spaced, parallel tracklines difficult to execute properly. It is possible to derive a heading-dependent correction to the magnetic compass using visual data and that this correction can enable a compass-equipped AUV to perform dense visual coverage of a seafloor patch of approximately 50 m x 75 m with 50 parallel tracklines [21]. This has resulted in a navigation suite that is capable of meeting the requirements for repeated surveying of the permanent reference sites.

III. IMOS AUV BENTHIC MONITORING PROGRAM

The initial development and testing phase of the AUV and core SLAM and reconstruction capabilities took place form 2005 to 2007. We mostly used cruises of opportunity, primarily for exploratory purposes and for collecting optical imagery to assist the interpretation of multibeam surveys. This period

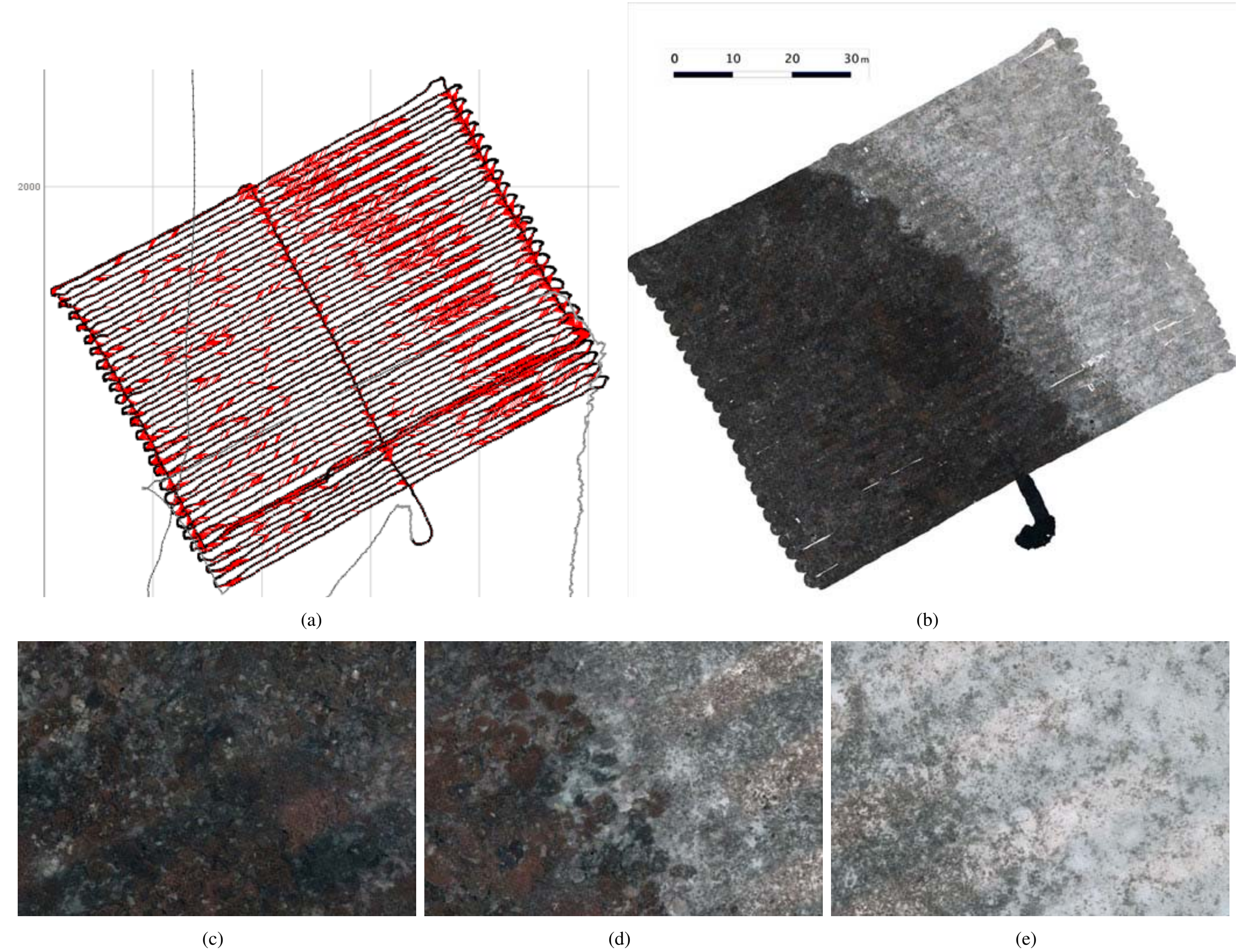


Fig. 2. Scott Reef dense grid (a) Simultaneous Localisation and Mapping has been used to refine the estimated vehicle trajectory. The red lines connect estimated vehicle locations for which visual loop closures have been applied. (b) The estimated vehicle track is used to generate a detailed three dimensional representation of the underlying surface covering approximately $3750m^2$ of the seafloor. The transition between dense coral and sandy substrate is clearly evident in this model. Surveys such as this provide an ideal opportunity to observe change in the benthos. Details of the reconstruction are shown for (c) dense coral coverage, (d) transition zone and (e) sandy substrate illustrating the detail of these mosaics.

allowed us to demonstrate the ability to collect geo-referenced, high quality imagery and generate large scale composites [22], [23]. These capabilities were considered unique and valuable to IMOS and we were funded as the IMOS AUV facility to provide AUV benthic imaging services to the marine science community in Australia. The basic model required a competitive bidding for the AUV and the science party would have to provide ship time. Personnel and transport costs were covered by IMOS. In its first three years (2007-2009) the use of the facility continued to be mostly exploratory.

One our science partners became familiar with our capabilities, they began to see how it could form the basis of a monitoring program based on precisely revisiting the same areas. The IMOS AUV benthic monitoring program (2010 to at least 2014) [24] was designed to provide data streams suitable for observing changes in benthic communities that can be related to climate change, climate variability and human activities. This observing program has a particular focus on reef habitats since reefs support long-lived organisms that are sensitive to environmental change as they are unable to relocate once established. Changes in environmental conditions are therefore likely to have a pronounced impact on these reefs that will be observable through a program of repeat monitoring. Precisely registered maps such as those generated by our AUV systems and collected periodically are providing researchers with the ecological data necessary to make quantitative inferences about the long term changes on the benthos. In the short term, the facility will also provide stakeholders with data useful for the effective management of marine parks and fisheries where the benthos provides a food source or plays a role in the lifecycle of the target species.

A. *Survey Design*

A nested hierarchical sampling design that takes advantage of AUV capabilities is used by the IMOS benthic monitoring program:

1) Broad scale, sparse grids on the order of 500 m to 1000 m on a side to determine spatial variability in

habitat structure, and in some cases cover a range of depths of interest.

2) Small-scale 25 m x 25 m full cover dense grids, providing contiguous coverage mapping for the establishment of long term monitoring sites.

This approach provides both high-resolution, full coverage surveys of selected areas that can be precisely revisited over a number of years as well as broader scale grids over depth gradients designed to examine the correlations between populations and underlying bathymetric processes that help shape their distribution. Target habitats are located in depths ranging between 15 m and 250 m.

Wherever possible, multiple full cover dense grid surveys of 25 m x 25 m are designated within each survey location for repeated surveying. This allows for replicates to aid in ecological analysis. The precise locations are chosen in areas characterised by prior multibeam sonar mapping (to facilitate effective depth and habitat sampling design), and/or prior AUV surveys. Each grid requires on the order of 45 minutes to complete and the vehicle is programmed to complete two to three of these at each site before the vehicle is recovered and moved to a new site.

The primary requirement of this observing program is the ability to revisit benthic sites and image the same location on the seafloor. Revisiting the location of a single image in surveys spaced out over a number of years is likely to prove difficult even with high-end navigation suites. The use of the dense grids allows an area to be revisited with a high degree of certainty as the majority of a 25 m x 25 m patch of the seafloor is likely to overlap between dives even if there is some offset in the estimated vehicle location as might be expected when using a standard GPS receiver. The broad survey grids, on the other hand, are not designed to be revisited precisely but are meant to capture spatial variability within a particular dive site. A standard set of oceanographic navigation instruments is therefore sufficient for our purposes although care must be taken with calibration of the instruments and the manner in which the navigation data is fused.

Wherever possible, sampling sites have been selected in proximity to IMOS oceanographic moorings within each geographic region in order to provide the best possible link between oceanographic conditions and biophysical processes and benthic dynamics. Additional sites focus on the expected limits of the distributions of habitat forming species of interest in order to provide a more accurate picture of factors affecting actual changes in distributional range and are more relevant to longer term, potentially climate related processes. The combination of these two survey designs will therefore allow us to address questions at a range of scales relevant to understanding the linkages of Australia's boundary currents with ecological processes.

B. Sample results for 2007-2012

The IMOS AUV Facility program has been running since 2007. Over the course of five years we have conducted several hundreds of dives at sites located around Australia. Figure 3 shows a summary of the dive locations visited during this period. The focus of the sustained observing program has shifted to the establishment of benthic reference sites on both the east and west coasts along the full latitudinal range of the continent. The symbols on the figure designate the survey sites and are colour coded by dominant habitat and sized proportional to the number of images currently available in the IMOS AUV Facility image archive.

Beyond that challenges of acquiring high resolution georeferenced imagery with the AUV, there is also a requirement to bridge the gap between these observations and the quantitative information required to characterise changes in marine habitats. The volume of data available to support these studies requires that much of the processing and data integration be automated to avoid bottlenecks associated with manual interpretation of imagery. The data itself is currently available online through the IMOS electronic Marine Infrastructure Initiative (eMII) facility and we are working to establish a shared and growing repository of consistently annotated / analyzed imagery that is readily accessible to end users and suitable for collaborative labelling and training of machine learning algorithms [25].

An example of the application of visual clustering techniques [15] to data collected in South East Queensland is shown in Figure 4. The images from the broad scale, sparse grid surveys were clustered based on colour, texture and rugosity queues extracted from the stereo imagery. The cluster parameters learned from the broad scale dives were then used to classify the observations from all of the dense dives from both the Northern and Southern regions of the survey site. It is interesting to note that the habitat distributions are strongly correlated with depth despite the algorithm having no notion of the spatial distribution or depths at which these images were collected. Consistent spatial trends and an examination of the resulting image clusters suggest that these methods are successfully grouping common habitat types based on their image signatures. These groupings can help to guide end users who are interested in performing detailed analysis of a particular subset of the habitats surveyed during a dive.

To allow the survey data to be compared across years, it is also important that the annual surveys can be co-registered. The real time navigation suite, including USBL observations, are sufficient to position the vehicle within 1-2 metre of its intended survey location. When the time between dives is hours, loop closures can be identified in successive dives using standard SLAM techniques [23]. However, over the course of a year or more, substantial changes in the benthos have often occurred and normal image features do not reliably find matches. We are currently working on developing multi-resolution matching techniques that use sonar data to provide gross registration across years from major morphological features [26]. Finer scale registration will need to account for variability in the benthos itself and is an area of active research and will exploit recent developments in the areas of image change detection [27].

When looking at surveys across years, it is typically more straightforward to identify common elements of the 3D meshes as gross features can be used to guide the visual inspection of the meshes. By providing the ability to not only collect images

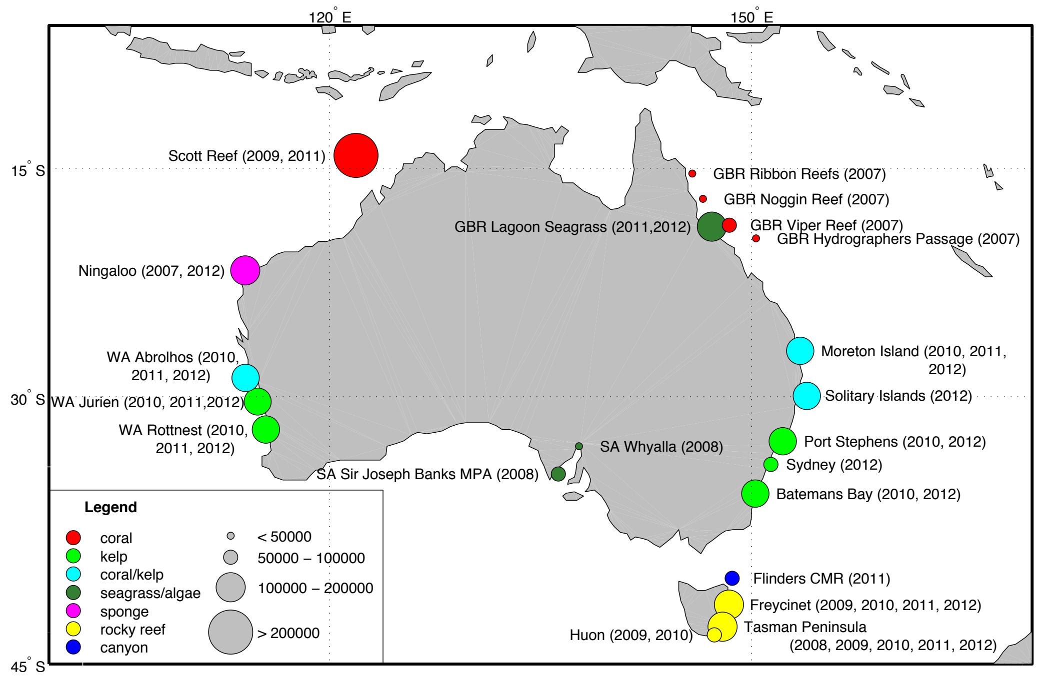


Fig. 3. Survey locations around the Australian coast. The circles are coloured by dominant habitat type and scaled based on the number of images currently available in the IMOS AUV Facility image archive.

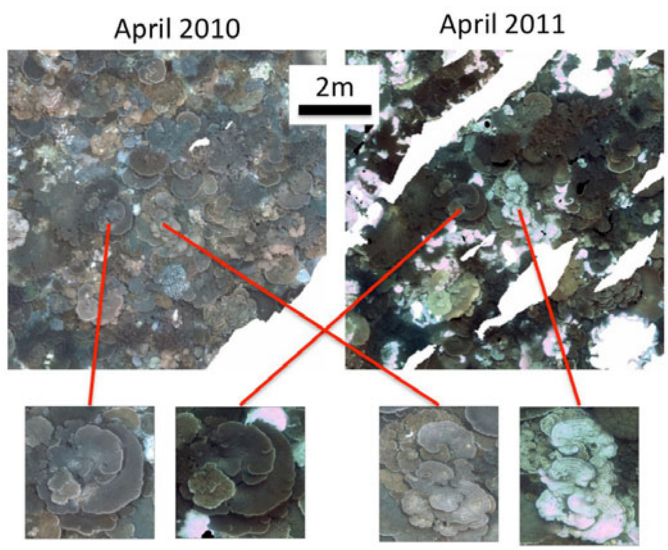


Fig. 6. Change in benthic habitats over a one year period. The red lines highlight common features between years facilitate comparison. Coral reefs off the Abrolhos Islands in WA show significant evidence of bleaching between 2010 (left) and 2011 (right). The white patches in the right hand figure are gaps between the parallel tracklines flown by the vehicle, mostly due to perturbations form strong swell.

over the same area of the seafloor but to quickly identify common features, it is possible to identify changes within the survey site. Figure 6 shows an example of a site that was revisited across a year and illustrate the changes we are able to detect using this approach to benthic observing.

IV. Lessons and New Challenges

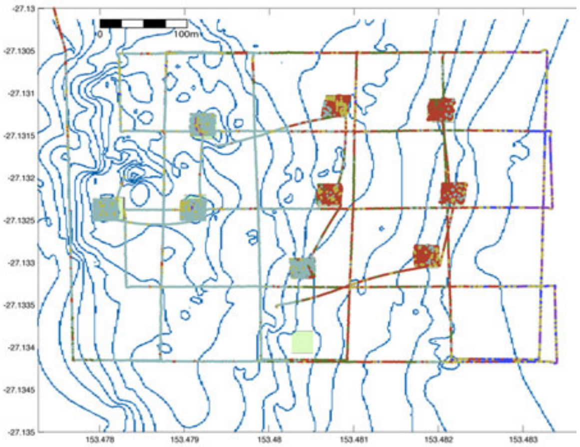
A. Lessons

After several years of operating the AUV-based benthic monitoring program, we have learned a few important lessons:

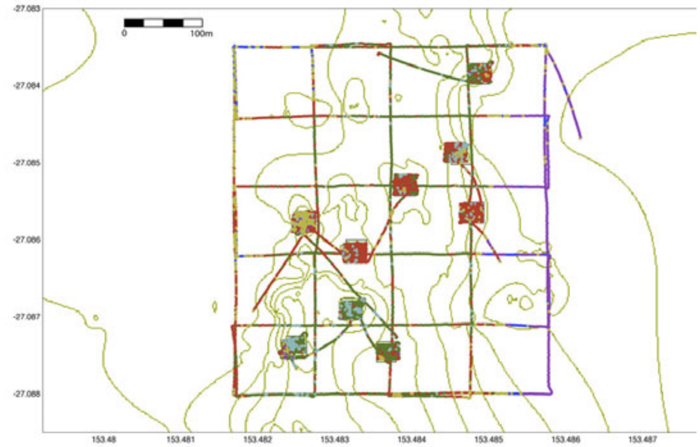
- Georeferencing and repeatability is critical for high value observations. This means proper calibrations are important and need to be performed and verified for every cruise. Given that they can take up valuable ship time, the simpler, faster and more reliable they can be made, the better.
- Data gathering for monitoring can be tedious since the thrill of exploration is, by definition, absent. This suggests that minimising human involvement by increasing autonomy can free us to work on improving capabilities, and can free the ship to perform other tasks while the AUV(s) perform the survey.
- Monitoring is a long term investment. Redundancy in vehicles and subsystems is important, as well as fast quality control of survey data as it is being acquired. Given the long duration of these programs, processing techniques that are robust to changes in the environment and in the equipment are necessary.
- Pixel or patch-level change detection is challenging and requires high accuracy reconstructions of geometry and reflectance.

B. New challenges and research directions

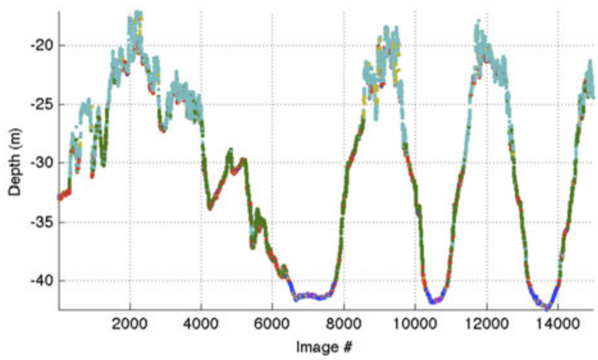
The demands of the benthic monitoring program have opened up several new areas for further research



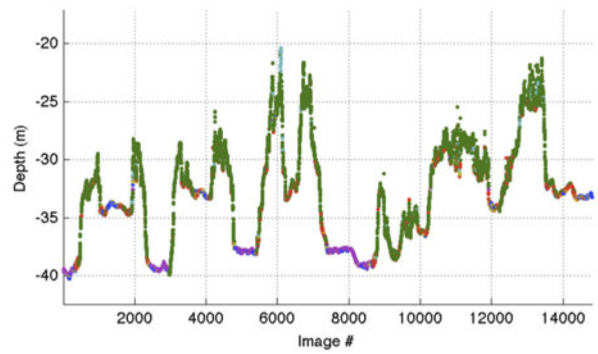
(a) South Henderson clusters



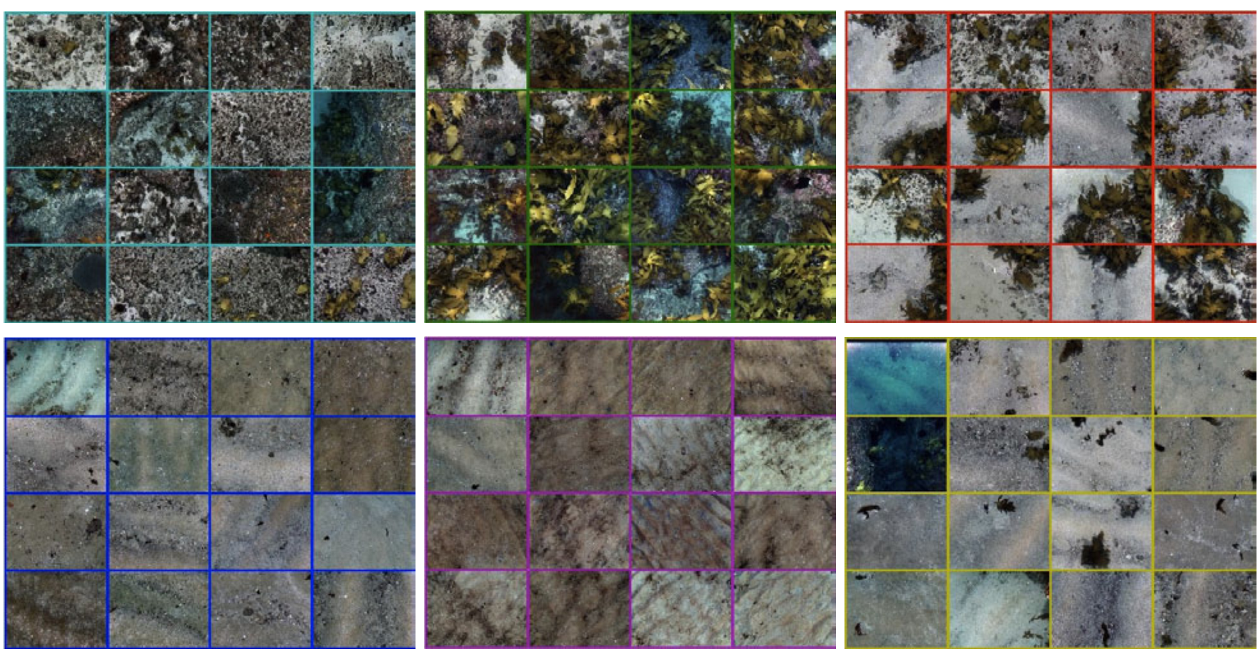
(b) North Henderson clusters



(c) South Henderson depth profile

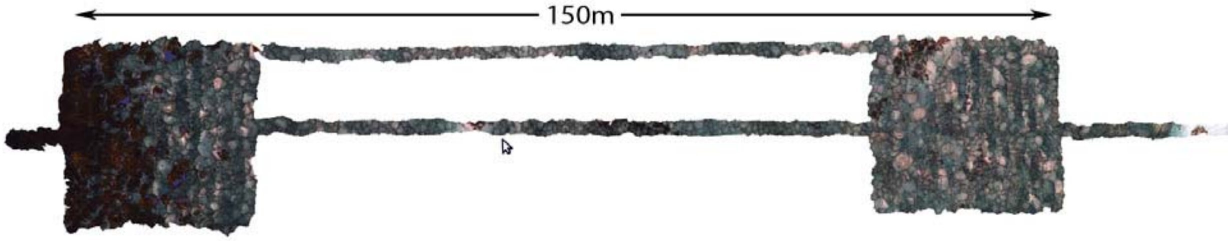


(d) North Henderson depth profile

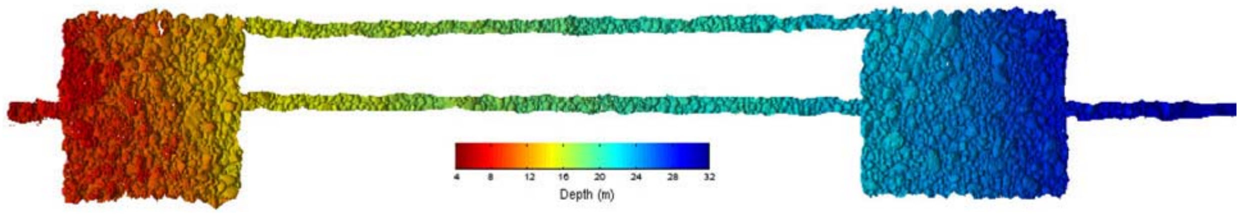


(e) Cluster samples

Fig. 4. Clustering results showing class labels overlaid on the vehicle path and depth profiles from dives completed off of Moreton Island in South East Queensland for (a) South Henderson and (b) North Henderson Reef. Each dot corresponds to the location of an image of the benthos, and its colour to a cluster. Subfigures (c) and (d) show the corresponding depth profiles of the broad grid surveys. Notice the strong correlation between the identified classes and both depth and spatial distribution. These patterns are identified by the clustering algorithm despite it having no notion of the spatial distribution of the images. (e) Samples from the resulting image clusters.



(a) Texture mapped mesh of shallow (left) and deep (right) survey sites at St. Helens Is., Tasmania



(b) Stereo based bathymetric profile of shallow (left) and deep (right) survey sites at St. Helens Is., Tasmania

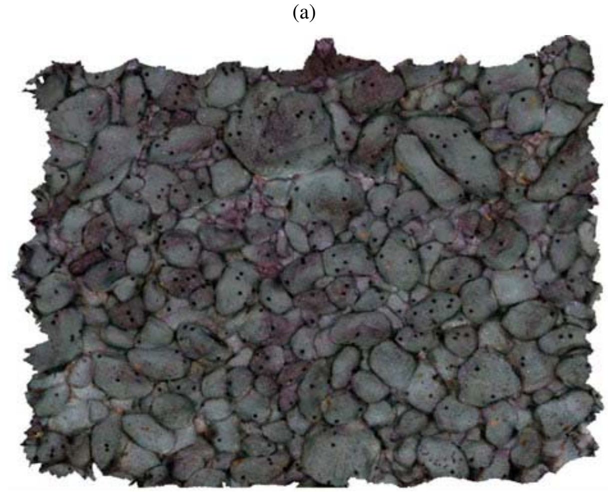
Fig. 5. (a) Dense seafloor bathymetry derived from stereoscopic imagery. In this instance, the AUV was programmed to complete double overlapping grids near shore. (b) The corresponding surface model derived from the stereo bathymetry.

1) Advanced optical imaging: Lighting correction is important when creating composite views of the seafloor given the strong attenuation of light in water. It is even more important when trying to detect and quantify change at the patch level, as well as when attempting to train classifiers of visual underwater imagery. We are investigating two approaches to lighting correction: a simple, data-drive approach that increases consistency in appearance by considering colour histograms as a function of range and arguing that, given sufficient data over similar bottom types, the corrected histograms should be the same independent of range [28]. The second approach attempts to model the image formation process through water. This requires modelling surface patch orientation in addition to reflectance and camera parameters. Figure 7 illustrates some of the artefacts present with naive processing of underwater imagery, such as the striping evident in the texture maps is a result of differences in illumination during reciprocal legs of the survey. The improved lighting corrected version is also shown, which largely eliminates gross lighting problems.

These insights related to high quality, consistent representation of underwater scenes have brought to the forefront research in novel sensing capabilities. Hyperspectral sensing and imaging is likely to play a significant role in properly characterising the reflectance of surfaces as well as increasing our ability to discriminate benthic organisms and substrates. We have currently investigating spectral unmixing of benthic spectrometer data from geological and archeological targets.

Light field cameras may offer a potential solution to many of our imaging problems. By measuring a richer representation of the light permeating a scene, these cameras open a range of applications and technologies in photography, vision and sensing. Also known as plenoptic cameras, these devices enable a range of impressive post-capture processing capabilities, including depth estimation, filtering, and video

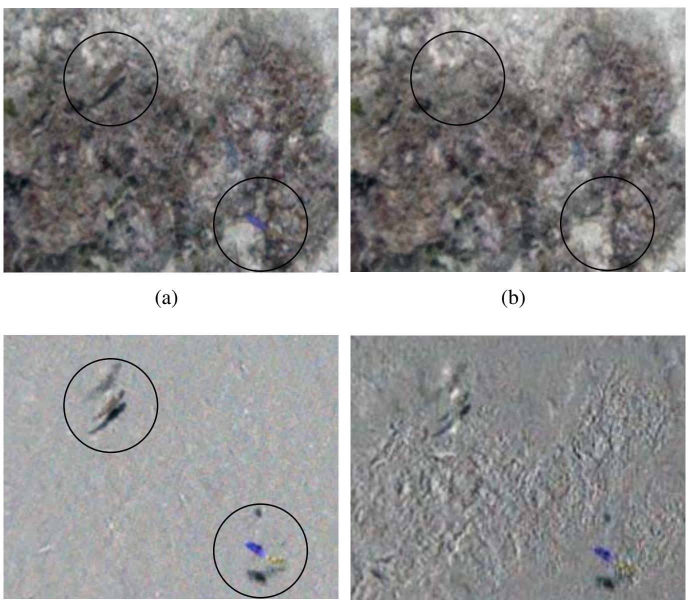
(a)



(b)

Fig. 7. Comparison of range and wavelength dependent correction based on histogram invariance

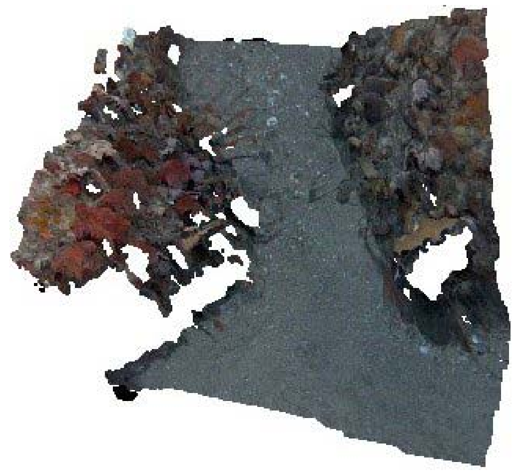
stabilization [29], [30], [31]. The optics of these cameras simultaneously offer a wide aperture and wide depth of field compared to conventional cameras [32], [33]. We have been exploring some of the capabilities of light field cameras in the context of marine robotics. In [34], the light gathering ability of the camera is combined with a linear hyperfan filter to reject noise, resulting in an impressive ability to pull useful imagery out of low light and turbid conditions, without impacting depth of field. In [35], we show how light field geometry can be employed to isolate moving distractors, such as fish, from underwater image sequences. This technique employs a single, linear filter capable of isolating moving and static scene elements, in spite of significant 3D scene structure and camera motion. Isolator distraction is useful in change detection and long-term monitoring programs, in which moving scene elements are easily misinterpreted as changes in the habitat. Fig. 8 depicts typical results. Finally, we generalize 2D optical flow-based visual odometry [36] to allow full six degree-of-freedom odometry by solving a single system of linear equations [37]. This development offers a very simple, constant-runtime solution for visual odometry, in place of conventional iterative and complex methods. This development may enable low-cost monitoring platforms to navigate using small, inexpensive cameras.



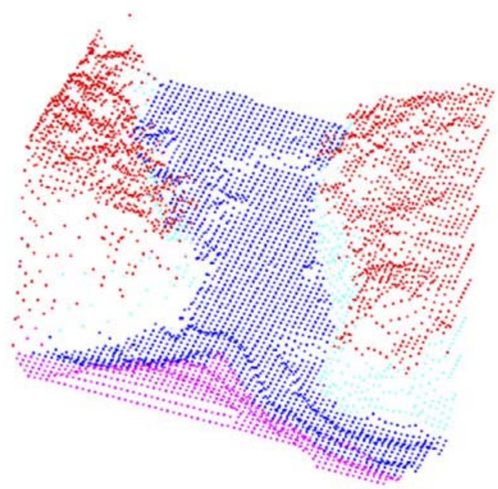
(a) (b) (c) (d)

Fig. 8. A complex underwater scene comprising static and dynamic elements (a) is problematic for long-term monitoring and change detection; light field geometry is exploited to allow a linear filter to isolate static (b) and dynamic (c) scene elements; naive approaches suffer from the apparent motion of the 3D scene (d)

2) Automated benthic image analysis: We have also been exploring methods that use multi-scale measures of rugosity, slope and aspect derived from fine-scale bathymetric reconstructions created using geo-referenced stereo imagery collected by an AUV to classify habitats [38], [39]. Rugosity is derived by considering the area of triangles within a window and their projection onto the plane of best fit, which is found using Principle Component Analysis (PCA). Through the process of obtaining the plane of best fit, slope and aspect are calculated with very little extra effort. Results of this work have been shown to be effective at distinguishing a number of habitats using data gathered by the AUV *Sirius* on surveys that cover several linear kilometres and consist of thousands of images. The ability to distinguish habitat types based on rugosity and slope was demonstrated and validated against a human labelled dataset. Additional research into fast active learning [40] and supervised classification [41] is shedding light on the potential and limitations of existing imaging infrastructure as well as traditional machine learning machinery. Future applications are likely to require scene understanding. Underwater environments are typically unstructured and present substantial challenges to traditional approaches for segmentation and classification of objects. We have started addressing some of these problems in the context of separating the ground from objects in underwater scenes [42] (Figure 9).



(a)



(b)

Fig. 9. Example of terrain segmentation. (a) Textured stereo mesh of a temperate reef. (b) Segmentation of terrain with an FFT-based approach. When compared to a human expert, blue points are correctly segmented as 'ground' and red points correctly as 'not ground', while cyan point are incorrectly considered 'ground' and magenta are incorrectly labelled as 'not ground'.

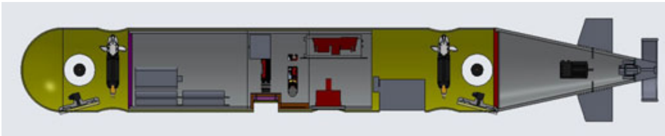


Fig. 10. Concept drawing for next generation of benthic imaging AUV for Australia's IMOS. Safety and ease of launch and recovery is a major concern.

3) Adaptive sampling: Bathymetric maps derived from sonar observations provide relatively low-resolution maps of the seafloor. Broad scale features of the terrain, such as surface roughness, slope, aspect and bottom hardness, provide some notion of the habitat structure. Combining this data with high-resolution observations that characterise the habitat composition provides opportunities for multiscale habitat mapping using a combination of shipborne and AUV observations [43]. Measurements of geomorphic features and backscatter intensity can be related to the fine scale observation of biological assemblages and substrate type to allow inferences to be made concerning the distribution of these habitats over wider regional scales. We have been examining methods suitable for broad scale habitat classification using a combination of high-resolution AUV imagery and shipborne multibeam sonar data [44], [45], [46], [47].

4) SLAM with other modalities: In addition to optical imagery we have developed SLAM approaches that are suitable for acoustic multibeam data [48], [49]. We have also developed SLAM variants for mid-water column (without DVL bottom lock) navigation [50], [51] and continue to have started investigating bundle adjustment improvements to initial SLAM solutions. Future work is likely to focus on robust, multi-modal, real-time implementations of SLAM that are capable of localising based on prior survey data and precisely repeat vehicle tracks.

5) Low cost autonomous monitoring: The ability to scale up a monitoring program that relies on robots to cover much larger areas depends on reducing the amount of human and ship-based supervision. We are seeking to reduce ship use with gateway buoys that will aid in positioning and communications. We also are investigating the use of mutliple-vehicles for geo-referencing without additional infrastructure, and vehicle designs that reduce risks to personnel and themselves during deployments and recovery (see Figure 10).

V. Conclusions and Future Work

The use of AUVs to support benthic observations on this scale is unprecedented and provides an opportunity to better understand the dynamics of these environments. Future work will include continue revisiting all these sites, further refinement of the algorithms used for the automated processing of the data and the development of techniques for quantifying fine-scale change over long temporal scales.

In particular, we hope to increase the robustness and efficiency of these surveys using real-time multi-modal (vision and multibeam) SLAM that exploits prior surveys. We will also examine the effectiveness of detecting changes in benthic habitats directly at the fine scale structural level (i.e. by comparing imagery or 3D reconstructions directly) vs. methods that infer change based on aggregate statistics for a particular dive site (such as percent cover of a particular habitat forming species). We are also developing collaborative annotation and training systems for classification of objects and organisms within images that will allow our end users to more effectively examine trends in the data across the entire dataset, and to do so in a standardized fashion.

We are also developing a new generation of autonomous benthic monitoring vehicles that will reduce the need for expensive ship time and increase safety and reliability of launch and recovery procedures.

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