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Monitoring of Benthic Reference Sites

Using an Autonomous Underwater Vehicle

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We have established an Australia-wide observation program that exhibits recent developments in autonomous underwater vehicle (AUV) systems to deliver precisely navigated time series benthic imagery at selected reference stations on Australia's continental shelf. These observations are designed to help characterize changes in benthic assemblage composition and cover derived from precisely registered maps collected at regular intervals. This information will provide 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 capitalize on the unique capabilities of AUVs into

Digital Object Identifier 10.1109/MRA.2011.2181772
Date of publication: 24 Febraury 2012

Figure 1. The AUV *Sirius* being retrieved aboard the RV Challenger following a mission in south east Tasmania. (Photo courtesy of the Australian Centre for Field Robotics.)

Table 1. 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	200 kg
Maximum speed	1.0 m/s
Batteries	2.28 kWh Li-ion pack
Propulsion	Three 150-W brushless dc thrusters
Navigation	
Attitude and heading	TCM2 compass/tilt sensor
Depth	Digiquartz pressure sensor
Velocity	Teledyne RD Instruments (RDI) 1,200-kHz navigator acoustic doppler current profiler
Altitude	RDI navigator
USBL	TrackLink 1,500 high accuracy (HA)
GPS receiver	U-Blox receiver
Optical imaging	
Camera	Prosilica 12-b 1,360 × 1,024 charge-coupled device stereo
Lighting	Two 4-J strobe
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 1,500 HA-integrated modem
Other sensors	
Conductivity and temperature	Seabird 37-serial interface (SI)
Chlorophyll-A, Turbidity, CDOM	Wetlabs combo fluorometer–turbidity sensor Ecopuck

Australia's integrated marine observation system (IMOS) [1] is providing a critical link between oceanographic and benthic processes. IMOS is a nationally coordinated program designed to establish and maintain the research infrastructure required to support Australia's marine science research. It has, and will maintain, a strategic focus on the impact of major boundary currents on continental shelf environments, ecosystems, and biodiversity. The IMOS AUV facility observation program is designed to generate physical and biological observations of benthic variables that cannot be cost effectively obtained by other means.

Through this program, the activities of the IMOS AUV facility have expanded from a focus on providing exploratory, benthic imaging missions to delivering repeated, sustained observations at a number of reference sites around the country. IMOS scientific end users have defined the location, extent, and frequency of surveying of these sites to be visited by the facility's AUVs. Observations collected by the facility's primary benthic imaging vehicle, the AUV *Sirius* shown in Figure 1, include detailed, high-resolution benthic imaging, multibeam swath bathymetry, conductivity, temperature, depth profiles and fluorometer data measuring chlorophyll-a, colored dissolved organic matter (CDOM), and turbidity at the benthic reference sites. More details about the vehicle specifications can be found in Table 1.

This article outlines the implementation strategy associated with the generation of data streams from the AUV facility and provides an overview of this ambitious initiative. We describe the technical challenges that were addressed to facilitate this work and examine the scientific rationale for such an observation program, showing how robotic systems are well suited to the task of collecting sustained observation data such as this. The requirements for answering questions concerning the impact of changing oceanographic conditions on benthic habitats are discussed. We also present preliminary outcomes from the first four years of our surveys from the sites around Australia. Examples of these outcomes highlight our ability to revisit survey sites across multiple years and illustrate how automated tools can be used to identify patterns within the large volumes of data being collected.

Robotics in Oceanography

Robotic and autonomous systems are playing a crucial role in improving our understanding of the world's oceans. The difficulty of observing the oceans in detail using remote sensing has led oceanographers to employ an increasing number and variety of in situ autonomous sensing systems. These systems trace their history back to a class of instrumented floats that have been used by oceanographers for more than half a century. Early drifters were developed to track ocean currents and did not carry any other science instruments. Modern floats, such as those used as part of the multinational Argo float array [2], take measurements of temperature, salinity, and depth and are deployed for periods of years. More than 3,000 Argo floats are currently adrift in the world's oceans, and their observations are used to validate and drive global-scale ocean circulation models.

In recent years, oceanographers have begun using autonomous underwater gliders to sample particular oceanographic phenomena [3]. These vehicles are equipped with wings that can be used to steer the vehicles horizontally while a buoyancy engine allows them conduct vertical profiles through the water column. There are currently four notable operational underwater gliders that are now routinely used as part of oceanographic studies investigating ocean circulation and mixing. All of these gliders are designed for taking long-term, in situ measurements of conditions within the water column with deployments lasting from one to six months at a time.

Manned submersibles and remotely operated vehicles (ROVs) also trace their history back to the mid-1970s and earlier. They allow people to observe deep ocean environments directly and to interact with this environment through the use of manipulators and direct feedback to operators. Modern ROV systems range from relatively small shoebox-sized vehicles used for inspection and shallow water operations to large workhorse-style ROVs. These are extensively employed in the oil and gas industry and scientifically used for the exploration of geological features, such as hydrothermal vents, in deep sea biology and for archaeological survey [4]–[6].

AUVs have recently begun to play an increasingly important role in modern oceanographic research. Tasks for which AUVs are suited range from deep water exploration and monitoring of oceanographic phenomena to high-resolution optical imaging [7], [8] and multibeam surveying in deepwater applications [9].

Robotic systems feature within a number of infrastructure facilities of the IMOS program. These include Australia's involvement in the international Argo float program, for which IMOS contributes approximately half of Australia's funding for the purchase and deployment of floats and the Australian National Facility for Oceanic Gliders (ANFOG). ANFOG currently operates over a dozen gliders at sites around the country, representing one of the largest fleets of its kind in the world. IMOS has also contributed significantly to the establishment and operation of the IMOS AUV facility. This is arguably the world's first benthic observation program to make extensive use of AUV systems for the purpose of monitoring benthic habitats on the scale described by this work.

Our recent work has demonstrated the ability of benthic imaging AUVs to rapidly and cost effectively deliver high-resolution, accurately georeferenced, and precisely targeted optical and acoustic imagery [10]. High-resolution imaging missions such as that used by this work are typically flown at a fixed altitude above the seafloor. An example of a dense three-dimensional (3-D) texture mapped model of the seafloor generated using the AUV *Sirius* is shown in Figure 2. The vehicle has completed 50 reciprocal track lines covering an area of 50 m $\times$ 75 m over the edge of a deepwater reef in Scott Reef in the north west of Western Australia. The vehicle collected on the order of 10,000 stereo image pairs during the course of this dive. A visual simultaneous localization and mapping (SLAM) algorithm has been used to identify the loop closures shown in Figure 2(a) to refine the vehicle's estimated trajectory [11]. The estimated vehicle trajectory is then used to generate a detailed, 3-D, texture-mapped surface model of the survey site [12].

Sustained Observations at Benthic Reference Sites

The IMOS strategic plan recognizes the importance of effectively linking physical and biological observations [13]. The IMOS AUV facility program provides data streams suitable for observation changes in benthic communities that can be related to climate change, climate variability, and human activities. The design of this observation program particularly focuses on reef habitats motivated by the fact that 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 at regular intervals, are 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. 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 life cycle of the target species.

Survey Design

The general sampling methodology using the AUV is designed to monitor the fundamental reef processes that maintain reef biodiversity and resilience. The processes of interest occur at a number of spatial scales, so a nested hierarchical sampling design has been adopted that allows changes to be observed at these differing scales. AUV dives feature:

1) long transects used to monitor broad community structure and integrity, community boundaries, and transitions
2) broad scale, sparse grids on the order of 500–1,000 m on a side to determine spatial variability in habitat structure
3) small-scale 25 m $\times$ 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

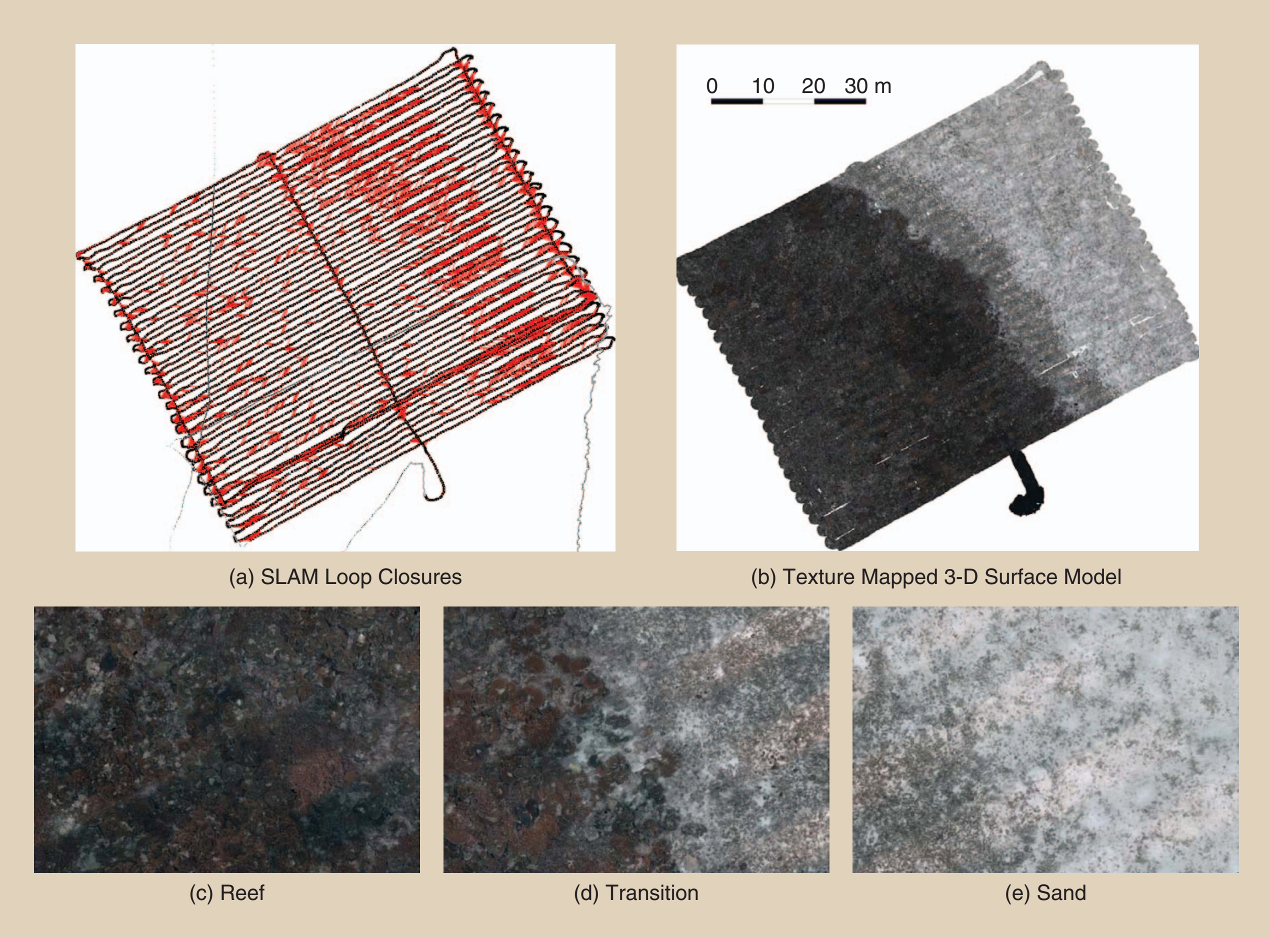

Figure 2. Scott Reef dense grid. (a) SLAM has been used to refine the estimated vehicle trajectory. The red lines connect estimated vehicle locations for which visual loop closures have been applied. (b) The estimated vehicle track is used to generate a detailed 3-D representation of the underlying surface covering approximately 3,750 m^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. (Images courtesy of the Australian Centre for Field Robotics.)

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 and 250 m. The sampling design will be optimized using information from the existing survey data to designate particular sites.

Because the feasible coverage at high resolution of any measurements will be small relative to the areas of interest, we employ standard ecological sampling designs using replicate, stratified transects. For the full-cover dense grid surveys, multiple fully overlapping survey patterns of 25 m $\times$ 25 m are designated within each survey location for repeated surveying using the benthic imaging AUV. These are located in areas characterized by prior multibeam sonar mapping (to facilitate effective depth and habitat sampling design) and/or prior AUV surveys and provide a contrast across a range of reef biotopes (e.g., communities with different dominants, morphology, and physical composition). Each grid requires on the order of 45 min 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.

Wherever possible, sampling sites have been selected in proximity to IMOS oceanographic moorings within each geographic region 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 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. Therefore, the combination of these two survey designs will allow us to address questions at a range of scales relevant to understanding the linkages of Australia's boundary currents with ecological processes. The close linkage and integration of these observations with other IMOS facility observations along the Australian east and west coasts will allow us to understand and observe processes at larger scales.

Navigation

The primary requirement of this observation 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 × 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 are fused.

We operate an ocean-going AUV called *Sirius* capable of undertaking the high-resolution, georeferenced survey work [14]. This platform is a modified version of a midsize robotic vehicle called *SeaBED* built at the Woods Hole Oceanographic Institution [15]. 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 1).

Real-Time Navigation

Our vehicle is equipped with a single-band GPS receiver, a Doppler velocity log (DVL), a depth sensor, a magnetic compass with integrated roll and pitch sensors, and an ultrashort baseline (USBL) acoustic positioning system deployed by the support vessel. The observations of velocity provided by the DVL are combined with the observations of attitude and depth using an extended Kalman filter [14]. The USBL observations, consisting of range and bearing measurements 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 USBL's 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 [16], which can introduce distortions of several degrees into the heading estimate. Even when soft and hard iron calibrations are performed, persistent heading-dependent errors of O (1°) are possible. While adequate to perform linear transects or broader acoustic surveys (particularly, when aided by acoustic positioning from a long baseline or USBL), the magnitude of these errors makes an intended dense *mow the lawn* pattern with reciprocal, closely spaced, parallel track lines that are difficult for the vehicle to complete. We have recently shown that it is possible to derive a heading-dependent correction to the magnetic compass using visual data that can enable a compass-equipped AUV to perform dense visual coverage of a seafloor patch of approximately 50 m × 75 m with 50 parallel track lines [17]. This has resulted in a navigation suite that is capable of meeting the requirements for repeated surveying of the permanent reference sites.

Simultaneous Localization and Mapping

To generate accurate models of the seafloor, it is important that the estimated vehicle trajectory is self-consistent with respect to the data being collected during each survey. We employ visual SLAM to optimally fuse uncertain navigation estimates and visual observations [11]. This allows us to further refine the estimated vehicle trajectory using the environmental data, including high-resolution imagery and multibeam sonar, collected during the survey. Cameras are capable of high-resolution observations so that if the same scene is imaged from different positions, it is possible to determine the relative poses of the cameras using observations of features in the scene. These constraints are fused into the vehicle's navigation solution to further refine the vehicle's estimated trajectory. Examples of loop closures identified in a dense survey are shown in Figure 2(a).

To allow the survey data to be compared across years, it is important that the annual surveys are coregistered. The real-time navigation suite, including USBL observations, is sufficient to position the vehicle within a meter of its intended survey location, particularly in shallow water. We have shown how loop closures can be identified in successive dives using standard SLAM techniques when the time span between dives is short [10]. However, over the course of a year or more, substantial changes in the benthos have often occurred and normal image features used by our SLAM system do not reliably find matches. We are currently working on developing multiresolution matching techniques that use sonar data to provide gross registration across years from major morphological features. Finer-scale registration will need to account for variability in the benthos itself and is an area of active research that will exploit recent developments in the areas of image change detection.

Delivering Data Products

We have demonstrated the ability of these AUV systems to collect the type of data required to support the observation program outlined herein. However, there is also a requirement to bridge the gap between the in situ observations provided by the AUV and the information required to answer specific scientific questions concerning changes in marine habitats. The sheer 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 and associated data products. The data are currently available online through the IMOS electronic marine infrastructure initiative 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 training of machine learning algorithms.

Georeferenced Imagery

One of the primary data streams being collected by the vehicle are the high-resolution images of the seafloor. It is important that these images are tagged with sufficient information to allow our end users to georeference their location and conduct principled scientific analysis of their content. Georeferencing of the images allows the observations to be related to other information being collected by the vehicle and ship-borne systems. Each image is delivered as a geotiff that is tagged with its geographic coordinates. This allows the images to be loaded into standard geographic information systems to be integrated with other data types. We also provide additional information relevant to the interpretation of the imagery including depth, altitude, vehicle pose, and oceanographic variables associated with each image.

Seafloor 3-D Reconstruction and Visualization

Although SLAM recovers consistent estimates of the vehicle trajectory, the estimated vehicle poses themselves do not provide a representation of the environment suitable for human interpretation. A typical dive will yield several thousand georeferenced overlapping stereo pairs. While useful in themselves, single images make it difficult to appreciate spatial features and patterns at larger scales. We have developed a suite of tools to combine the SLAM trajectory estimates with the stereo image pairs to generate 3-D meshes and place them in a common reference frame [12]. These meshes are generated once the vehicle is recovered and take 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 suitable for the investigation. In contrast to more conventional photomosaicking approaches [18], [19], the full 3-D 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. This is a useful data exploration tool for the end user to develop an intuition of the scales and distributions of spatial patterns within the seafloor habitats.

Examples of the detail achieved in the meshes derived from the data collected as part of urchin barrens surveys in Tasmania are shown in Figure 3 [10]. The top subfigure shows a segment of the dense reconstruction texture mapped using the color imagery. The striping evident in the texture maps is a result of differences in illumination during reciprocal legs of the survey. Also shown are the stereo-derived bathymetric surface model onto which the texture map is projected and the detailed views of a segment of the mesh. Both the boulders in the field and patches of kelp are evident in the resulting surface.

Sample reconstructions produced using data collected during recently completed surveys in Western Australia are shown in Figure 4. While it is possible to examine the individual images that were used to generate these 3-D surface models, the spatial structure of each habitat is more evident in the composite mesh. It is also more straightforward to identify common elements of these meshes when examining the surveys across years as gross features can be used to guide the visual inspection of the meshes. By providing the ability to not only collect images over the same area of the seafloor but to quickly identify common features, it is possible to identify changes within the survey site. Figure 5 shows two examples of sites that were revisited across a year and illustrate the changes we were able to detect using this approach to benthic observation.

Image-Based Habitat Classification

While the visualization of detailed 3-D reconstructions improves our ability to understand the spatial layout of seafloor features, further analysis and interpretation of the data gathered during a dive 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 [20]. 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 and focus attention on features of interest. 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 [21], [22].

We are also investigating techniques suitable for classifying habitats when little or no a priori training information is available [22]. We have developed methods based on the variational Dirichlet process (VDP) that allows very large volumes of image data to be clustered in a fully automated manner. We have explored suitable features for such clustering, including color, texture, multiscale measures of rugosity, slope, and aspect (or orientation) derived from fine-scale bathymetric reconstructions created using georeferenced stereo imagery collected by an AUV [23]. An example of the application of these techniques to data collected in South East Queensland is shown in Figure 6. The images from the broad-scale, sparse grid surveys were clustered based on color, texture, and rugosity queues extracted from the stereo imagery. The VDP parameters learned from the broad-scale dives were then used to classify the observations from all of the dense dives from the northern and southern regions of the survey site. These results have been plotted over the vehicle track and have been combined with a geotiff of the depth contour in the area in Figure 6. It is interesting to note that the habitat distributions are strongly correlated with depth despite the

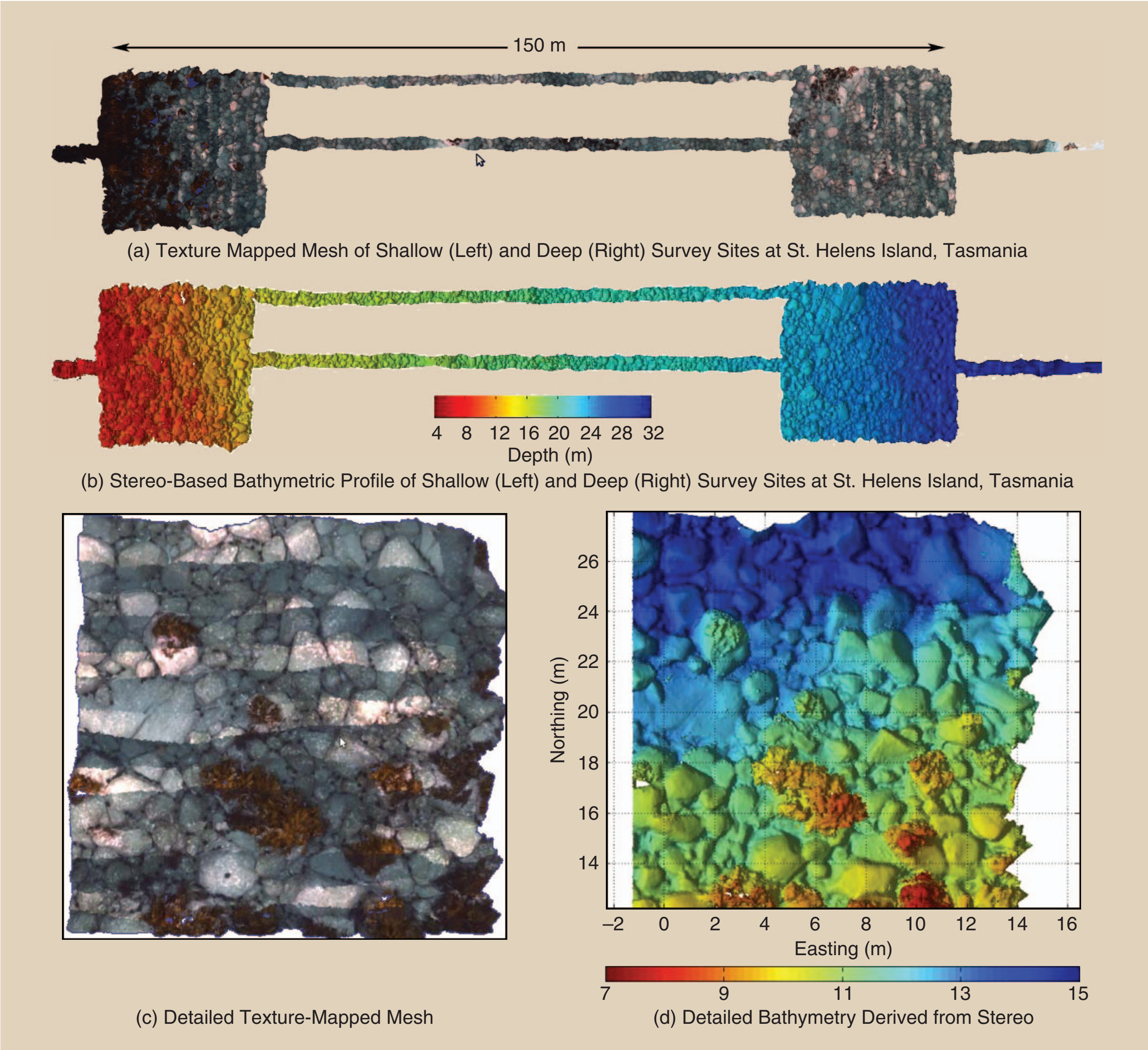

Figure 3. (a) A dense seafloor bathymetry derived from stereoscopic imagery. In this instance, the AUV was programmed to complete double overlapping grids near shore. (b) The corresponding surface model derived from the stereo bathymetry. (c) Details of 3-D reconstruction of the boulders overlaid with the texture-mapped imagery. (d) When the texture mapping is removed, the structure of the scene becomes apparent. The stereo bathymetry allows the large boulders and the remnant kelp patches covering the survey site to be seen in fine detail. (Images courtesy of the Australian Centre for Field Robotics.)

VDP 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.

Results to Date

The IMOS AUV facility program has been running since 2007. Over the course of four years, we have conducted hundreds of dives at sites located around Australia. Figure 7 shows a summary of the dive locations visited during this period. As outlined above, the focus of the sustained observation 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 color coded by dominant habitat and sized proportional to the number of images currently available in the IMOS AUV facility image archive. Table 2 shows details of the locations, number of images, and minimum and maximum depths imaged at each site.

The first deployments undertaken as part of the establishment of the IMOS AUV facility benthic reference

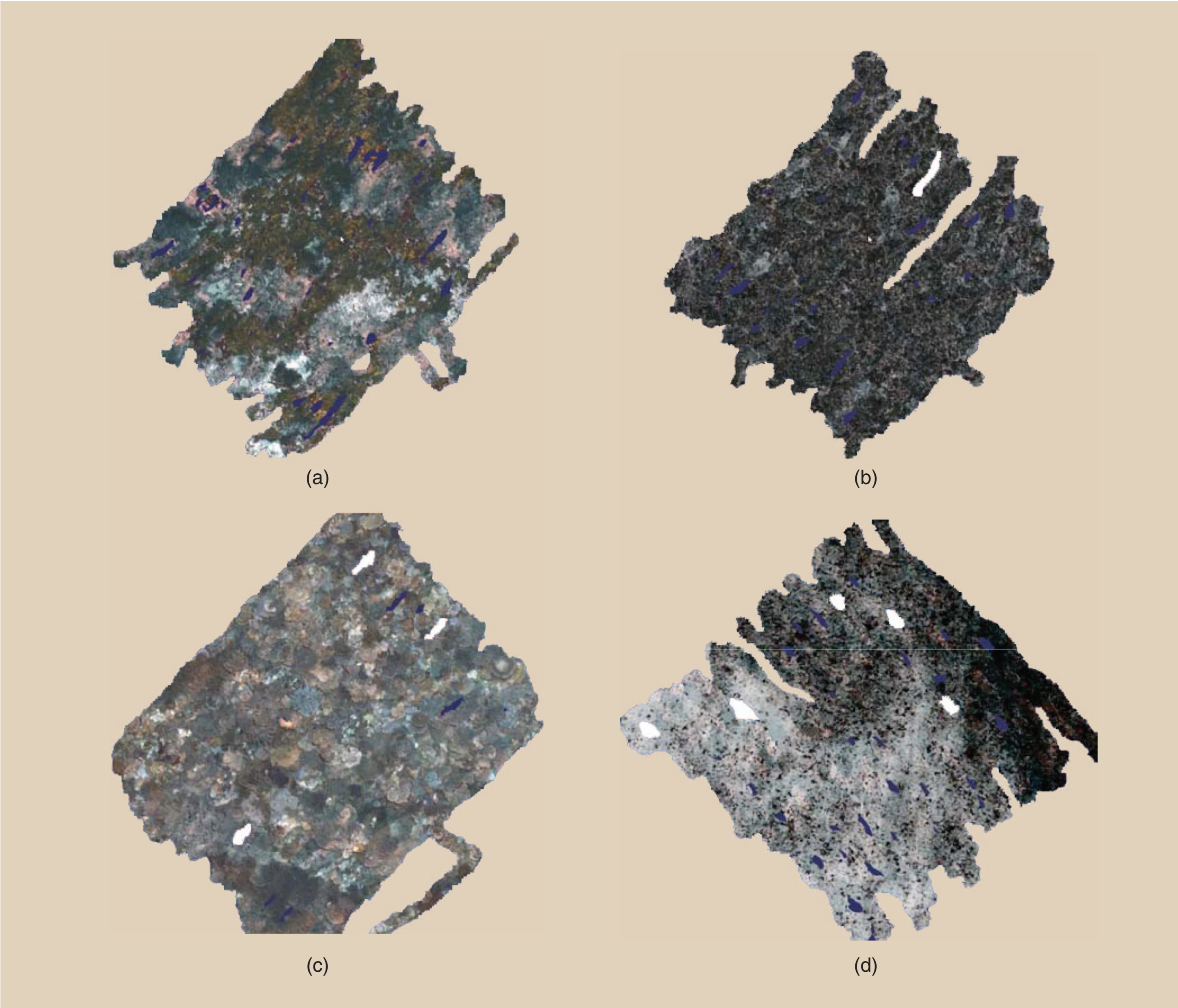

Figure 4. Representative 3-D texture-mapped surface models of individual grid surveys covering an area of approximately 25 m × 25 m from dives at sites along the temperate West Australian coast. The gaps in the models are a result of areas of the survey where the reciprocal track lines did not overlap. Despite these holes, these models can be readily compared to assess the dominant habitats within each survey location. (a) Jurien Bay 15 m—kelp-dominated rocky reef, (b) Jurien Bay 48 m, (c) Abrolhos 15 m—coral reef, and (d) Abrolhos 40 m. (Images courtesy of the Australian Centre for Field Robotics.)

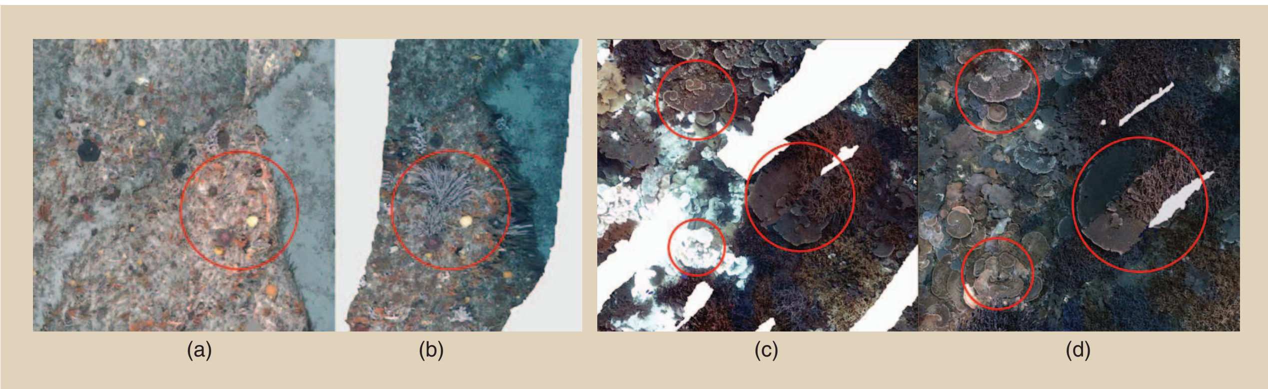

Figure 5. Changes in benthic habitats over a one-year time frame. The red circles highlight common features between the models to facilitate comparison. The site off the Freycinet Peninsula in Tasmania was surveyed in (a) 2010 and (b) 2009. Significant changes in some organisms are evident in the texture-mapped surface models. (b) Coral reefs off the Abrolhos Islands in Western Australia show significant evidence of bleaching between (c) 2011 and (d) 2010. The large, solid white patch in the left-hand figure is a gap between the parallel track lines flown by the vehicle. (Images courtesy of the Australian Centre for Field Robotics.)

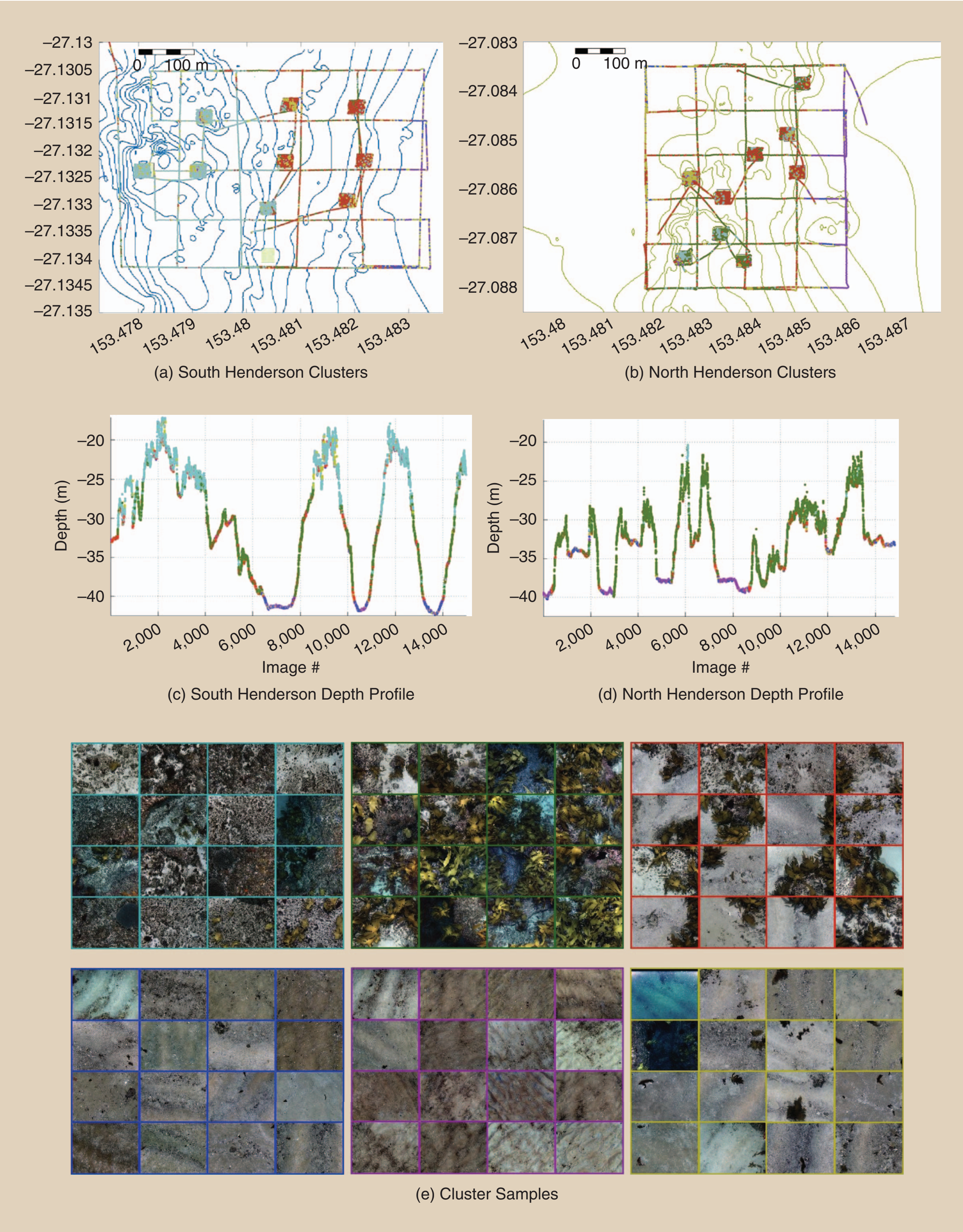

Figure 6. VDP clustering results showing class labels overlaid on the vehicle path and depth profiles from dives completed off of Moreton Island in Southeast Queensland for (a) South Henderson and (b) North Henderson Reef. Each dot corresponds to the location of an image of the benthos and its color 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 distributions. These patterns are identified by the VDP clustering algorithm despite having no notion about the spatial distribution of the images. (e) Samples from the resulting image clusters. (Images courtesy of the Australian Centre for Field Robotics.)

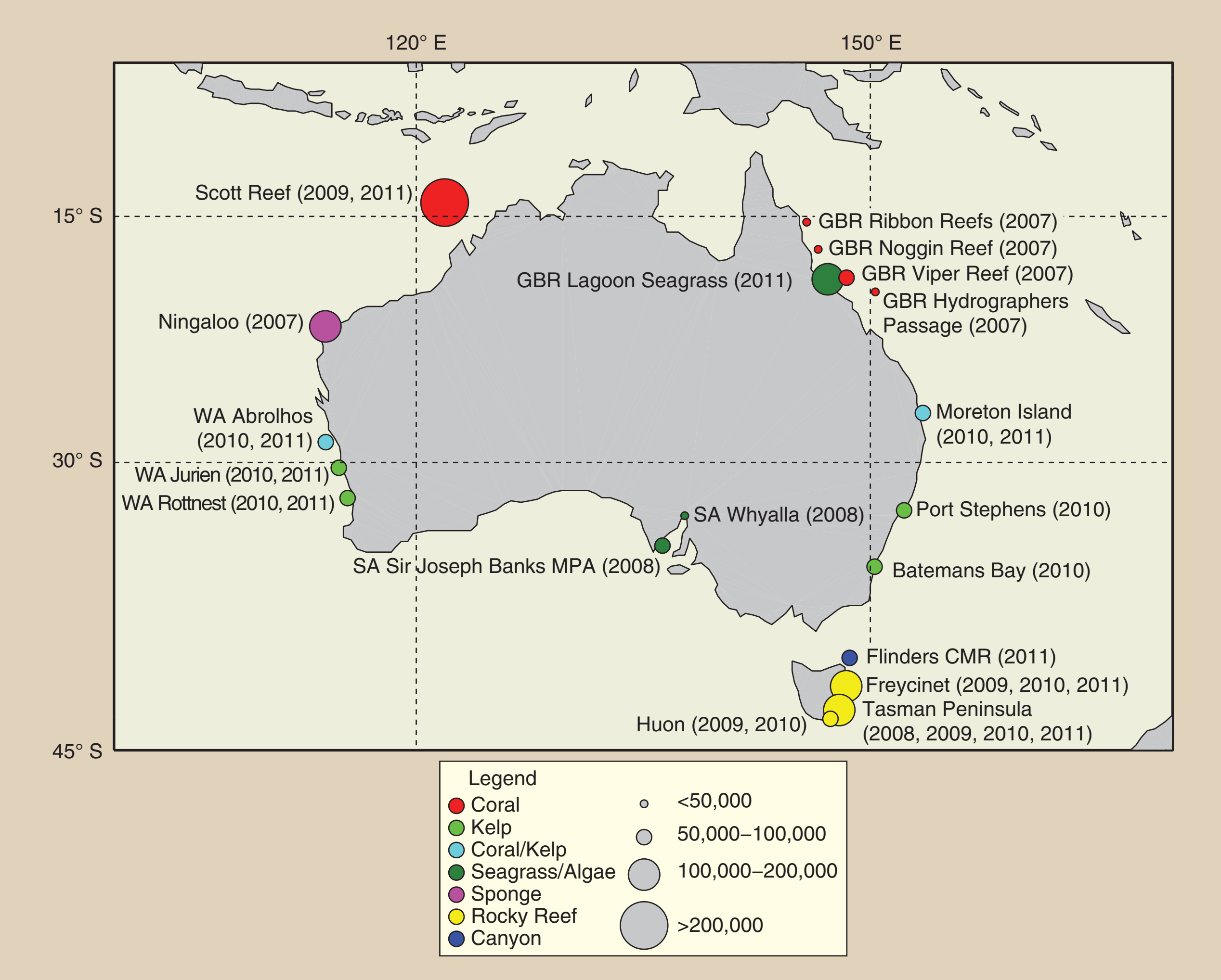

Figure 7. Survey locations around the Australian coast. The circles are colored by dominant habitat type and scaled based on the number of images currently available in the IMOS AUV facility image archive. (Image courtesy of the Australian Centre for Field Robotics.)

site program were completed off the coast of Western Australia during April 2010. We have established the reference sites using the survey design described in this article in Tasmania, Western Australia, Queensland, and New South Wales, focusing on coastal habitats predominantly in 20–60 m of water depth. Repeat grids have been completed in Tasmania, Western Australia, and Queensland.

Conclusions and Future Work

This article has described a recent initiative to establish a nationally focused observation program to provide precisely navigated time series benthic imagery using AUVs at selected reference stations on Australia's shelf. The objective of this work is to link observations of oceanographic features provided through IMOS facilities to changes in the underlying benthic habitats at sites around Australia. Linking biological changes to physical drivers will be an important aspect of understanding how these environments are changing in response to variability in climate and anthropogenic pressure. 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 revisiting all of the sites outlined in this article, 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. We will draw on recent advances in image-based object recognition, fine-scale substrate and habitat modeling, quantitative ecology, geospatial data analysis, physical surrogates, and oceanographic models to develop techniques that allow observations to be related across space and time. In particular, we hope to increase the robustness and efficiency of these surveys using real-time multimodal (vision and multibeam) SLAM that exploits the prior surveys conducted at each site. We will also examine the effectiveness of detecting changes in benthic habitats at the fine-scale structural level (i.e., by comparing imagery or surface models

Table 2. IMOS AUV facility dive summary.

	IMOS Ref. Site	Dominant Habitat	Year(s)	Latitude	Longitude	No. Img. (k)	Depth Minimum	Maximum
Tasmania								
Flinders CMR	Yes	Deepwater Canyon	2011	−40.53	148.6402	80	11	225
Freycinet MPA	Yes	Rocky Reef	2009, 2010	−41.933	148.4203	162	12	118
Tasman Peninsula	Yes	Kelp, Rocky Reef, Sponges	2008–2011	−43.084	147.9691	112	20	94
Huon MPA	Yes	Rocky Reef, Sponges	2010	−43.515	147.3863	80	1,1	84
NSW								
Port Stephens	Yes	Kelp	2010	−32.698	152.2555	53	8	51
Bateman's Bay	Yes	Kelp	2010	−35.785	150.2888	89	15	50
Queensland								
Relict Reefs	No	Deepwater Reef	2007	−17.78	147.7869	115	16	147
Seagrass GBR Lagoon	Yes	Seagrass	2011	−18.99	147.206	132	35	46
Moreton Island	Yes	Kelp/Coral Reef	2010, 2011	−27.11	153.4819	100	15	40
WA								
Rottnest Island	Yes	Kelp	2010, 2011	−32.02	115.4402	84	11	42
Jurien Bay	Yes	Kelp	2010, 2011	−30.299	114.8543	94	12	84
Abrolhos Islands	Yes	Kelp/Coral Reef	2010, 2011	−28.811	113.9932	71	9	46
Ningaloo	Yes	Sponges	2007	−21.908	113.967	111	10	247
Scott Reef	Yes	Coral Reef	2009, 2011	−14.118	121.8672	520	10	103
SA								
Sir Joseph Banks	No	Algae/Kelp	2008	−34.65	136.2712	55	3	28
Whyalla	No	Algae	2008	−32.995	137.7418	34	2	8

directly) versus methods that infer change based on aggregate statistics for a particular dive site (such as percent cover of a particular habitat forming species). There is also a requirement to develop 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 data set.

Acknowledgments

This work is supported by the Australian Research Council (ARC) Centre of Excellence program, funded by the ARC and the New South Wales State Government, and IMOS through the Department of Innovation, Industry, Science and Research National Collaborative Research Infrastructure Scheme and Education Investment Fund. The authors thank the captains and crews of all of the vessels used to facilitate the deployment and recovery of the vehicle. They also acknowledge the help of all those who have contributed to the development and operation of the AUV, including Christian Lees, Andrew Durrant, Ritesh Lal, Paul Rigby, Jeremy Randle, Bruce Crundwell, and the late Duncan Mercer, George Powell, and Alan Trinder.

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