AUV-assisted Surveying of Relic Reef Sites

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Abstract—This paper describes the Autonomous Underwater Vehicle (AUV) Sirius and presents its participation in a scientific expedition to survey drowned reefs along the shelf edge of the Great Barrier Reef (GBR) in Queensland, Australia. The primary function of the AUV was to provide geo-referenced, high-resolution optical imagery to facilitate validation of seabed habitat characterisation based on acoustic data. We describe the AUV capabilities and its operation in the context of the cruise objectives to document these relic reef sites. The data processing pipeline involved in generating SLAM-based navigation and large scale 3D visualizations of survey data is briefly described. We also present preliminary results illustrating the type of data products possible with our system and how these complement data gathered by other ship-borne instruments on the cruise.

I. INTRODUCTION

Submerged fossil coral reefs are common along the shelf edge of the Great Barrier Reef (GBR) but no systematic high-resolution mapping, imaging or sampling of these sea floor features has ever been attempted. Preliminary data indicates these features are fossil reef systems that grew and drowned episodically in response to abrupt sea level and climate changes, most recently during the last 20 kyr (last ice age). These reefs likely record a unique archive of abrupt climate changes and how the GBR responded to periods of environmental stress. As such, these reefs have direct implications for environmental managers tasked with predicting how the GBR might respond to future climate change scenarios, as well as providing crucial baseline data about the modern substrates, habitats and biological communities that characterise these poorly studied shelf environments.

In Sep-Oct 2007 a research cruise set off to investigate the shelf edge, upper slope and submarine canyons along the GBR margin [Webster et al., 2008a]. Broad scale, ship-based multibeam swath and sub-bottom sonar mapping were complimented with smaller scale, high resolution Autonomous Underwater Vehicle (AUV) seabed imaging, as well as traditional rock dredging and sediment sampling. The primary role of the AUV Sirius was to collect geo-referenced optical imagery to provide validation of interpretations made from large-scale sonar multibeam and sub bottom profiling surveys. This paper presents preliminary results from the AUV in the context of the cruise objectives.

A. GBR Fossil Reefs

Drowned reefs on the edge of continental shelves or drop off zones of oceanic islands have been recognized in many different areas of the world. Investigations off Barbados [Fairbanks, 1989], Hawaii [Webster et al., 2004a], Papua New Guinea [Webster et al., 2004b] and more recently Tahiti [Camoin et al., 2005] have confirmed the significance of these reefs as unique archives of abrupt global sea level rise and climate change. Similar structures occur along the GBR, having been observed in the regions of Hydrographers Passage, Ribbon Reef [Davies and Montaggioni, 1985], [Harris and Davies, 1989], [Hopley et al., 1997], [Hopley, 2006], Flora Passage, Bowl Reef, and Viper Reef [Hopley et al., 1997][Beaman et al., 2008].

The succession of barrier reefs occupy the outer shelf between -40 and -130 m and have the potential to provide unique and critical information on the course of sea level and climatic history off eastern Australia. It is thought that they also play an equally important role as habitats and substrates for present day biological communities. Their location and depth beyond SCUBA has made their study difficult, with previously collected data including intermittent bathymetric profiling, sidescan imaging, single channel seismic profiling and reconnaissance sampling [Harris and Davies, 1989], [Hopley et al., 1997].

The research cruise described in this paper proposed to improve our understanding of the relationship between the structure and composition of drowned and modern reefs and to investigate any variations within the succession of drowned shelf edge reefs. Key objectives of the expedition included:

- defining the age of these reefs
- establishing their spatial distribution, morphology, and composition
- determining their relationships with past sea levels and the cause of their demise
- assessing their importance as modern substrates and biological habitats
- stimulating further study by proposing sites for the Integrated Ocean Drilling Program (IODP)

B. AUVs in Oceanography

AUVs are becoming significant contributors to modern oceanography, increasingly playing a role as a complement to traditional survey methods. A nested survey design strategy is observable in most practical uses, where broad-scale sensing helps guide the deployment of the high-resolution imaging AUV which, in turn, informs further sampling. Large, fast survey AUVs can provide high resolution acoustic multibeam
Cruise transect

Drowned reefs

Fig. 1. Documenting drowned reefs on the Great Barrier Reef (a) The ship track taken during the research cruise showing the four survey locations selected [Webster et al., 2008b] (b) early multibeam profiles showing the drowned reefs [Beaman et al., 2008].

and sub-bottom data by operating a few tens of meters off the bottom, even in deep water [Grasmueck et al., 2006] [Marthiniussen et al., 2004]. High resolution optical imaging requires the ability to operate very close to potentially rugged terrain. The Autonomous Benthic Explorer (ABE) has helped increase our understanding of spreading ridges, hydrothermal vents and plume dynamics [Yoerger et al., 2007b] both using acoustics and vision. The Seabed AUV is primarily an optical imaging AUV, used in a diverse range of oceanographic cruises, including coral reef characterization [Singh et al., 2004a]. Recently, the related AUVs Puma and Jaguar searched for hydrothermal vents under the arctic ice [Oceanus, 2008].

The University of Sydney’s Australian Centre for Field Robotics operates an ocean going AUV called Sirius capable of undertaking high resolution, geo-referenced survey work. This platform is a modified version of a mid-size robotic vehicle Seabed built at the Woods Hole Oceanographic Institution [Singh et al., 2004b]. 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 including a high resolution stereo camera pair and strobes, multibeam sonar, a depth sensor, Doppler Velocity Log (DVL) including a compass with integrated roll and pitch sensors, Ultra Short Baseline Acoustic Positioning System (USBL), forward looking obstacle avoidance sonar, a conductivity/temperature sensor and combination fluorometer/scattering sensor to measure chlorophyll-a and turbidity. The on-board computer logs sensor information and runs the vehicle’s low-level control algorithms. Sirius is part of the NCRIS Integrated Marine Observing System (IMOS) AUV Facility, with funding available on a competitive basis to support its deployment as part of marine studies in Australia.

C. Outline

The remainder of this paper is organized as follows. Section II describes the various methods used to characterise the submerged reefs, while Section III provides details of the benthic habitat mapping algorithms used for constructing high resolution models of the seafloor. Section IV shows results of these activities, relating the AUV outcomes to the objectives of the project and showing their relationship to corresponding data collected by ship mounted instruments during the cruise. Finally, Section V provides conclusions and an outline of ongoing and future work.

II. Study Methods

The science party approached the problem of surveying drowned shelf reefs using multiple sensing/sampling modalities suited to the field objectives outlined previously. These objectives formed the criteria by which 21 days of ship time were awarded aboard the R/V Southern Surveyor, Australia’s Marine National Facility operated by CSIRO [CSIRO MNF RV Souther Surveyor, 2008].

A. Ship-based Seafloor Mapping

The first field objective of this cruise was to map four study sites along the Queensland margin (Figure 1) where the approximate location of submerged reefs is known. Detailed multibeam bathymetric and backscatter (sea floor reflectivity) surveys (Simrad EM300) were used to help determine their spatial distribution, depth and morphology. This data will help to establish if the submerged reefs are regionally significant features with consistent depths, as well as their relationship with shelf width, slope angle and finer-scale bottom features. Sub-bottom profiling using the shipboard Topas PS-18 and a sparkler array provided information as to whether shelf edge reefs were built up or the surroundings were eroded away (constructional/erotional) features, and to provide estimates of the thickness and character of sediments between the succession of drowned reefs.

B. AUV Surveys

A second field objective was to conduct seabed optical ground truthing using a high-resolution stereo camera mounted
on an AUV. While a towed camera sled is traditionally used for optical characterization [Barker et al., 1999], an AUV-based approach offers improved image quality, precise positioning and the ability to operate over very rough bottoms. Typically the AUV will operate at slower speeds than a sled so that coverage is reduced, but in the case of optical ground truthing this tends to be compensated by the ability to target specific bottom features.

The AUV, which weighs 200 kg, was programmed to maintain an altitude of 2m above the seabed while travelling at 0.5 m/s (1 knot approx) during surveys. Typical missions lasted from two to four hours with the AUV surveying transects across drowned reef and inter-reef areas to assess the substrate types and character of the modern epibenthic assemblages associated with shelf edge reefs. In addition to 2 Hz stereo imagery and multibeam data, the AUV’s onboard CT and Ecopuck Fluorometer took water column measurements, establishing the present day oceanographic conditions on the shelf edge.

C. Dredging and Grab Sampling

A third field objective was to collect dredged rock samples from the tops of the shelf edge reefs. The detailed bathymetric and video surveys provide targeted ground truthing sites in each study area to obtain rock and sediment samples using rock dredges. These dredges were towed parallel to contours and along features of interest in order to collect samples of similar age and composition from the last phase of reef growth. This method has proved effective in sampling analogous deposits in the southern GBR [Davies et al., 2004], Hawaii [Ludwig et al., 1991] and Tahiti [Camoin et al., 2006]. Post-cruise sample analyses will involve sedimentary facies, radiometric dating, and palaeoclimate investigations to establish the age and composition of the reefs, the timing and rate of drowning and ecosystem response to rapid sea level rise, environmental stress, and changes in sea surface temperatures and ocean chemistry. The data will be integrated with the geophysical data sets to better understand reef growth and demise.

III. AUV-BASED BENTHIC MAPPING

One of the key features of the present cruise was the availability of a high resolution optical and acoustic imaging AUV. This vehicle’s primary role was in validating the seafloor characteristics of significant features observed in the large-scale bathymetric and sub-bottom profiling data. The high spatial resolution and capacity to geo-reference the resulting imagery provides an invaluable mechanism for observing the extent and composition of particular benthic habitats. Unlike dredging, the AUV survey data maintains the spatial relationships of observed seafloor features of interest.

A. Simultaneous Localisation and Mapping

Navigation underwater is challenging because electromagnetic signals attenuate strongly with distance. Ubiquitous absolute position estimates such as those provided by GPS are therefore not readily available. Acoustic positioning based systems [Yoerger et al., 2007a] can provide absolute positioning but typically at lower precision than that provided by the instruments on-board the AUV. Using a naive approach, the mismatch between navigation precision and sensor precision results in ‘blurred’ maps. A more sophisticated approach uses the environment to aid in the navigation process. Simultaneous Localisation and Mapping (SLAM) is the process of concurrently building a feature based map of the environment and using this map to obtain estimates of the location of the vehicle. The SLAM algorithm has seen a considerable amount of interest from the mobile robotics community as a tool to enable fully autonomous navigation [Dissanayake et al., 2001] [Durrant-whyte and Bailey, 2006]. Pioneering work in the deployment of the SLAM algorithm in reef environments has been reported following trials with the Australian Centre for Field Robotics’ Unmanned Underwater Vehicle Oberon and the AUV Sirius operating on the Great Barrier Reef in Northern Australia [Williams and Mahon, 2004][Williams et al., 2006]. This work laid the foundation for 3D reconstructions of these highly unstructured environments. Related work at the Woods Hole Oceanographic Institution has also examined the application of SLAM [Eustice et al., 2006][Roman and Singh, 2007] and Structure from Motion (SFM) [Pizarro et al., 2003] methods to data collected by ROVs and AUVs.

Our current work has concentrated on efficient, stereo based Simultaneous Localisation and Mapping and dense scene reconstruction suitable for creating detailed maps of seafloor survey sites. Methods for stereo-vision motion estimation and their application to SLAM in underwater environments have been proposed by Mahon [Mahon et al., 2008], [Mahon, 2008]. These novel approaches, based on the Visual Augmented Navigation techniques proposed by Eustice [Eustice et al., 2006], enable the complexity of recovering the state estimate and covariance matrix in a Visually Augmented Navigation framework to be managed. This has allowed these algorithms to run on significantly larger mapping problems than was previously feasible. These techniques have been used to facilitate the construction of seafloor maps using the data collected during the cruise reported in this paper.

A comparison of the estimated trajectories produced by dead-reckoning and SLAM is shown in Figure 2. The filters integrate the DVL velocity observations together with measures of depth, heading, roll and pitch. The dead-reckoning filter is not given access to imagery and is therefore not able to correct for drift which accumulates in the vehicle navigation solution. In contrast, loop closures identified in the imagery allow for this drift to be identified and for the estimated vehicle path to be corrected. This survey of a 100m x 100m area in 60m of water included over 6500 image pairs. A total of over 3000 loop-closure observations were applied to the SLAM filter, shown by the red lines joining observed poses. Applying the loop-closure observations results in a trajectory estimate that suggests the vehicle drifted approximately 10 meters south-west of the desired survey area.
Fig. 2. (a) Comparison of dead-reckoning and SLAM vehicle trajectory estimates for one of the grid surveys. The SLAM trajectory is shown in black, while the dead-reckoning estimates are shown in blue. The SLAM estimates suggest the vehicle has drifted approximately 10 meters north of the desired survey area over the course of approximately one and a half hours of surveying. (b) Three dimensional reconstruction of the drowned reef during a GBR survey. The site was in approximately 60m of water and was selected based on multibeam bathymetric models collected from the surface. Darker areas occur when the vehicle maneuvers over a reef bommy, some up to 6m in height. Detailed views of small reef bommies are shown in (c) and (d).

B. Seafloor 3D Reconstructions

Although the techniques used for SLAM allow consistent estimates of the vehicle trajectory to be recovered, the estimated vehicle poses themselves do not provide a representation of the environment suitable for habitat assessment purposes. This requires the ability to identify patterns in the benthic coverage by visualising how the structure of the environment relates to the benthos. A suite of tools has been developed for creating and visualising accurate models of the seafloor, thereby providing marine scientists with a method for assessing the spatial distribution of various organisms of interest.

A typical dive will yield several thousand geo-referenced overlapping stereo pairs. While useful in itself, single images make it difficult to appreciate spatial features and patterns at larger scales. It is possible to combine the SLAM trajectory estimates with the stereo image pairs to generate 3D meshes and place them in a common reference frame (see Figure 2).
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. Spatial relationships within the data are preserved and scientists 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 tool for the end user to develop an intuition of the scales and distributions of spatial patterns, even before any automated interpretation is attempted.

To generate a 3D reconstruction, a coarse set of 3D points is first triangulated from visual features [Harris and Stephens, 1988] consistent with epipolar geometry. A mesh is generated from the point cloud using a delauney triangulation with outlier rejection based on triangle edge length. The mesh is then transformed from the local camera reference frame to a common, global reference frame using the SLAM poses generated previously.

Once all meshes have been placed into a global reference frame they can be integrated to form a single watertight mesh. We use a voxel-based representation to discretize the mesh and determine the overlap and intersection of different surfaces [Curless and Levoy, 1996]. Given that the uncertainties in feature and pose locations are available based on the stereo and SLAM solutions, we use these uncertainties to provide the weightings with which to combine surface. This approach utilizes the probabilistic uncertainty in the estimate of vertex locations in weighting their merging.

In contrast to 2D reconstruction afforded by simple mosaicing [Pizarro and Singh, 2003], a parametric mapping of the imagery onto the meshes is used to effectively mosaic the images while properly accounting for the structure of terrain. Doing so decreases the distortion in the resulting texture mapped surfaces. The process determines the projective camera viewpoints that have imaged a particular triangle on the mesh and then assign two varying parameters ($u, v$) to each vertex that are mappings into the corresponding image. If multiple camera viewpoints see the same triangle (which is true of almost all triangles in the mesh) the choice of what texture to display on each triangle can be made in several ways. Trivially the closest or the most orthogonal view can be chosen however this creates strong seams in areas of misregistration. To avoid this we implement a novel live blending scheme using pixel shaders in a GPU. The technique is based upon the band limited blending proposed by Burt [Burt and Adelson, 1983].

LOD in 3D meshes [Clark, 1976] allows viewing extremely large models with limited computational bandwidth by reducing the complexity of a 3D scene in proportion to the viewing distance or relative size in screen space. Some AUV missions have upwards of 10,000 pairs of images which expand to hundreds of millions of vertices when processed to generate the stereo meshes. It is simply intractable to load all of this data directly into memory. To view this data we use a discrete paged level of detail scheme, where several discrete simplifications of geometry and texture data are generated and stored on disk. These are paged in and out of memory based upon the viewing distance to the object.

IV. RESULTS

Four sites along the extent of the Great Barrier Reef, as shown in Figure 1, were selected for detailed bathymetric mapping, AUV seafloor imaging, dredging and grab sampling to determine substrate composition during the R/V Southern Surveyor cruise SS07/2007 [Webster et al., 2008b]. Over the course of the three week voyage the AUV was deployed at a dozen locations undertaking both overlapping grid surveys of particular features as well as cross shelf transects to document the variability in benthic habitats at varying depths.

The vehicle’s role was in validating the seafloor characteristics of significant features observed in the large-scale bathymetric and sub-bottom profiling data. The high spatial resolution and capacity to geo-reference the resulting imagery
provides an invaluable mechanism for observing the extent and composition of particular benthic habitats. Unlike dredging, the AUV survey data maintains the spatial relationships of observed seafloor features of interest. Furthermore, sampling using dredging may introduce bias towards things that actually break off when a tow sled is dragged along the sea floor. The AUV imagery on the other hand provides an image of everything within the field of view of its camera that can then be analyzed to describe the composition of taxa within the survey area.

The AUV imagery shows a variety of of benthic communities and substrates that include red algae-encrusted fossil rock, thriving hard and soft coral, gorgonians (sea whip or fan) and sponge communities and *Halimeda* (green algae). Post-cruise analysis of the AUV and multibeam data is currently being used to derive quantitative information about the distribution of benthic communities and habitats.

Figure 3 shows an example of data collected during one of the deployments. The AUV was deployed following high resolution bathymetric surveying to examine ancient foreshore structures. The vehicle was initially deployed over relic reefs in 50m of water. It then travelled to the North-East over a succession of deep, relict reefs, descending to a depth of 150m. Sub-bottom profiling and dredging were also undertaken in the same area. Once the vehicle was recovered, it was possible to examine the bottom composition correlated with the depths. As expected from the sub-bottom profiling data, an area between 100-135m of water depth corresponding to a relict shoreline feature was characterised by hard substrate supporting modern deep water benthic assemblages.

V. CONCLUSIONS

Properly instrumented AUVs can fill an important niche as part of multi-disciplinary research cruises such as the one reported on here. They present a novel tool for collecting rich, high resolution, geo-referenced data sets that are complimentary to more traditional ship borne measurements. In this case the imagery produced by the AUV has proven invaluable in validating the sonar data interpretation and in providing very high resolution, fine scale interpretation of habitat characteristics. Just as important as a reliable and capable platform is the ability to quickly produce consistent and accurate representations of the survey data. This allows for feedback into cruise planning. The value of the AUV as a tool to support interpretations from acoustic data was illustrated very clearly on this cruise. On the basis of the study reported in this paper, the International Ocean Drilling Program (IODP) has scheduled drilling to take place at sites surveyed during this cruise on the strength of the data collected (including the AUV data).

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