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Repeated AUV Surveying of Urchin Barrens in North Eastern Tasmania

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Abstract— **This paper describes an approach to achieving high resolution, repeated benthic surveying using an Autonomous Underwater Vehicle (AUV). A stereo based Simultaneous Localisation and Mapping (SLAM) technique is used to estimate the trajectory of the vehicle during multiple overlapping grid based surveys. The vehicle begins each dive on the surface and uses GPS to navigate to a designated start location. Once it reaches the designated location on the surface, the vehicle dives and executes a pre-programmed grid survey, collecting co-registered high resolution stereo images, multibeam sonar and water chemistry data. A suite of navigation instruments are used while the vehicle is underway to estimate its pose relative to the local navigation frame. Following recovery of the vehicle, the SLAM technique is used to refine the estimated vehicle trajectory and to find loop closures both within each survey and between successive missions to co-register the dives. Results are presented from recent deployments of the AUV *Sirius* at a site in North Eastern Tasmania. The objective of the deployments described in this work were to document the behaviour of barrens-forming sea sea urchins which have recently become resident in the area. The sea urchins can overgraze luxuriant kelp beds that once dominated these areas, leaving only rocky barrens habitat. The high resolution stereo images and resulting three dimensional surface models allow the nocturnal behaviour of the animals, which emerge to feed predominantly at night, to be described. Co-registered images and resulting habitat models collected during the day and at night are being analysed to describe the behaviour of the sea urchins in more detail.**

I. INTRODUCTION

This paper describes an approach to achieving high resolution, repeated benthic surveying using an Autonomous Underwater Vehicle (AUV). The work is presented in the context of a study whose objective was to document the extent that the barrens-forming urchin *Centrostephanus rodgersii* impacts on habitats at depths at the limit of normal air-based scientific diving study sites in the north east of Tasmania (see Figure 1). Driven by a changing regional climate, this barrens-forming sea urchin has recently undergone poleward range-extension to Tasmania where grazing of diverse and economically important macroalgal beds has occurred [11], [1], [2]. Invading diverse and productive macroalgal beds, incursion of *C. rodgersii* in Tasmania is an important issue given the species' ability to catastrophically overgraze algal-dominated habitat [11], [3], which has resulted in widespread and persistent sea urchin barrens throughout the species' historical range in New South Wales (NSW) [4]. In NSW the sea urchin has formed and maintains barrens over approximately 50% of all near-shore rocky reefs [5].

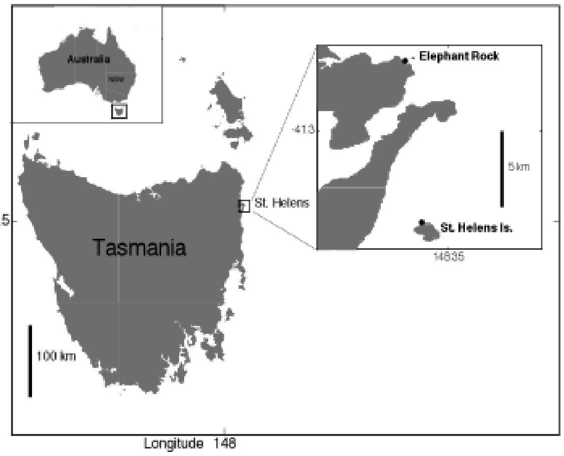

Fig. 1. Study sites in Tasmania, southeastern Australia. The AUV *Sirius* was deployed during the day and at night at two sites (Elephant Rock and St. Helens Is. - see expanded section) near St. Helens, in Tasmania's North East. Dive sites targeted recently formed barrens and adjacent macroalgal boundary habitat as a complement to on-going studies of urchin populations in the area.

Benthic acoustic and optical imaging AUVs have become effective complements to traditional survey methods; however their use has been largely restricted to exploratory missions at depths and in regions difficult to map at high resolution by other means [6], [7], [8]. To address pressing questions about the effect of climate change and direct anthropogenic impacts on coastal and deep sea benthic ecology [3], AUVs must start operating in a monitoring capacity. So far, these efforts have largely focused on physical oceanographic [9] or pelagic phenomena [10]. The proven ability of benthic imaging AUVs to rapidly and cost-effectively deliver high resolution, accurately geo-referenced, and precisely targeted optical and acoustic imagery makes AUVs ideally suited to the kinds of repeat surveys that will be necessary to monitor changes in the benthos, particularly beyond depths readily sampled by SCUBA divers. Changes in benthic community structure derived from precisely registered maps collected at regular intervals will provide stakeholders with data critical to both monitoring climate change impacts and effective management of reefs, particularly where the benthos provides important habitat for biodiversity and commercially targeted species.

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In this work, we illustrate how a stereo based Simultaneous Localisation and Mapping (SLAM) technique is used to estimate the trajectory of an AUV during multiple overlapping grid based surveys. The SLAM technique is used to refine the estimated vehicle trajectory and to find loop closures both within each survey and between successive missions to co-register dives. Results demonstrate how the AUV was used to perform repeated surveys during the day and night at a number of sites to document the behaviour of the *C. rodgersii* sea urchins which emerge to feed at night. By co-registering successive dives, it is possible to quickly identify overlapping images and to use these to compare the numbers of sea urchins seen on the same set of rocks during day and night. The texture mapped seafloor maps also allow scientists to assess the distribution of sea urchins at scales significantly larger than a single image illustrating the effectiveness of precisely co-registered surveys.

The remainder of this paper is organized as follows. Section II summarises the ecological motivation behind the study reported on in this paper while Section III describes the AUV and discusses developments required to facilitate dense, repeated surveys of the study sites. Section IV provides an overview of the deployments and examines the behaviour of the sea urchins during repeated day and night deployments. Finally, Section V presents conclusions and directions for future work.

II. ECOLOGICAL MOTIVATION

Since its first detection on the Tasmanian mainland coast in 1978, the sea urchin *C. rodgersii* has established itself across eastern Tasmania with barren areas now occurring in some locations, particularly in the north east [11]. The potential for broad-scale ecological shifts from luxuriant macroalgal beds to sea urchin barrens in Tasmania therefore poses a major threat to local biodiversity and valuable reef-based fisheries that depend on macroalgal habitat [11], [12], [3]. Understanding the characteristics of *C. rodgersii* populations and the spatial pattern and processes of barrens formation is important in assessing options to manage this sea urchin within Tasmania.

The recent nature of the *C. rodgersii* range extension and an increasing occurrence of grazing in Tasmania suggest that the sea urchin has the capacity to form widespread barrens over much of this coastline [11], [2]. Studies to date have been largely limited to depths that can be easily accessed by divers. The deployments described here involved replicated transects on reefs in the study region below depths efficiently surveyable by SCUBA diving and were designed to obtain quantitative estimates of key species/features at sites within each reef system stratified by depth. The ability for the AUV to repeat its surveys allows the behaviour of the animals to be studied over timescales of days and we plan to repeat these surveys on a bi-annual basis to examine long term trends in barrens formation.

III. AUV-BASED BENTHIC HABITAT MAPPING

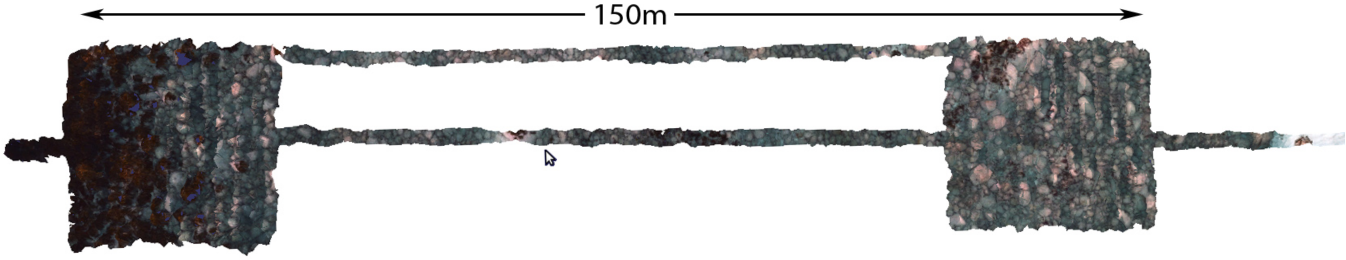
The University of Sydney's Australian Centre for Field Robotics operates an ocean-going AUV called *Sirius* capable of undertaking high resolution, geo-referenced survey work [13]. This platform is a modified version of the WHOI *SeaBED* vehicle [14]. This class of AUV has been designed specifically for relatively low speed, high resolution imaging and is passively stable in pitch and roll.

The objectives of this study were to complete high-resolution, full coverage seafloor surveys at selected sites during the day and at night to help understand the behaviour and population density of the sea urchins. In order to achieve repeated surveys, the vehicle was programmed to execute a dense survey pattern over a target study area. The vehicle begins each dive on the surface and uses GPS to navigate to a designated start location. Once in place, the vehicle dives and follows a pre-programmed grid survey, collecting high resolution stereo images, multibeam sonar and water chemistry data. A suite of navigation instruments, including a depth sensor, Doppler Velocity Log (DVL), compass and pressure sensor, are used while the vehicle is underway to estimate its pose relative to the local navigation frame. Following recovery of the vehicle, an efficient, stereo-based SLAM technique [15], [16] that maintains an estimate of the vehicle trajectory and uses seafloor features provide observations of the relative pose of the vehicle throughout the dive. Loop closures both within each survey and between successive dives are used to co-register the deployments.

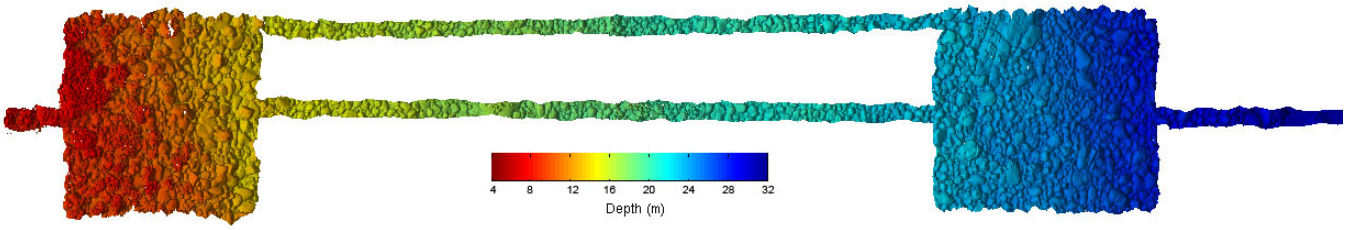
A typical dive will yield several thousand geo-referenced overlapping stereo pairs. While useful in themselves, single images make it difficult to appreciate spatial features and patterns at larger scales. It is possible to combine the SLAM trajectory estimates with the stereo image pairs to generate 3D meshes and place them in a common reference frame [17], [13]. 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 of features within the environment. Figure 2 shows an example of a dense stereoscopic reconstruction of the seafloor generated using the data collected by the AUV. The top subfigure shows a segment of the dense reconstruction texture mapped using the colour 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 detailed views of a segment of the mesh. Both the boulders in the field and patches of kelp are evident in the resulting surface.

IV. DEPLOYMENTS

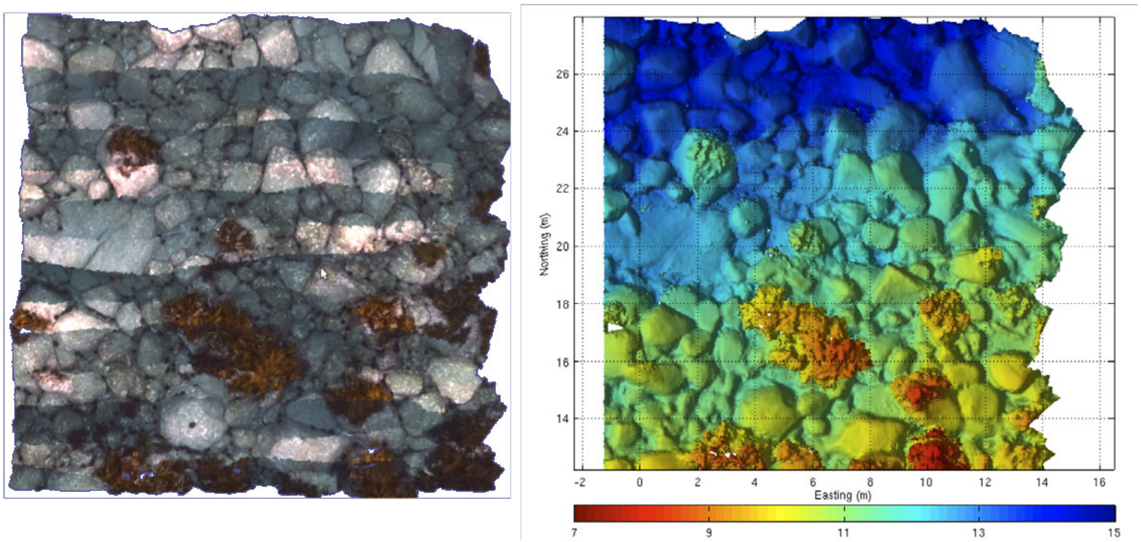
Six dives, each lasting between 1.5 and 3 hours, were completed within a sixteen hour period at the two study sites



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



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



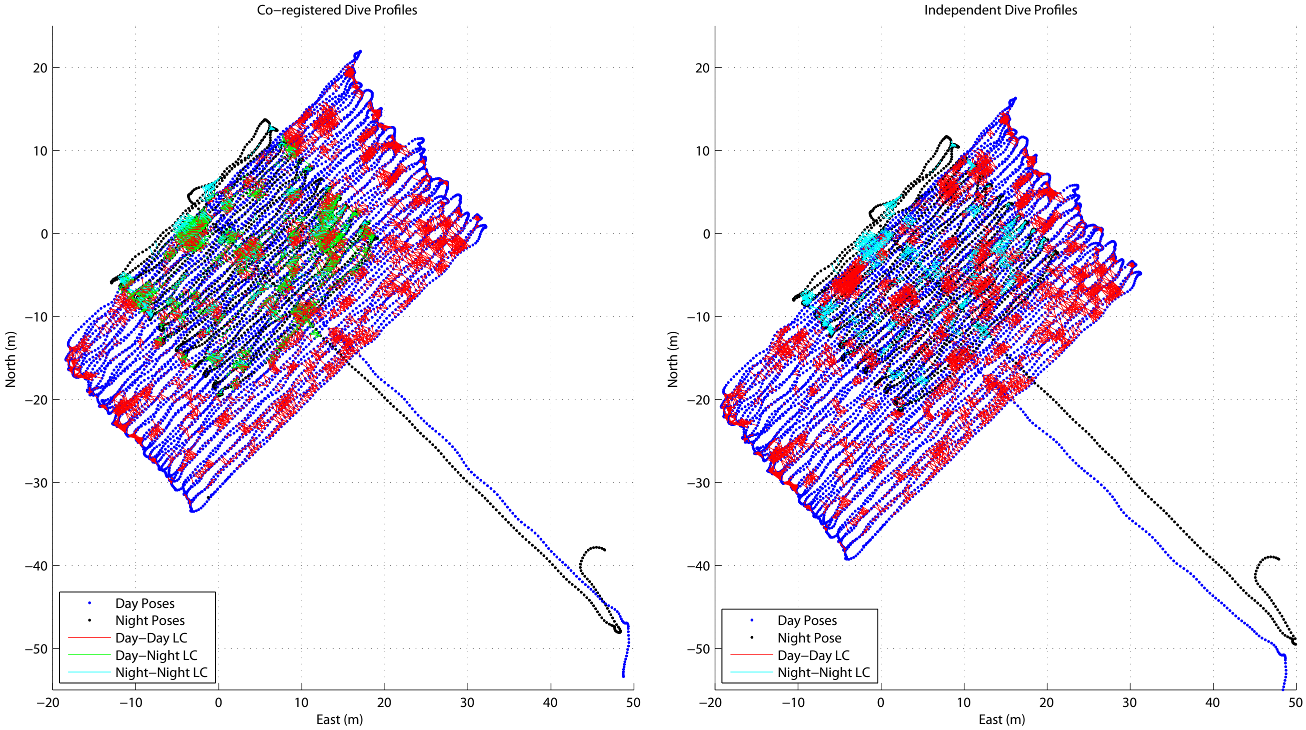
(c) Detailed texture mapped mesh

(d) Detailed bathymetry derived from stereo

Fig. 2. (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 three dimensional reconstruction of the boulders overlaid with the texture mapped imagery. (d) When the texture mapping is removed, the structure of the scene becomes apparent. Note the large boulders covering the survey site. The stereo bathymetry is of fine enough detail that the remnant patches of kelp can be seen in the resulting model.

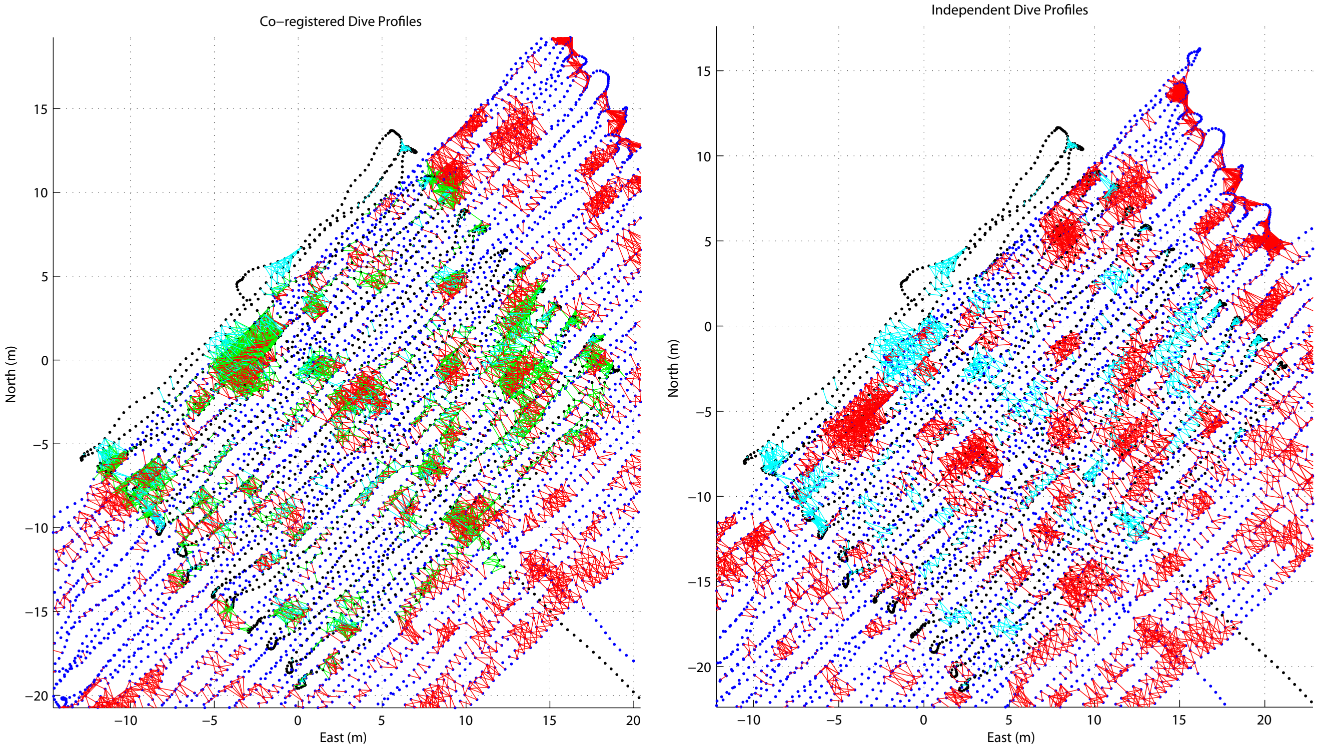
shown in Figure 1. There was a shallow and deep dive at each site and each dive location was revisited during the day and at night.

Figure 3 shows the estimated paths of the vehicle from two deep dives at the site known as Elephant Rock. The first dive, completed during the day, covered an area of approximately 50m x 30m while the second dive, at night, covered an area of approximately 25m x 25m. The vehicle initialised the estimate of its pose within the local navigation frame using the GPS observations on the surface. Although this places the estimated vehicle pose within a few meters of the desired survey location, there is still some offset between the navigation frames due to differences in the GPS solution as we do not have ready access to a differential correction when operating at remote off-shore sites. The dives were completed without using the SLAM solution while the vehicle was underway. Once recovered, we can rerun the navigation solution and use SLAM to refine the estimated vehicle trajectory. In this case the estimated vehicle trajectories have been co-registered by running the SLAM solution on the first dive and then reinitialising the estimate of the vehicle pose when it was deployed at night using the GPS observations on the surface. The SLAM algorithm was used to identify loop closures both within the second dive



(a) Co-registered surveys

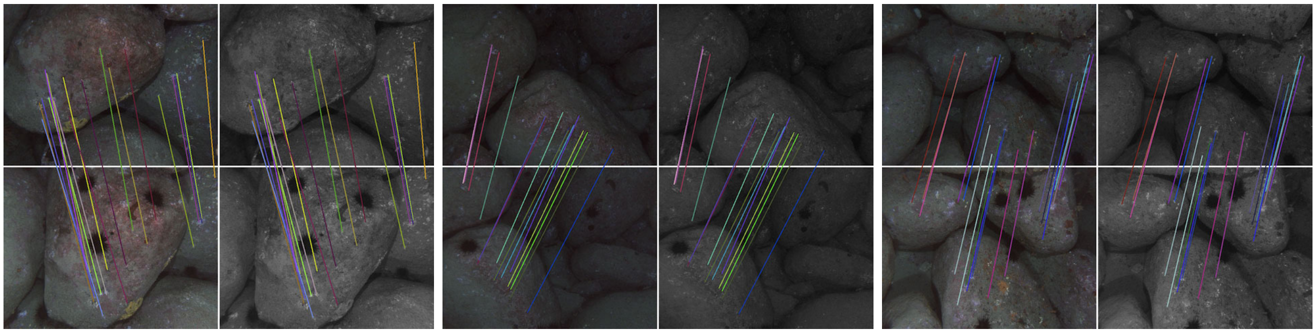
(b) Independent surveys



(c) Details of coregistered surveys

(d) Details of independent surveys

Fig. 3. An example of two dense, overlapping grid based surveys co-registered using SLAM. (a) Shows the two dive profiles when co-registered using SLAM. The vehicle travelled on the surface to a location in the deeper part of the survey area before diving. It followed a line up to the local origin before beginning the dense survey. This initial transect acts as an anchor on which which loop closures can be identified. The estimated camera locations for the daytime dive are shown in blue and the night trajectory in black. Loop closures are found within the day time dive (red), within the night dive(cyan) and between the two dives (green). (b) Shows the two dive profiles navigated independently. Notice that the two anchor legs have changed their relative position and that the relative positions of the two dive profiles is not consistent with the co-registered dive. (c) & (d) show more detailed views of the dive profiles illustrating the distribution of loop closures.



(a) (b) (c)

Fig. 4. Sample loop closures between day and night dives. The top pairs of images are from the daytime survey while the lower pair were captured at night. The coloured lines link the SIFT features identified for the loop closure. The lower images show a number of sea urchins and sea cucumbers that have emerged to feed at night. Lighting is provided by a pair of strobes mounted in the forward and aft of the vehicle resulting in consistent lighting independent of ambient conditions.

as well as between the two dives. These loop closures are shown in the figure using the colour coded loop closure line segments connecting individual poses from which the images were captured. Sample loop closure image pairs linking the two dives are shown in Figure 4. Notice that more sea urchins are more visible on the rocks in the night time dive.

The independently navigated estimates of vehicle trajectories are also shown in Figure 3(b) and it is apparent that there are significant differences in the relative positions of the estimated vehicle paths for the two dives. We have used the matched visual features identified in the loop closures to assess the improvement in the co-registration of the two navigation solutions when compared with independently navigated estimates of the vehicle trajectory. The three dimensional feature locations derived from the stereo images are used by the SLAM filter to compute a relative pose from which the images were captured. This is integrated into the filter as an observation of the relative pose between estimated vehicle poses. Using the final estimated vehicle states, we can reproject the observed 3D feature locations into the navigation frame and compare the differences in estimated feature positions from the two vehicle poses comprising the loop closure. Figure 5 shows histograms of the L^2 norm of the difference in feature positions for both the co-registered and independently navigated vehicle trajectories. Notice that the distribution of differences for the day-day and night-night feature locations are consistent between the co-registered and independently navigated solutions. The night-day distributions, however, show that the co-registered navigation solutions are yielding distributions similar to those for the links within each dive but that the night-day solution for the case where the two solutions are navigated independently has a mean error in the estimated feature locations of 5m. This is consistent with the expected GPS drift over the course of the ten hours between these two dives.

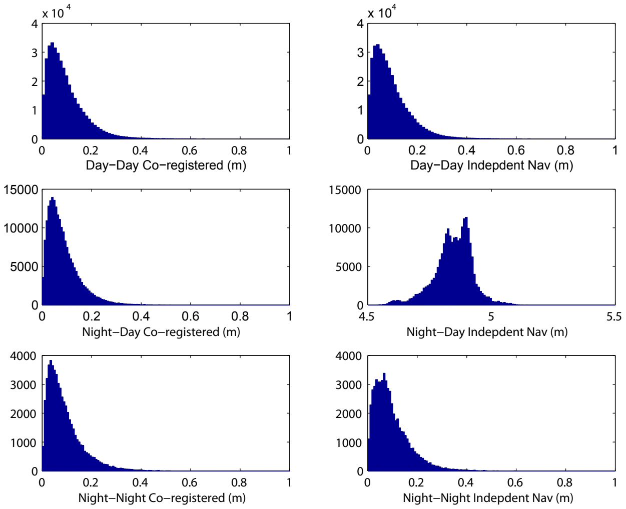


Fig. 5. Histogram of differences between L^2 norm of the relative poses for loop closures calculated using the common features identified in the images and the final SLAM based estimates of the camera poses.

There are two main motivations for co-registering multiple dive profiles in the manner described here. The first is to provide consistent estimates of feature locations within the mosaics of the survey areas. This could conceivably be achieved by using a batch technique to register the resulting maps following the survey and in all likelihood would be adequate for ecological study purposes. The second is to facilitate the development of more precisely repeatable survey capabilities. The ability to use the original SLAM map to identify areas of the survey that are being revisited should allow for these surveys to be more precisely repeated if the SLAM algorithms can be run online. The results presented here suggest that it is possible to identify areas of a survey that are being revisited and to use this information to co-register the two surveys. The use of external positioning information, such as that provided by long baseline acoustic arrays or ultra-short baseline acoustic transceivers, might improve the relative estimate of positions for multiple dives but are unlikely to yield fine-scale registration such as that achieved here, particularly in acoustically difficult environments such as the boulder fields featured in this study.

Figure 6 shows an example of the texture mapped habitat models derived based on combining the estimated vehicle path with the stereoscopic imagery, with more sea urchins

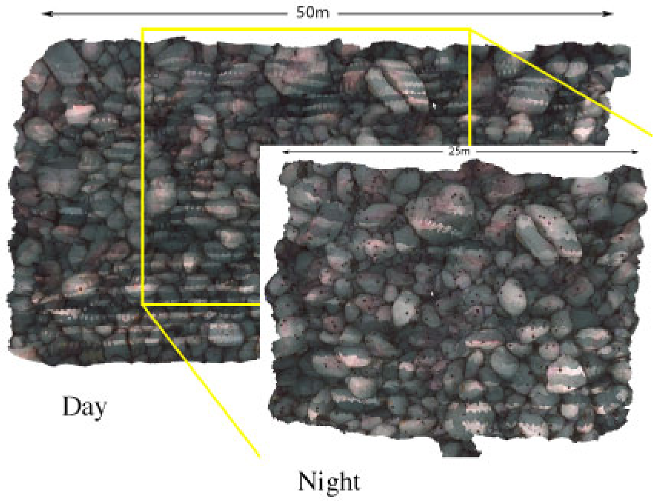


Fig. 6. Texture mapped habitat models derived from stereoscopic imagery registered using the AUV navigation solution. The night and day dives over the same study site allow the behaviour of the sea urchins to be examined in detail. Notice the large numbers of sea urchins (black dots) on the rocks in the night time model. Close examination of the day time model reveals that the sea urchins are hidden within the crevices of the rocks.

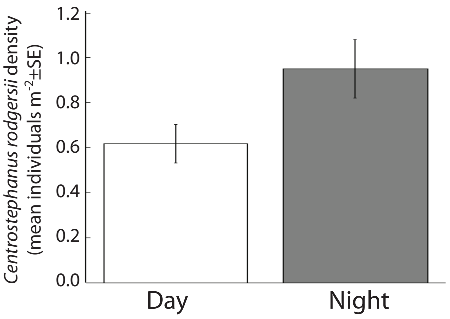


Fig. 7. Comparison of *C. rodgersii* density as estimated from meshed AUV imagery during day and night sampling of identical reef-scapes at St. Helens, north eastern Tasmania. Density estimates were obtained by counting sea sea urchins within 5 randomly placed 20 m by 2 m virtual quadrats overlayed on each meshed reef-scape. One-way analysis of variance revealed a significant 'nocturnal effect' on sea urchin density (F1,38=4.61; P=0.038).

visible in the night time model. The high resolution stereo images and resulting three dimensional surface models allow the behaviour of the sea urchins, which emerge from crevices to feed at night, to be described. Traditional SCUBA based studies rely on completing transects through a study area, with divers collecting population statistics over a defined area. The surface models generated using the data collected by the AUV have been analysed using a similar approach. Across the four reef-scapes mapped by AUV during day and night (i.e. shallow and deep deployments at both sites), the density of visible *C. rodgersii* increased by approximately 54% at night (see Figure 7). Although a first glance at the surface models suggests that there are very few emergent sea urchins on the rocks during the day, the resolution is sufficient to observe them hiding in the cracks between the rocks. The great majority of the sea urchins that are observed during the day are located in crevices. The images and resulting habitat models are now being analysed in more detail and the derived statistics are being compared with survey statistics collected by divers using closed-circuit rebreathers to calibrate the observations made by the AUV. The high resolution meshes are also allowing the biologists to examine potential sampling biases by varying the design of the survey transects within the habitat models. This type of experiment would be considerably more difficult to accomplish using diver based operations.

V. CONCLUSIONS AND FUTURE WORK

This paper has reported on an expedition to survey urchin populations in North Eastern Tasmania. We have shown how data collected by an AUV can be co-registered using SLAM to provide repeated observations of seafloor features. In this case, generating models such as these allows marine biologists to examine the behaviour of sea urchins over significantly wider areas, and at greater depths, than would otherwise be achievable. These surveys were completed in approximately 30m of water. While not deep by AUV deployment standards, this depth represents the usual limit of air-based scientific diving and it would be very difficult to recover similar data using diver based operations. Although the detailed analysis of the data to derive estimates of urchin population density is on-going, we have illustrated how an AUV can be used to perform repeated surveys over temporal scales longer than a single dive. Repeated surveys such as those completed here can be used to inform ecosystem models, in this case the day/night behaviour of barren-forming sea urchins. We anticipate that repeated surveys, e.g. annually, conducted on longer timescales will provide critical timeseries data for assessing the impact of climate change and anthropogenic stresses on benthic habitats.

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