Repeatable Robotic Surveying of Marine Benthic Habitats for Monitoring Long-term Change

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Abstract— **This paper presents recent developments in data processing of multi-year repeat survey imagery and precision automatic registration for monitoring long-term changes in benthic marine habitats such as coral reefs and kelp forests. A method is presented for correcting underwater images for the effects of perspective-dependant lighting and attenuation in the water column. Additionally, two different methods are presented for precision alignment of imagery maps collected over multiple years. The first method employs scan-correlation optimisation using the topography generated via structure-from-motion using the image data. The second method uses mutual information optimisation to register imagery maps, providing robustness to changes in the colour and brightness of objects in an underwater scene across multiple years. Results are presented from field data collected in Tasmania and Western Australia between 2009 and 2011.**

I. Introduction

Benthic marine habitats such as coral reefs, seagrass meadows and kelp forests are environments that have significant economic value worldwide and are expected to face increasing pressures from human impacts such as urban development, fishing and climate change. Long-term monitoring of these habitats provides a means for detecting and quantifying changes in the distribution and abundance of different species, aiding our understanding of human impacts. The Australian Centre for Field Robotics operates an ocean-going Autonomous Underwater Vehicle (AUV) called *Sirius* capable of undertaking high-resolution, geo-referenced surveys which is currently used as part of Australia's Integrated Marine Observing System (IMOS) [6]. As part of the IMOS program, *Sirius* is deployed at several key locations along Australian coastal waters on a yearly basis to perform repeated surveys and collect data which can be used for long-term monitoring. The AUV employs a variety of navigation sensors including Global Positioning Systems (GPS) at the surface and ship-borne Ultra-Short BaseLine (USBL) positioning while underwater to re-localise itself in the same location across multiple years with an accuracy of approximately $\pm$5m. Precision revisiting of exactly the same area of benthos across multiple years provides higher statistical power for temporal change detection and provides the ability answer questions about changes in individual organisms, in contrast to variable site selection in a given area [2].

This paper focuses on developments in data processing of multi-year repeat survey imagery and other map data for precision automatic registration and change detection. Change detection is made challenging by the lack of precise geo-registration accuracy (errors of $\pm$5m) with respect to cm-level changes that can occur across multiple years in habitats such as coral reefs. Registration of data across multiple years must be performed using the map and image data itself, which is further complicated by changes in the benthic coverage and assemblages that occur over multiple temporal and spatial scales. Additionally, variations in the water column properties and vehicle perspective that change between years have significant effects on the colour and brightness in images collected, confounding quantitative analysis of change. In this paper, we discuss a method for correcting underwater images for the effects of perspective-dependant lighting and attenuation in the water column that results in inconsistency in images collected from different perspectives of the same object over multiple AUV dives. We discuss two methods for precision alignment of imagery maps collected over multiple years. The first method employs scan-correlation optimisation using the topography generated via structure-from-motion using the image data. The second method uses mutual information optimisation to register imagery maps, providing robustness to changes in the colour and brightness of objects in an underwater scene across multiple years. Results are presented from field data collected in Tasmania and Western Australia between 2009 and 2011.

II. Methodology

A. AUV-based Benthic Surveying

At each reference site, the AUV *Sirius* is deployed at the surface and uses GPS to navigate to a starting location. The vehicle then dives and performs a pre-programmed trajectory along the seafloor collecting stereo-image pairs, mutlibeam sonar and water column data. Different survey trajectories are used including long transects, broad-scale sparse grids and dense grids where overlapping imagery is used to provide a small-scale 25x25m patch of contiguous coverage, suitable for re-localisation within the accuracy limits of the AUV navigation system. Once the survey is complete, the vehicle returns to the surface and is recovered. Post-processing of the stereo-imagery and other navigation data via Simultaneous Localisation and Mapping (SLAM) and 3D reconstruction [4], [3] is used to provide 3D photo-textured topographic reconstruction of the seafloor along with a geo-referenced mosaic map.

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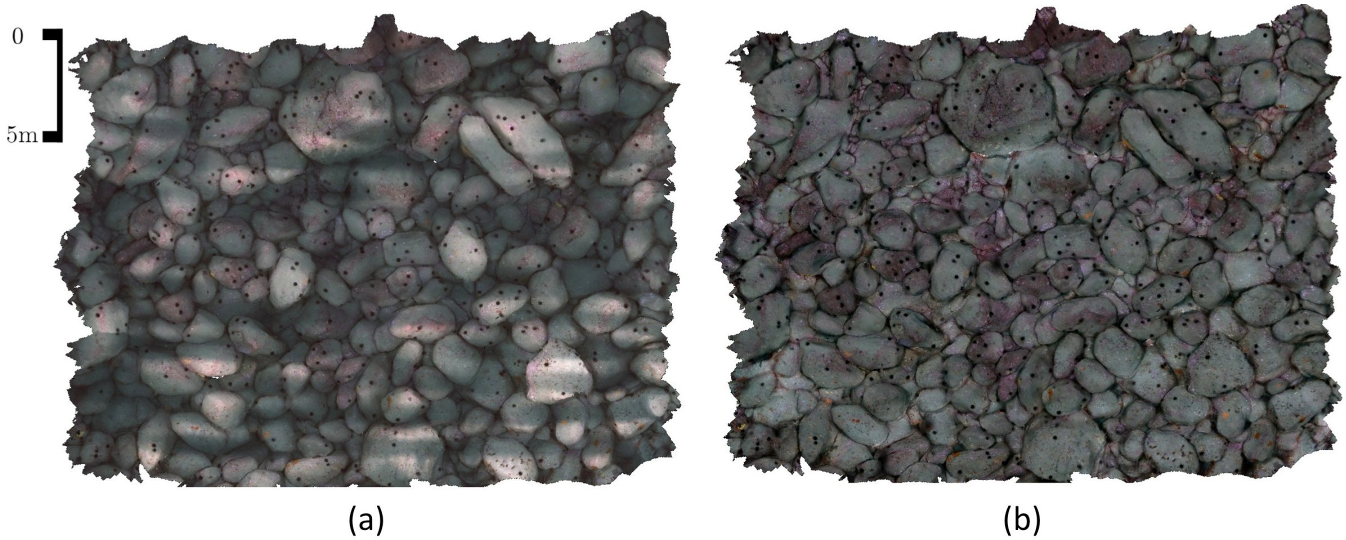

Fig. 1. Colour-consistency processing for 3D terrain reconstruction: (a) 3D photo-textured scene using standard colour corrected textures and, (b) 3D photo-textured scene using full water attenuation colour corrected textures.

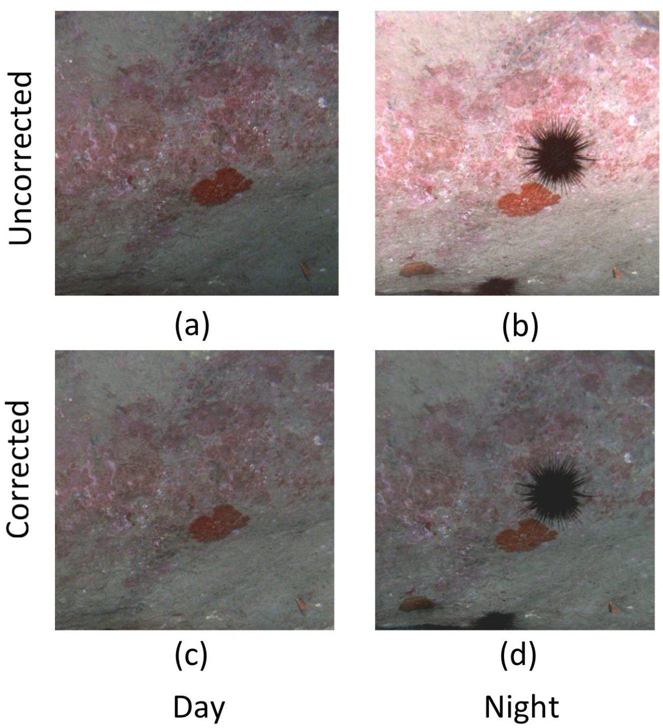

Fig. 2. Colour-consistency processing for imagery collected during a day vs. night repeat survey: (a) and (b), uncorrected imagery of the same rock face in day and night mission imagery. The small change in perspective between missions results in lighting and colour differences between missions. (c) and (d), attenuation colour-corrected imagery for the same area day and night. The measured colour and brightness is consistent, enabling quantitative change detection.

B. Imagery Colour-Correction

When capturing images underwater, the water column imposes several effects on images that are negligible in air such as colour-dependant attenuation and lighting patterns. These effects cause problems for human interpretation of images and also confound automatic change analysis techniques (see Figure 1 (a)). Our approach exploits the 3D structure of the scene generated using structure-from-motion techniques and accounts for distance-based attenuation, vignetting and lighting pattern, improving the consistency of imagery and photo-textured 3D models.

Using the generated 3D topography and AUV navigation solution, a range-image is created for each of the images captured by the stereo-camera on the AUV. Using all of the collected images from the dive, a scatter-plot is built of pixel intensities (in three colour channels) and image position versus range to the seafloor at the corresponding pixel. This data is then used to estimate the parameters of an image formation model accounting for camera response function, vignetting and range-dependant attenuation for each colour channel. The image formation model is then used to correct images to provide consistency under changes in the perspective of the camera, such as position in the image and range to the object (see Figure 1 (b)). Further details of the approach are discussed in [1].

C. Multi-survey Map Registration Algorithms

In a previous study [7], Scale Invariant Feature Transform (SIFT) image features were used to co-register multiple 3D image maps collected by the AUV comparing the same area from daytime to nighttime (over a 12 hour period). Subsequently, the same techniques were applied to multiple dives conducted over large timescales (i.e. a year) but it was found that the local contrast features employed by SIFT were not reliably matched in this case. This is likely

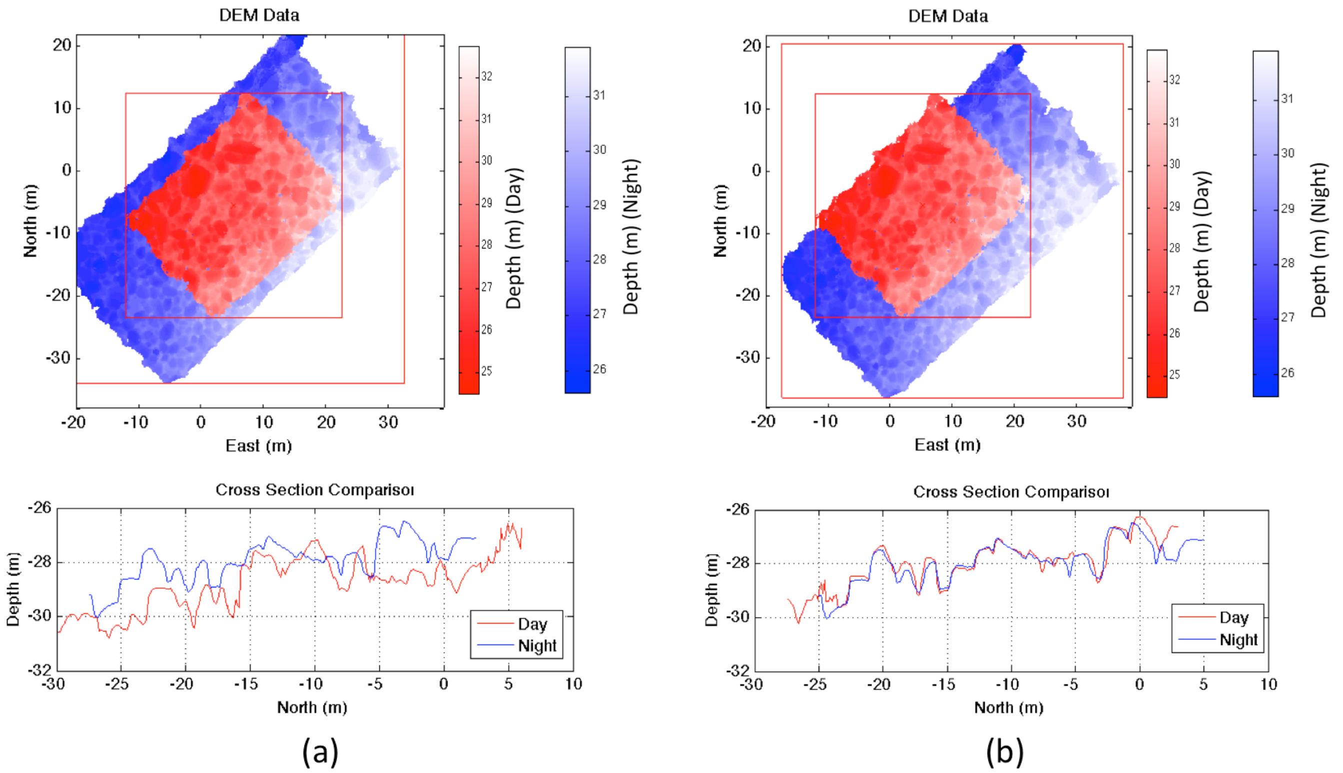

Fig. 3. Digital Elevation Map (DEM) registration of day (shown in red) and night (shown in blue) repeat surveys: (a) Original terrain map alignment based on navigation data and, (b) final terrain maps after scan correlation alignment. Lower figure displays a North-South cross-section taken through both DEM models at 5m East of the map origin before and after alignment.

due to significant changes occurring at the pixel-level in images (from millimetres to centimetres in the map) over this time period. Instead, we employed wider-scale matching techniques to register multiple dives.

For benthic areas that exhibited significant relief (for example high-relief reef or boulder fields), a scan-correlation method was used to register 3D topography maps. Digital Elevation Maps (DEMs) derived from the stereo image data were compared between dives along a fixed grid of different offset values at a resolution of 10cm over the North-South (x) and East-West (y) directions. At each potential offset, the overlapping section of DEMs were extracted and the difference in height (Δz at each point in the overlapping grids) was computed. At each potential offset value, the correlation cost $c_{x,y}$ was computed:

$$c_{x,y} = \log\left(\frac{\frac{1}{N}\sum_{x,y}\Delta z^2}{\sigma_{z_1}\sigma_{z_2}}\right) \tag{1}$$

where σ_{z_1} is the standard deviation of heights in the first DEM, σ_{z_2} is the standard deviation of heights in the second DEM and N is the total number of overlapping points for a given offset in (x, y). The offset which resulted in the lowest correlation cost $c_{x,y}$ was chosen to register the maps into a single corrected coordinate system.

For benthic areas that exhibited small relief (i.e. low-relief reef) but greater variations in colour and texture visible in the imagery, we used a mutual information optimisation [5] to register imagery mosaics. Mutual information was used as a consistency metric rather than direct correlation between intensity values due to the variations in object colours across years. At each potential offset, the overlapping section of grey-scale image mosaics were extracted and a joint histogram of the greyscale intensity values ($\mathbf{J}$) computed. The mutual information between the image intensity distributions was then calculated using:

$$\begin{aligned} M_{x,y} &= -\sum_{m2}\left(\sum_{m1}\mathbf{J}\log\sum_{m1}\mathbf{J}\right) - \ldots \\ &\sum_{m1}\left(\sum_{m2}\mathbf{J}\log\sum_{m2}\mathbf{J}\right) - \sum_{m1,m2}(\mathbf{J}\log\mathbf{J}) \end{aligned} \tag{2}$$

where $\sum_{m1}$ is the summation over bins corresponding to the first map, $\sum_{m2}$ is the summation over bins corresponding to the second map and $\sum_{m1,m2}$ is the summation over all bins of the joint histogram.

III. Results

A. Colour-Consistency Processing

Two AUV dives were performed over an underwater boulder field site located off the coast of Tasmania, in Southeast Australia. The dives were performed approximately 12 hours apart (once during the day and once during the night) as

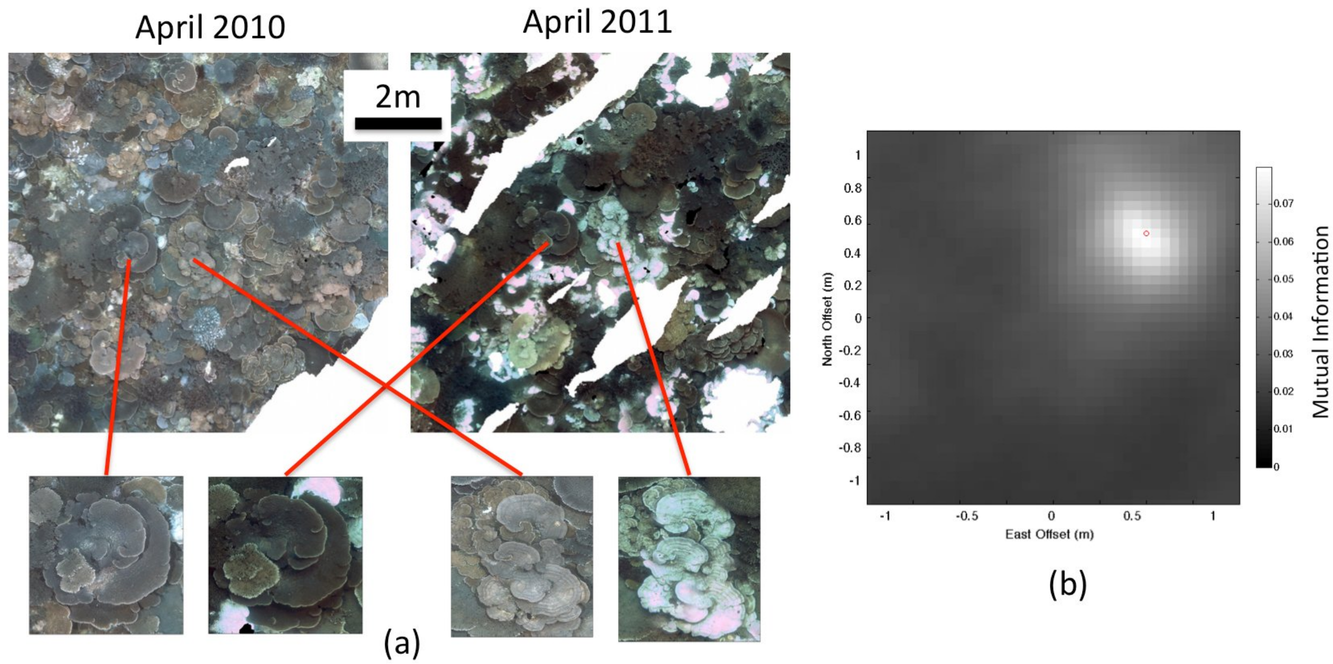

Fig. 4. Mutual information registration of coral mosaics across a 12 month period: (a) AUV mosaics of a coral reef from April 2010/April 2011 with highlighted sections of both un-affected and bleached coral, co-registered using mutual information optimisation of the mosaic greyscale images. (b) Mutual information utility surface as a function of offset between the mosaics used in computing the optimal registration of the mosaics.

part of a study of the behaviour of sea-urchins, which were known to be predominantly active at night. The resulting data was used to assess the imagery colour correction and scan-correlation co-registration algorithms.

Results of the imagery colour correction when applied to the day-time dive are shown in Figure 1. Figure 1 (a) illustrates the original 3D reconstruction using textures taken from uncorrected images and Figure 1 (b) illustrates the reconstruction using textures corrected using our lighting and attenuation correction algorithm. The left model exhibits considerable correlation between the intensity/colour of image textures and the average distance from which each part of the surface was imaged from, in particular a horizontal banding pattern that corresponds to overlapping swaths during image collection that occur at slightly different heights above the terrain. The distance and general spatial correlation has been essentially removed in the corrected-texture model to the right.

Figure 2 shows a comparison of images taken over the same location in both the day (Figure 2 (a) and (c)) and night (Figure 2 (b) and (d)) dives. The original uncorrected images are shown in Figure 2 (a) and (b). The night-time image appears brighter and more red than the day time as the image was captured closer to the terrain (due to small variations in the AUV trajectory during repeat missions). Figure 2 (c) and (d) illustrate the corrected images. The effects of colour and distance-dependant attenuation have been removed from the data and the corresponding images across missions are much closer to being radiometrically consistent. The consistency enhances the ability to detect changes (such as the presence of the sea-urchin during the night-time dive) using image-differencing and other change detection techniques.

B. Multi-Mission Registration

Figure 3 shows the results of the scan-correlation matching algorithm when applied the the DEM models generated from the Tasmanian day/night dives. Figure 3 (a) illustrates the DEM models overlaid in their original geo-referenced coordinate systems as provided by the navigation sensor on the AUV. Figure 3 (b) illustrates the final alignment of the two models after applying scan correlation and a corresponding cross-section of the two 3D models.

To assess multi-mission registration algorithms over larger timescales, two AUV dives were performed over subsequent years (April 2010 and April 2011) over a section of low-relief reef off the coast of Western Australia. The reef was found to have undergone a bleaching event in which a large proportion of the coral had turned white. Figure 4 (a) shows both the overall 2010/2011 mosaic maps compared prior to alignment and zoomed-in sections of the mosaics after alignment. The mutual information optimisation is able to co-register the mosaics even in the presence of large colour changes (i.e. bleached coral) between years. Figure 4 (b) shows the calculated mutual information as a function of the considered offset between the mosaic maps, illustrating a global maximum corresponding to the optimal alignment.

IV. Conclusions and Future Work

This paper has discussed recent developments in automatic registration and colour correction of multi-year AUV imagery surveys performed as part of a long-term benthic habitat monitoring program. As part of ongoing research we have developed data processing tools for image consistency correction and spatial registration of maps collected over multiple years. Future work will focus on real-time registration and localisation methods that will allow the AUV to precisely repeat a previous survey. This will maximise the utility of the collected data as well as reduce the accuracy requirements of external geo-referencing systems such as USBL.

V. Acknowledgments

This work is supported by the ARC Centre of Excellence programme and Linkage Project LP0989998, funded by the Australian Research Council (ARC) and the New South Wales State Government.

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