USING STEREO-VIDEO FOR DEEP WATER BENTHIC HABITAT SURVEYS

Shortis, M. R.[1], Seager, J. W.[2], Williams, A.[3], Barker, B. A.[3] and Sherlock, M.[3]

[1]RMIT University, Australia

[2]SeaGIS P/L, Australia

[3]CSIRO Marine and Atmospheric Research, Australia.

Abstract

Towed body systems of various configurations have been used for many years to map the seabed. Prior to the last several years, single video camera systems were widely used to gather qualitative data, or collect often low-accuracy quantitative data using laser dot patterns projected into the field of view. The introduction of stereo-video systems has enabled the capture of accurate and reliable spatial information with estimates of accuracy and precision. CSIRO has recently adopted stereo-video on a towed body system used for habitat mapping and biodiversity survey work in the deep ocean (100 to 2,000 m depths). This paper provides an overview of the research context, describes the towed body system, reports on the addition of stereo-video to the system and the status of ongoing developments in the project. Applications of the system to managing marine biological resources are illustrated using examples from surveys undertaken recently off south east Australia.

Introduction

Global attention on marine benthic biodiversity conservation has rapidly increased over the last few decades due to a growing awareness of processes and human activities that are degrading the marine environment. Part of the response to the widespread concern for effective conservation is the implementation of marine reserves or Marine Protected Areas (MPAs). In addition, the acknowledgement that fisheries need to be managed for ecological sustainability, rather than simply on the basis of regulating catch or effort, has generated the need to understand and quantify the interactions of fishing gear with the benthic environment (Hobday *et al.*, 2006; McShane *et al.*, 2007). These responses have generated a need for multi-scale maps of seabed habitat (figure 1) to inform planning and operational management (Williams *et al.*, 2005).

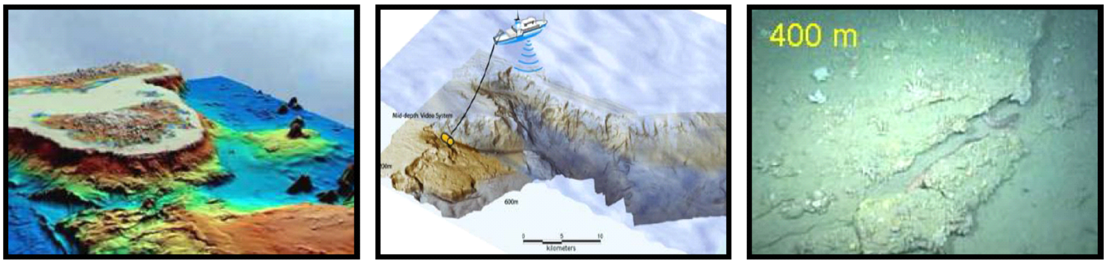


Figure 1. Multi-scale mapping of habitats – regional, feature and fine scales.

Australia is developing a national network of reserves in offshore waters where most areas are expected to be deeper than SCUBA diving depths (>50 m); this is the case off south-eastern Australia where the first part of the network has been declared (DEWR, 2007). As well, a large proportion of total fisheries catches in Australia are taken below SCUBA depths. Mapping to support both conservation and fisheries management therefore leads to a requirement for remote data capture during surveys and monitoring in deep water regions. Information from surveys is being integrated to produce habitat maps at various scales of resolution so that the multi-scale structure of benthic habitats (see figure 1) can be understood and natural regions can be identified as planning units.

Broad scale mapping information is efficiently gathered and classified by hydro-acoustic methods, but these techniques require validation from photographic and physical samples at finer scales (Kloser *et al.*, 2007). Geo-located images from video or still cameras are typically used to provide this fine-scale detail. Geo-location of the images on the seabed is critical to relate the sampled area to environmental co-variates extracted from hydro-acoustic and other sensors. The integration of fine scale samples is needed to understand the broad scale issues across the fishery regions or management planning units as a whole.

Single towed or dropped video cameras, or video and still cameras on towed bodies or sleds, have been widely used to gather qualitative sample data such as habitat classifications or fish counts. Deep water operations demand very robust systems and suitable lighting to operate in the high pressure, low temperature, low light environment. However towed systems have the advantage of efficient data capture along many kilometres of transects and the ability traverse rough and steep seabed topography. In addition, towed systems can capture many other types of data along transects, including positional data, providing a multi-dimensional sample of information along an accurately located path.

Towed systems commonly include a live video feed from broadcast quality cameras. These systems are relatively low cost and have high reliability. Power and data transmission requirements are modest and well understood. The medium resolution images are adequate for habitat classification, but broadcast quality systems suffer from motion blur due to the interlaced image capture. It is increasingly common for towed systems to incorporate high resolution, frame capture digital still cameras to provide unequivocal species identification from selected snapshots of individual flora and fauna.

In general, the single cameras used in these systems have not been calibrated and quantitative data has not been a priority, however low-accuracy quantitative data can be estimated through the use of parallel lasers to define the scale of the images. This approach can be extended through the use of additional, crossing laser beams to define a pattern used to determine the orientation and range of the platform relative to the sea bottom (Davis and Pilskaln, 1993). The technique allows mapping of features, but like any single camera approach is limited by scale estimation at a single location (Harvey *et al.*, 2002b) and the assumption that the seabed is a plane within the field of view.

The addition of a second video camera to a towed system is a relatively modest investment and does not substantially increase the demands on power or data transmission. Stereo-cameras have the substantial advantage that accurate and reliable three dimensional data can be determined from measurements taken from the stereo images (Harvey and Shortis, 1996). The accuracy and reliability of the dimensional information from stereo-images permits many fewer measurements to achieve the same statistical confidence as that from single images with parallel or crossing lasers because of the poorer accuracy (Harvey *et al.*, 2002b). Minimising the number of measurements required is important where there is a very low frequency of samples of a particular species or habitat type (Harvey *et al.*, 2001), which is a common circumstance for deep benthic surveys.

However the main advantage of stereo-camera systems is that three dimensional data is readily available. Whilst length measurements are the primary tool for many applications, surface areas and volumes can also be accurately estimated (Abdo *et al.*, 2006). Accordingly, rather than making assumptions such as a planar seabed within the field of view, the actual surface topography can be measured directly. This level of detail is only possible using stereo-images, because of the accurate three dimensional measurements that are possible when calibrated stereo-cameras are used as the measurement system.

This paper describes a towed body system developed in Australia for habitat mapping, and details on the use of calibrated stereo-cameras that enable quantitative data to be extracted from imagery. Applications of the data for managing marine biological resources are illustrated with a range of examples.

Towed Body System

The towed body system is a sensor platform that records a variety of measurements and information along transects. The body is deployed over the stern of the vessel using a gantry and is towed at an optimum speed of 1-1.5 knots that enables the pilot to "fly" the platform just above bottom. The platform operates to depths of 2,000 metres and is connected to the vessel via a 3,200 metre steel-armoured cable containing fibre-optic and conducting wires. Deployments are typically 30-60 minutes duration, producing transects of 1-3 km in length, but, if required, the body can be towed continuously for several hours.

Sensors record altitude, pressure, pitch, roll, water temperature, conductivity and fluorescence. The recordings are indexed to navigation data from the differential global positioning system (DGPS) on the vessel and links to ultra short baseline (USBL) tracking beacon data on the towed body, so that measurements can be accurately geo-located. All sensor data is captured to a log file and combined with vessel DGPS and USBL information. Several sources of incoming data are displayed graphically on a custom-made LabView "console" on an onboard PC screen to provide feedback to the pilots for control of the system. The console is also the switching interface for components. AC power is supplied to the system from the ship. Calibration and data processing requirements for the non-imaging sensors is described in Williams *et al.* (2007) and Kloser *et al.* (2007).

Two PAL video cameras, configured as a stereo-pair with a separation of 600 mm, transmit live video sequences that are recorded on time-coded digital video (DV) tape. A separate forward-looking camera provides an additional view for navigation and obstacle avoidance. Two 250 watt incandescent lights provide illumination for the video cameras. Ideally the cameras view the seabed obliquely from 1-3 metres above the seabed. Depending on the slope of the seabed and the attitude of the towed body, the useful field of view of the cameras will vary between 1 to 5 metres.

The distance from the cameras to objects to be measured varies commensurately, however the illumination of the scene prevents reliable measurements at a ranges greater than approximately 5 metres, depending on turbidity and surface reflectance.

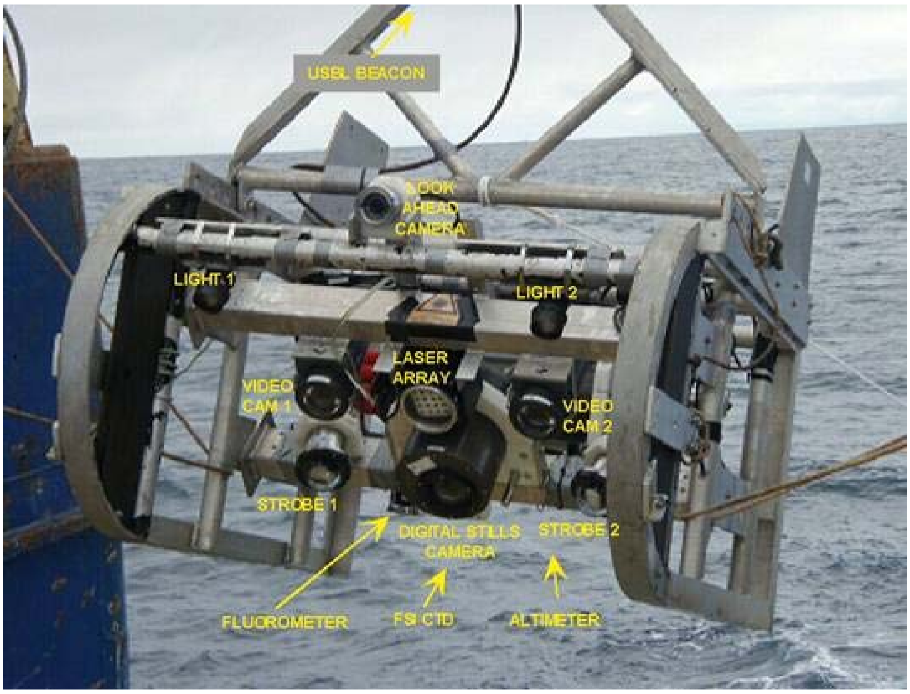


Figure 2. CSIRO towed body platform

Identification of species is important for habitat mapping, so a high resolution digital still camera is a vital component of the system. The camera and strobe illumination is remotely triggered by the operator or programmed to fire at set intervals. Images are captured to the internal storage of the camera and later uploaded to the logging computer. At this stage there are no plans to incorporate a stereo-pair of digital still cameras, although stereo digital stills have been used very successfully for some under-water applications to quantitative measurement (Abdo *et al.*, 2006). However as a measure to overcome the limitation of PAL video resolution, high-resolution (1392 x 1040 pixel) progressive scan cameras are under evaluation for the stereo-video imaging, based on experience with a proto-type system used in aquaculture (Harvey *et al*, 2004). The high resolution images improve the measurement accuracy from the stereo image pairs, the cameras are accurately synchronized and image sequences are recorded direct-to-disk in readiness for immediate analysis.

Stereo-Camera Calibration

Video cameras used for marine science applications are not purpose-built for accurate and reliable measurements from the captured images, but instead follow different design imperatives to optimise the quality of the images and the utility of operation. This consumer oriented design regime results in small departures from a perfect central projection, such as lens distortions, which must be modelled in a calibration process so that the errors in the optical path can be corrected (Shortis and Harvey, 1998). Underwater use introduces another level of complexity because of the additional effects of view port and water refractive interfaces between the camera lens and the object to be measured.

The camera calibration model does not need to contain additional terms for the effects of the refractive interfaces of the underwater housings, as analysis of the effects of the refractive surfaces in the optical path in an ideal camera housing shows that images are displaced radially from the centre of the image (Li *et al.*, 1996). Whilst the assumptions that the optical components of the housing are perfectly symmetrical around the optical axis of the camera and refractive surfaces are perfectly perpendicular to the optical axis are unlikely to be fulfilled in practice, it is clear that the primary component of the refractive effect is radial. As a consequence, the approach that has been adopted has been to allow the refractive effects of the optical components and refractive interfaces to be absorbed by the standard camera calibration parameters used in close-range photogrammetry (Harvey and Shortis, 1996). The standard model includes radial lens distortion parameters that absorb the main component of the additional refractive effects, whilst secondary effects are at least partly corrected by other calibration parameters.

Shallow Water Calibration

To determine the camera calibrations, the stereo-cameras are pre- or post-calibrated in shallow water, usually in a swimming pool, using the techniques developed by Shortis and Harvey (1998). The calibration technique requires multiple photographs of a 3D array of high contrast targets. Photographs are taken from a variety of viewpoints of the target array and using a variety of camera roll angles in order to provide an interlocking network of many views of many targets, and simultaneously produce a randomised scatter of measured image locations across the format of the images. The 3D target array, usually in the form of a light, easily manoeuvrable calibration fixture, has the size determined by the field of view of the cameras and the likely working distance for the measurements. It is impractical to manoeuvre towed body systems in the same way as a hand-held camera, so instead the calibration fixture is tilted and rotated in the field of view of the camera (see figure 3) rather than the cameras moving around the target array (Harvey and Shortis, 1996).

After a semi-automated target image measurement process, the network analysis computations produce various estimates of the internal consistency of the calibration. The primary indicator is the root mean square (RMS) image residual for all target image measurements, which is expressed as a fraction of the pixel size for the image sensor. RMS image residual values generally range from 1/20 to 1/30 of a pixel for an in-air calibration network, dependent primarily on the target image quality and integrity of the calibration model (Shortis *et al.*, 1995). The result for the shallow water calibrations of the towed body stereo-camera system is typically a RMS of no better than 1/15 pixels. The result is degraded compared to the equivalent result in air due to the impact of assumptions in the calibration model, non-uniformities of the refractive interfaces and the dispersion of the water medium (Newton, 1989). The latter leads to a reduction in contrast, as compared to in-air images, that reduces the quality of the target image measurements.

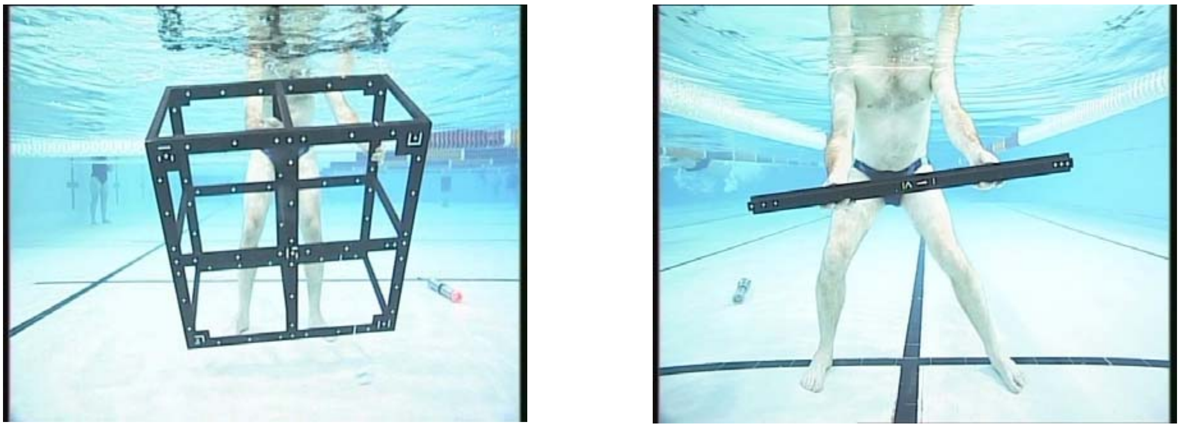


Figure 3. Typical images for shallow water calibration (left) and length validation using a known length (right). The LED is used for synchronisation checks.

The relative position and tilts, also known as relative orientation, of the two cameras is derived from post-processing of all synchronised stereo-pairs used in the calibration. Experience has demonstrated that a weakness of the calibration model for refraction is the integrity of the full light path from the first water-port interface through to the image sensor. A consistent spatial relationship between the view port and the camera lens is critical to this stability. Rigid mounting of the camera housings to the frame and a rigid connection between the cameras and the view ports generally ensures the stability of the relative orientation of the cameras (Shortis *et al.*, 2000).

Based on the relative orientation, the system is then validated in the pool environment by introducing a known length that is measured manually by an operator. Thirty to fifty measurements of the length are made at a variety of distances and orientations within the field of view and expected working range of the system (see figure 3), in order to realistically replicate the measurements likely to be taken with the towed body stereo-camera system during a typical deployment. The RMS error of these validation measurements is typically less than 1 mm over a length of 1 m, equivalent to a length accuracy of 0.1%, and the errors show no significant trends within the working volume that would otherwise warrant systematic compensation.

This is a best case scenario in conditions of excellent water clarity and high contrast targets. Experience with shallow water measurement of fish silhouettes in more realistic conditions, together with validated measurements of live fish in the field, indicate that length measurements will have a field accuracy of 0.2% to 0.7% (Harvey *et al.*, 2002a, 2002b, 2003, 2004).

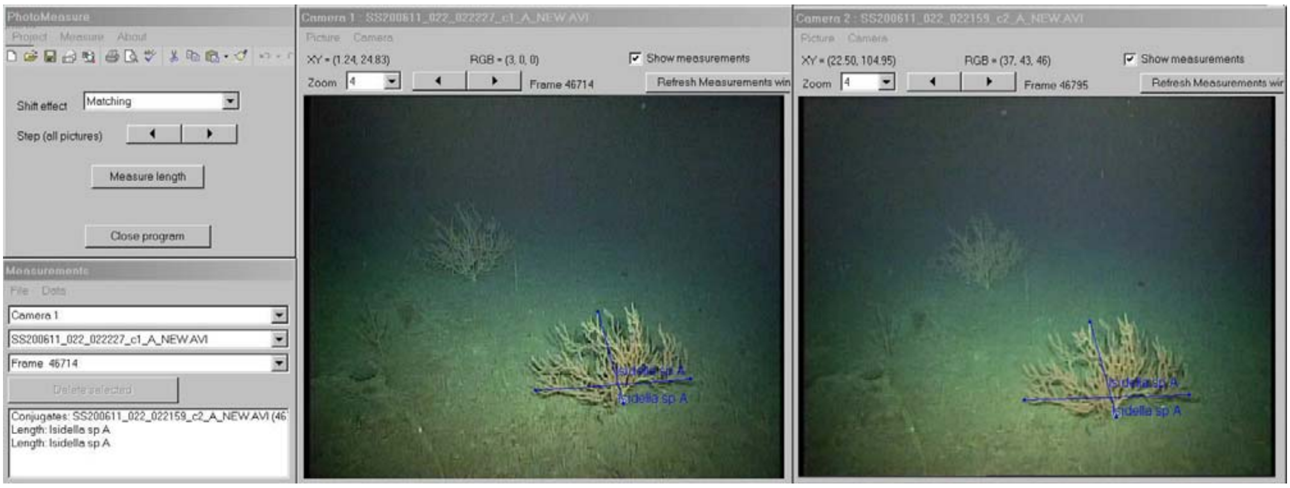
Deep Water Operations

For deep-water operations there may be measurement inaccuracies resulting from the application of a camera calibration carried out in shallow water to imagery gathered at much greater depths. Stereo-camera calibrations are generally carried out at depths of 1-3 m for operational convenience, however the stereo-cameras can subsequently be deployed to depths of up to 2,000 m. Under these conditions of considerably increased water pressure and decreased temperature it is expected the camera housings and view ports will deform, and the deformation may adversely affect camera calibration and subsequent stereo measurement.

Initial testing for the effects of depth have clearly indicated that there is an impact on the calibration of the stereo-camera system. The first experiment used continuous calibration based on a laser array system (Shortis *et al.*, 2007). Measurements to a depth of 500 m has confirmed the presence of significant systematic errors in the calibration, however the test did not include an independent scale determination. A second experiment was based on a scale bar attached to the towed body so that it appeared in the edge of the field of view of the cameras. A range of distances on the scale bar were measured at every 100 m of depth whilst the system descended to 1120 m and returned to the surface over a period of 110 minutes. Variations of up to 8 mm over a length of 1.2 m, corresponding to an error of 0.8%, were recorded. Current research is analysing the effects of pressure and temperature on the camera housing so that these effects will be fully understood and appropriate modifications to the housings can be implemented.

Measurements from Video Sequences

Stereo-video images enable accurate 3D measurements of point locations. Distances, areas and volumes can be derived from these measurements and used to characterise marine fauna (see figure 4) and seafloor habitat features such as boulders, crevices and ledges. These fine spatial scale metrics complement information typically gathered at coarser scales by techniques such as acoustic mapping (see figure 1). Similar stereo-video techniques were originally developed for measuring the lengths of fish to estimate population size structure (Harvey and Shortis, 1996) and are based on operator-identified points of interest in the stereo-images.



Shift effect: Matching

Step (all pictures)

Camera 1

SS200611_022_022227_c1_A_NEW.AVI

Frame 46714

Conjugates: SS200611_022_022159_c2_A_NEW.AVI (46
Length: Isidella sp A
Length: Isidella sp A

Camera 1 : SS200611_022_022227_c1_A_NEW.AVI

XY = (1.24, 24.83) RGB = (3, 0, 0) ☑ Show measurements

Zoom 4 Frame 46714

Camera 2 : SS200611_022_022159_c2_A_NEW.AVI

XY = (22.50, 104.95) RGB = (37, 43, 46) ☑ Show measurements

Zoom 4 Frame 46795

Figure 4. Example of an operator measurement of the height of a deep-water coral.

Because manual measurement and analysis of large volumes of video sequences is time consuming, labour intensive and therefore costly, there is considerable potential benefit in automating measurement processes. For example, CSIRO researchers collect 100+ hours of video recordings annually during biodiversity and fishery habitat surveys. Currently, the automation techniques employ motion analysis, image segmentation against the background, and colour matching to identify the presence and percentage cover of benthic fauna, and differentiate habitat types in video sequences (see figure 5). Initial results show promise for rapidly quantifying the cover of complex structures such as the reefs formed by stony corals (see figure 8), but tuning and validation against manual scoring techniques remains a work in progress (Williams *et al.*, 2008). Stereo-measurement can then provide the sizes of individual animals or seabed features within selected image pairs to estimate population characteristics.

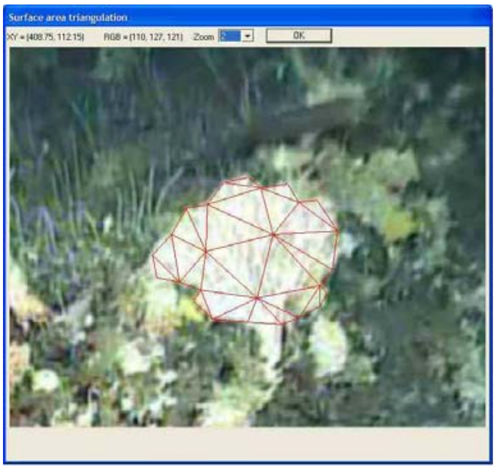
Figure 5. Example of candidate regions detected from motion analysis (stony coral at approximately 1,000 m depth). The 'footprint' area of analysis can be specified and is shown here as a grey trapezoid.

The motion analysis techniques were initially developed to identify candidates for counting and sizing fish in aquaculture (Harvey *et al.*, 2004). Motion analysis is first used to identify sections of the image sequences that contain features of interest, effectively eliminating portions of the video that are devoid of features and not of direct interest to habitat mapping. This processing is effectively an image compression technique that dramatically reduces the amount of video sequences requiring inspection, and reduces digital video file sizes. The motion analysis is then used to estimate the percentage cover of selected regions within the video transects. The motion detector can be tuned to detect featureless versus feature-rich regions, or specific marine fauna or flora.

The fundamental algorithm of the motion detector uses differences in intensity between consecutive frames. The most common approach recognises differences in colours based on thresholds and gains (Cheng *et al.*, 2001; Ohta *et al.*, 1980). A pixel is detected as a change if the difference between consecutive frames, multiplied by the gain, exceeds the threshold. Gains are used to amplify subtle differences and detect changes that would otherwise be below the threshold. Specific locations in the colour space of the images are used to identify the objects of interest. An operator will select these depending on the feature or species to be detected. The detected candidate regions are discriminated from noise using a region size range specified by the operator.

Region growing is subsequently used to either complete the outlines of candidate features detected with motion analysis, or can be used to grow the outline of a feature manually selected by an operator (Adams and Bischof, 1994). The region growing algorithm can be configured to use colour, colour statistics and texture, which are the most readily identified visible signatures of benthic communities and sessile organisms.

It is also possible to use stereo-image matching to determine volumes and surface areas of complex structures such as animals or physical features. This process is semi-automatic with the region of interest in one of the images defined initially by motion analysis processing. Operator selection of key points followed by epipolar searching and image matching (Gruen and Baltsavias, 1988) is then used to provide additional 3D locations within the boundary on the left and right images. The 3D data points are used to define the surface based on a Delaunay triangulation, from which surface area and volume can be derived (see figure 6). An accumulation of such measurements can be used as an estimator of biomass of a particular features or species of interest within a transect. A critical factor in the effectiveness and robustness of the algorithms will be the improvement of image quality and resolution to be provided by the digital progressive scan cameras and direct-to-disk system. As can be seen from figures 7 and 8, the image quality from the standard video system and the general reduction in image contrast caused by attenuation through the multiple refractive interfaces and water medium is a limiting factor.



XY = (408.75, 112.15) RGB = (110, 127, 121) Zoom 2

Figure 6. Example of a 3D measurement of surface area using a triangulation mesh.

Applications

The vast majority of deep seabed is not mapped in detail and remains unseen, although acoustic multi-beam technology and photographic methods are increasingly providing data for key areas (Kloser *et al*. 2007). A primary contribution of video data to multi-scale surveys of the seabed is the definition of habitat. Video transects add fine scale detail to areas mapped and differentiated by multi-beam acoustics at coarser scales, typically grids of 20-30 m^2 in deep water. Video transects can be used to target contrasts in acoustic maps to validate changes between habitats (see figure 7). Information on the biological associations with physical components of habitats enable mapped acoustic data, which has large coverage and is relatively inexpensive to collect, to be used as a proxy for the distribution of biodiversity (Kloser *et al.,* 2007). Based on analysis of the video sequences, abundance measures such as density or cover can be made at a variety of scales of taxonomic resolution (species to community types), and can be related to habitat types at a variety of spatial scales (Williams *et al.*, 2007). A key step in the use of image data for these purposes is to move from qualitative to quantitative applications.

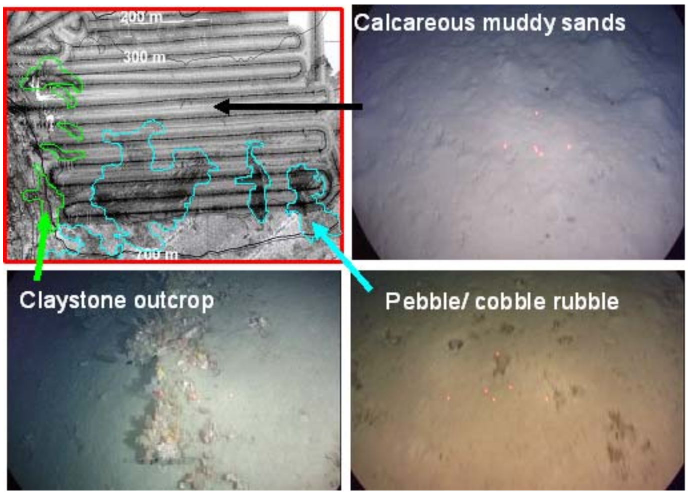


Figure 7. Fine scale habitat identification by video within terrains defined by multi-beam acoustics.

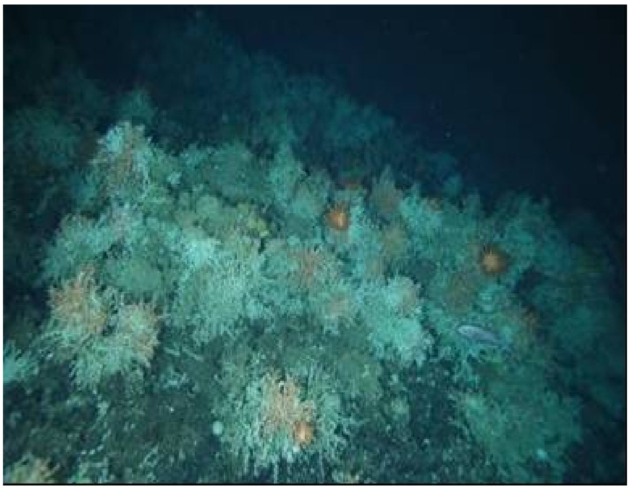


Figure 8. Fragile stony coral and rich biodiversity on a seamount at 1,100 m depth.

The non-extractive nature of video sampling gives it a significant advantage over conventional physical sampling with an epibenthic sled or trawl, particularly for monitoring. While biodiversity mapping relies on initial physical collection to provide an inventory of fauna, sensitive environments such as seamount coral communities (figure 8) benefit greatly from subsequent monitoring that is non-extractive, especially in conservation areas. Video surveys will never replicate the species-level resolution possible from collections of benthic fauna, but it is often possible to capture data for distinctive species. Description of fauna at the resolution of community types is sufficient for many purposes such as identifying relationships with acoustic data, or detecting gross impacts. In addition, video measurement is very effective for species where area measures are most relevant, for example encrusting species or aggregated communities. Where species have strong habitat associations and habitats have high spatial heterogeneity at scales of tens to hundreds of metres, video sampling will also provide more robust measures of abundance because the data are continuous and do not integrate across habitats. In contrast, samples from mobile collecting devices such as sleds or trawls do integrate across habitats, mixing the fauna and adding considerable uncertainty to abundance estimates (Kloser *et al.*, 2007). A combined measure of the heights of many individual animals and the plan area of their distributions provide measures of habitat heterogeneity, habitat value for other structural habitat-associated fauna such as fishes, and importantly for changes over time. Size-related metrics provide the basis for tracking the slope and intercepts of size spectra which have been identified as a reliable indicator for the health of fish populations (Rice, 2000).

'Exploratory' photographic surveys frequently provide valuable knowledge about the existence of rare fauna or unknown habitat associations, but quantifying these attributes of benthic biodiversity is enabled by stereo-video. For example, a survey in 1994 identified aggregations of a stalked crinoid at 200 m depth in a single submarine canyon off SE Australia (see figure 9). Crinoids have been in the fossil record of the Earth for millions of years but are now relatively rare; this is the only known aggregation in temperate Australian waters. Recording its presence was of value to conservation planning, but estimating its density and abundance using stereo-video will permit the persistence of this remnant population to be monitored into the future.

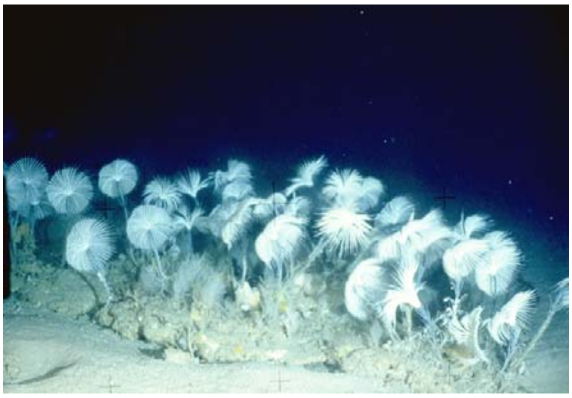


Figure 9. The rare stalked crinoid *Metacrinus cyaneus* at 200 m water depth

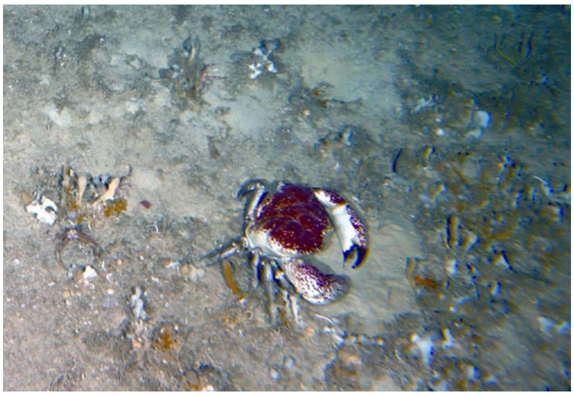


Figure 10. A giant crab *Pseudocarcinus gigas* amongst sponges and bryozoans at 340 m

In Australia, image data have been used to underpin risk assessment approaches for regulating different activities within specific sub-areas of Marine Protected Areas ('zoning') and for evaluating the effects of fishing on benthic habitat. A qualitative model, Fishery Risk Assessment (DEH, 2005), was used as the basis for zoning within the recently announced South-east

Commonwealth Marine Reserve network. This is the first temperate deep sea network of marine reserves in the world (DEWR, 2007). The potential impacts from a range of different fishing gears was assessed by an expert panel of scientists and commercial fishers using catalogues of benthic habitat images (Williams *et al.*, 2005). A semi-quantitative fishery risk assessment model developed by CSIRO (Hobday *et al.*, 2006) was used by the Australian Fisheries Management Authority to assess the risk from fishing on species, habitats and communities in all Commonwealth fishery areas. Both MPA and fishery risk assessment methods for habitat relied heavily on the data produced by the towed body system described here.

While qualitative image data may be used to estimate the vulnerability of habitat types, and to record the presence or absence of direct impacts, it will frequently be necessary to have quantitative data to determine the source and seriousness of impacts. Whether impacts have natural or anthropogenic causes will determine if mitigation is possible, and quantifying their extent can help show whether there is a risk to ecosystem structure and function, and therefore if management intervention is required. For example, quantitative photographic mapping of the distribution of the iconic giant crab off SE Australia revealed that a dominant component of the adult habitat is made up by low-relief, bryozoan-based ‘thickets’ (see figure 10). This habitat has a limited distribution on the outer continental shelf and upper continental slope (150 to 350 m depths) where bottom fish-trawling and giant crab trap fisheries overlap (Williams *et al.*, 2007). Measurement data are now being used to identify the sources of visible impacts on this habitat by measuring the dimensions of marks left by fishing gears, and quantifying the extent of habitat degradation at local scales by estimating the occurrence or footprint of impacts, such as overturned boulders, per swept area of video transect (see figure 11).

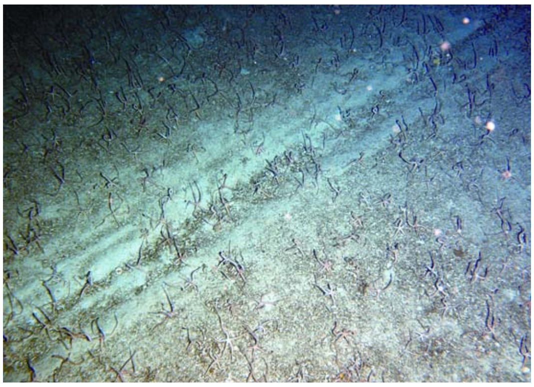


Figure 11. Image showing direct physical impact of fishing gears: degradation of low-relief benthic communities at 132 m depth.

Conclusions

This paper describes the development and incorporation of stereo-video to a towed body system and illustrates some of its applications to mapping and understanding sea bed habitat in deep water. The system provides the ability to acquire quantitative data, such as abundance, size and area measurements, from stereo-video with known estimates of accuracy and precision. It has important applications for conservation and fishery management, particularly by providing fine-scale, continuous, non-integrated, non-extractive data on animal and habitat distributions. On-going enhancements of the system, namely progressive-scan high resolution video imagery and deep water self-calibration, will substantially improve the accuracy, resolution and utility of the system in the future. Ultimately the research will lead to automation of the process of accurately identifying and estimating the percentage coverage of benthic features and biomass of the sample of sessile organisms.

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