STEREO-VIDEO SURVEYS OF DEEP WATER HABITATS

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ABSTRACT:

Towed body systems of various configurations have been used for many years to map the seabed. Until recently, 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 use of stereo-video and the calibration of the system. Applications of the system to managing marine biological resources are illustrated using examples from surveys undertaken recently off south east Australia.

1. INTRODUCTION

Global attention on marine benthic biodiversity conservation has rapidly increased over the last few decades, primarily due to the depletion of fish stocks and degradation of the environment. The response to a widespread concern for effective conservation has resulted in the implementation of Marine Protected Areas (MPAs), which has consequently generated the need for multi-scale maps of seabed habitat (Williams *et al.*, 2005). 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).

Australia is developing a national network of MPAs in offshore waters where virtually all 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). Further, a large proportion of total fisheries catches in Australia are taken below SCUBA depths, leading to a requirement for remote data capture to survey and monitor deep water regions.

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

As a consequence, deep benthic[1] habitats are being mapped to support the development of an integrated and ecosystem-based approach to plan (Kloser *et al*., 2007) and manage human activities. Information from surveys is being integrated to produce habitat maps at various scales of resolution so that the multi-scale structure of benthic habitats (figure 1) can be understood and natural regions can be identified as planning units.

Research information on deep seabed habitats has to be gathered remotely and information is required from many locations, consequently towed camera systems are an integral part of the mapping capability. Towed systems are able to take data along many kilometres of transects, and traverse rough and steep seabed topography. A key role for geo-referenced video sequences is to provide fine-scale detail that complements coarser scale of mapping provided by hydro-acoustics (Kloser *et al.*, 2007). This integration of scales is needed to understand the broad scale issues across the fishery regions or management planning units as a whole.

This paper describes a towed body system developed in Australia for these purposes, and focusses on the incorporation of stereo-cameras that enable quantitative data to be taken from imagery. Applications of the data for managing marine biological resources are illustrated with a range of examples.

2. TOWED BODY SYSTEM

The primary survey tool is a towed camera platform that records continuous, medium resolution stereo-video sequences and intermittent high-resolution digital still images along transects. 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. Two PAL video cameras, configured as a stereo-pair, transmit live video sequences that are recorded on time-coded DV tape. 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 imagery can be accurately geo-located. Geo-

[1] Living on the surface of bottom sediments in a water body.

location of sampling on the seabed is critical to relate the sampled area to environmental co-variates extracted from hydro-acoustic and other sensors. Calibration and data processing requirements for the various sensors is described in Williams *et al.* (2007) and Kloser *et al.* (2007).

A separate forward-looking camera provides an additional view for navigation and obstacle avoidance. Additional sensors record altitude, pressure, pitch, roll, water temperature, conductivity and fluorescence. 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. Two 250 watt incandescent lights provide illumination for the video cameras. Strobes provide illumination for the digital still imagery.

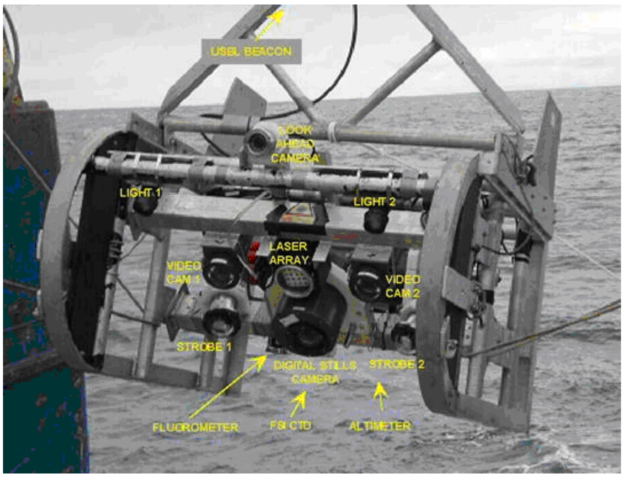

Figure 2. CSIRO towed body platform

The towed 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 cameras view the sea floor obliquely from 1-3 metres above the seabed. 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.

The resolution of the video images is a limitation, so high resolution digital still images enable qualitative analysis at a greater level of detail. The digital still camera 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 pair of digital still cameras, although stereo digital stills have been used very successfully for some under-water applications of 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.

3. STEREO-CAMERA CALIBRATION

3.1 Shallow Water 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. 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.

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 standard requirements of a multi-station self-calibrating photogrammetric network are required, such as multiple convergent photographs, camera roll at each location and a 3D array of high contrast targets. 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) to replicate the convergent multi-station network (Harvey and Shortis, 1996).

The positions of the targets in the images are measured semi-automatically based on the centroid location of each target in each image. It is immaterial if the frame distorts or is dis-assembled between calibrations, although the frame must retain its structural integrity during a calibration sequence. The results of the photogrammetric network computation for the self-calibration include the locations and orientations of the synchronised pairs of images, the calibrations of the cameras and revised coordinates of the target positions on the frame. The overall dimensional scale of the photogrammetric network of images and targets is determined by distance constraints between targets on the rigid arms of the frame.

RMS image residuals range from 1/20 to 1/30 of a pixel for an in-air self-calibration network based on centroid measurements, 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 precision of the centroids.

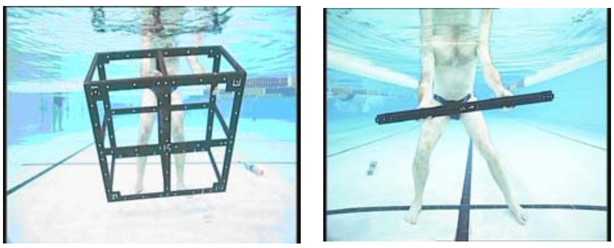
Figure 3. Typical images for shallow water calibration (left) and length validation using a known length (right). The LED is used for synchronisation checks.

An independent check on accuracy is provided by the length measurements on the rigid arms of the frame. The RMS error of the distances indicates the base line integrity of length measurements made with the stereo-video system. Based on centroid measurements, the RMS value is typically 0.05 mm, signifying a high level of accuracy demonstrated by the self-calibration measurements.

The relative orientation of the cameras is derived from post-processing of the locations and orientations of all synchronised stereo-pairs in the photogrammetric network. 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). Experience has demonstrated that a weakness of the implicit 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.

For subsequent measurements in the field, the photogrammetric network provides the required calibrations and the relative orientation of the stereo-cameras. The system is then validated in the pool environment by introducing a known length which is measured manually at a variety of distances and orientations within the field of view and expected working range of the system (see figure 3). 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%. 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.*, 2002, 2003, 2004).

3.2 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.

4. 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 (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 figures 1 and 7). 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.

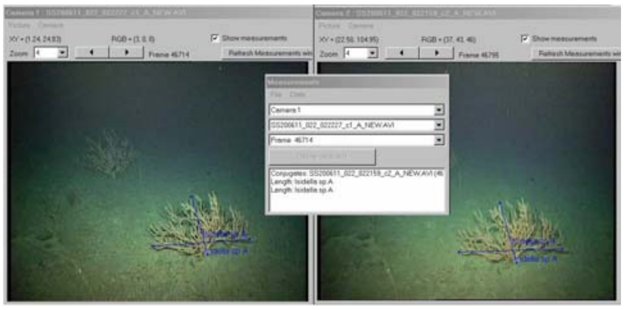

Figure 4. Example of an operator measurement of the height of a deep-water coral.

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 (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 identification techniques remains a work in progress (Williams *et al.*, 2008). Stereo-measurement can then provide the sizes of individual animals or substratum features within selected image pairs to estimate population characteristics.

Figure 5. Candidate region of stony coral detected within an interest window (grey trapezoid) from motion analysis.

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.

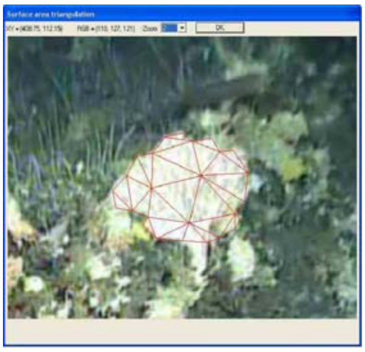

Figure 6. Example of a 3D measurement of surface area using a triangulation mesh.

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.

5. APPLICATIONS

The vast majority of deep seabed is not mapped in detail, 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 at fine scales. 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 biological resolution, 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 in deep water habitat mapping is the move from qualitative to quantitative applications.

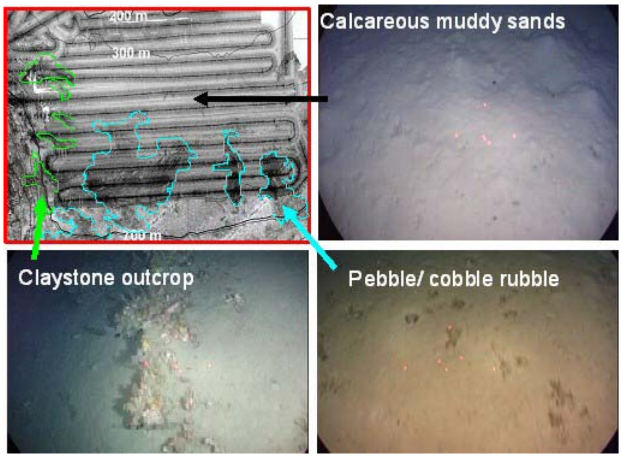

Figure 7. Fine scale habitat identification by video within terrains defined by multi-beam acoustics.

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.

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 size distributions which have been identified as a reliable indicator for the health of fish populations (Rice, 2000).

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

Video surveys frequently provide valuable knowledge about the existence of rare fauna or unknown habitat associations. For example, a survey in 1994 identified aggregations of a stalked crinoid at 200 m depth in a single submarine canyon off SE Australia (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 the presence of crinoids 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.

In Australia, information from still and video images has been used to underpin risk assessment for regulating different activities within specific sub-areas of Marine Protected Areas and for evaluating the effects of fishing on benthic habitat. Figure 10 depicts the first temperate deep sea network of marine reserves in the world, the South-east Commonwealth Marine Reserve network (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) which 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.

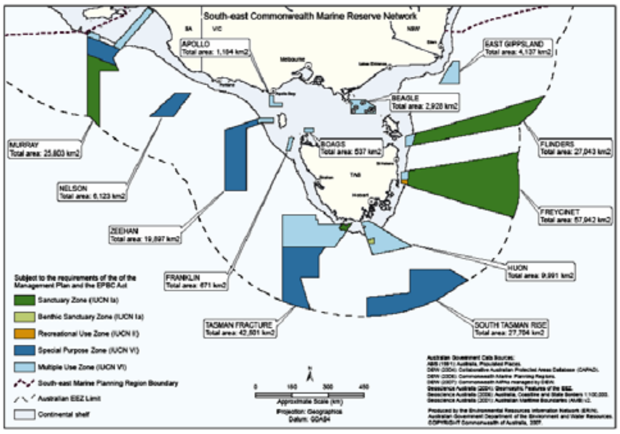

Figure 10. South-east Commonwealth Marine Reserves (DEWR, 2007).

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’ (figure 11). 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).

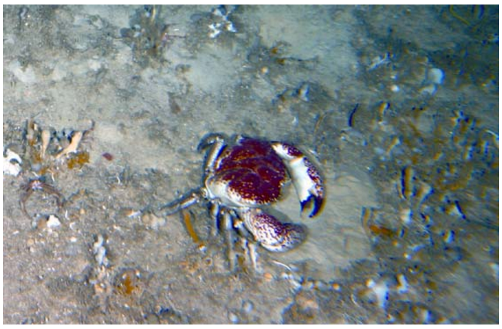

Figure 11. A giant crab *Pseudocarcinus gigas* amongst sponges and bryozoans at 340 m.

Video sequences are now being used to identify and measure the sources of visible impacts on this habitat, for example marks left by fishing gears (figure 12), and the extent of habitat degradation, such as overturned boulders, per swept area of video transect.

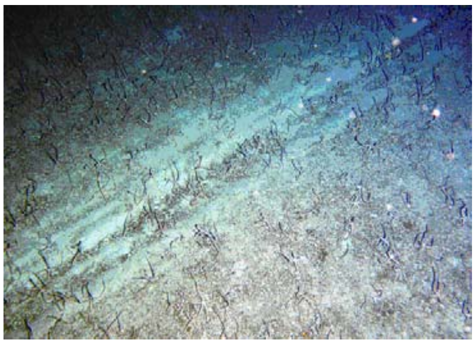

Figure 12. Direct impact of fishing gears: degradation of low-relief benthic communities at 132 m depth.

6. CONCLUSIONS

This paper describes the use of stereo-video on 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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