Title
Visualising multi-hectare seafloor habitats with BioCam

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Article
Range or resolution? We often get asked this question when mapping the seafloor. And it is important because the data we choose to collect fundamentally changes the science that can follow. Photos taken by camera equipped autonomous underwater vehicles (AUVs) represent one extreme of the range resolution trade-off. The sub-centimetre resolution colour information in strobe illuminated images can reveal detailed information about the seafloor. But taking images like these typically requires hover-capable AUVs to operate at altitudes of 2 to 3 metres above the terrain, which limits the area visible in each image frame to edge lengths of a couple of metres, and also limits the speed AUVs operate at to avoid collision with rugged terrains. Visual surveys like these normally cover a few 1,000 m^2/h, several orders of magnitude less than AUV acoustic surveys that achieve resolutions of tens of centimetres to metres. The desire to visually map larger areas has driven the development of high altitude (6-10 m) imaging technology. Taking images from higher altitudes increases the area mapped during visual surveys in two ways. First, a larger footprint can be observed in each image, and second, the lower risk of collision when operating at higher altitudes allows flight-style AUVs to be used (e.g. Autosub6000 shown in Figure 1), where these are faster and more energy efficient than the hover-capable vehicles typically used for visual surveys. Combined, these factors allow for an order of magnitude increase in the area covered, allowing several tens to more than a hundred hectares of the seafloor to be mapped in a single AUV deployment.

BioCam is a high-altitude 3D imaging system that uses a stereo-pair of high-dynamic range scientific complementary metal-oxide semiconductor (sCMOS) cameras, each with 2,560 x 2,160 pixel resolution that are mounted in a 4,000 m rated titanium housing. The housing has domed windows to minimise image distortion, and also includes low-power electronics for communication, data storage and control of the dual LED strobes and dual line lasers BioCam uses to acquire 3D imagery. The LED strobes each emit 200,000 lumens of warm hue white light for 4 ms. The lasers each project a green line (525 nm, 1 W Class 4) onto the seafloor at right angles to the AUV's direction of travel to measure the shape of the terrain. The optical components are arranged along the bottom of the AUV, with an LED and laser each mounted fore and aft of the cameras as shown in Figure 2. A large distance between these illumination sources and the cameras ensures high-quality images and high-resolution bathymetry data can be gathered from target altitudes of 6 to 10 m.

The large dynamic range of the sCMOS cameras is necessary for high-altitude imaging because red light attenuates much more strongly than green and blue light in water, as seen from the appearance of the raw images in Figure 3. A large dynamic range allows the low intensity of red light to be detected with sufficient bit resolution to restore its colour information, whilst simultaneously detecting the much more intense light of the other colour channels without them saturating. The dense range information gathered using the dual lasers allows the distance light travels from the strobes to each detected pixel to be calculated for accurate colour rectification (see Figure 3). The rectified colour is projected onto the laser point cloud, and this information is fused with AUV navigation data to generate texture mapped 3D visual reconstructions [1]. The BioCam processing pipeline calibrates the dual laser setup using in situ measurement data so that quantitative length, area and volumetric measurements can be made together with estimates of dimensional uncertainty without the need to observe any artificial calibration targets in the field [2].

Although 3D reconstructions are useful for studying detailed information about the seafloor, exploring them is both time consuming and subjective. To help plan more effective data acquisition during research expeditions, it is valuable to be able to rapidly understand large georeferenced image datasets in expedition relevant timeframes. For this, we have developed location-guided unsupervised learning methods [3] that can automatically learn the features that best describe images in a georeferenced dataset without needing any human input for interpretation. These features are used to cluster images into groups with similar appearances, identifying the most representative images in each cluster, and also allowing scientists to flexibly query datasets by ranking all images in order of their similarity to any input image. Both the clustering and query returns can be visualised using georeference information to identify spatial patterns in the datasets.

Figure 4 shows an example of a 3D visual reconstruction together with the full-field dimensional uncertainty estimates of data collected during a survey of the Darwin Mounds marine protected area (MPA) located at 59° 54' N, 7° 39' W, 160 km north-west of Cape Wrath, Scotland at a depth of approximately 1000 m. BioCam was mounted with a laser to camera baseline of 1.6 m on the flight-style Autosub6000 AUV, which operated at 6 m altitude and 1 m/s forward speed to cover 30,000 m^2/h. The setup achieved a resolution of 3.3 mm across track and 2 mm in depth. The close up in the figure shows individual colonies of cold-water-coral (consisting mainly of *Desmophyllum pertusum* and *Madrepora oculata*) forming a ring around the base of a micro-mound that measures approximately 5 m across and 20 cm high. Figure 5 shows the results of clustering, representative image identification and content-based query carried out on-board the ship during the Darwin Mounds cruise. The cluster and query results show that cold-water-coral colonies are most densely distributed around the bases of mounds, several of which are significantly larger (up to 75 m wide and 5 m high) than the micro-mound in Figure 4, forming ring patterns more broadly throughout the 30 ha region mapped during the dive. The clustering results also show that xenophyophores, a large single cell organism recognised as a vulnerable marine ecosystem indicator species at the Darwin Mounds, are most densely distributed in the tails of the mounds. The ability to recognise biological zonation associated with mounds, in particular micro-mounds that are difficult to observe in lower resolution acoustic data, described here illustrates how the combination of sub-centimetre resolution 3D visual mapping and the methods developed to summarise observations and flexibly answer queries can generate rapid human insight and so help focus efforts in observation and downstream analysis.

References

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[3] Takaki Yamada, Adam Prügel-Bennett, Blair Thornton, Learning features from georeferenced seafloor imagery with location guided autoencoders, Journal of Field Robotics 38 (2021) 52–67, DOI: 10.1002/rob.21961

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Figure 1: BioCam and Autosub6000 being recovered off the coast of Scotland after a photographic survey mission during the DY108/109 cruise of the Royal Research Ship Discovery.

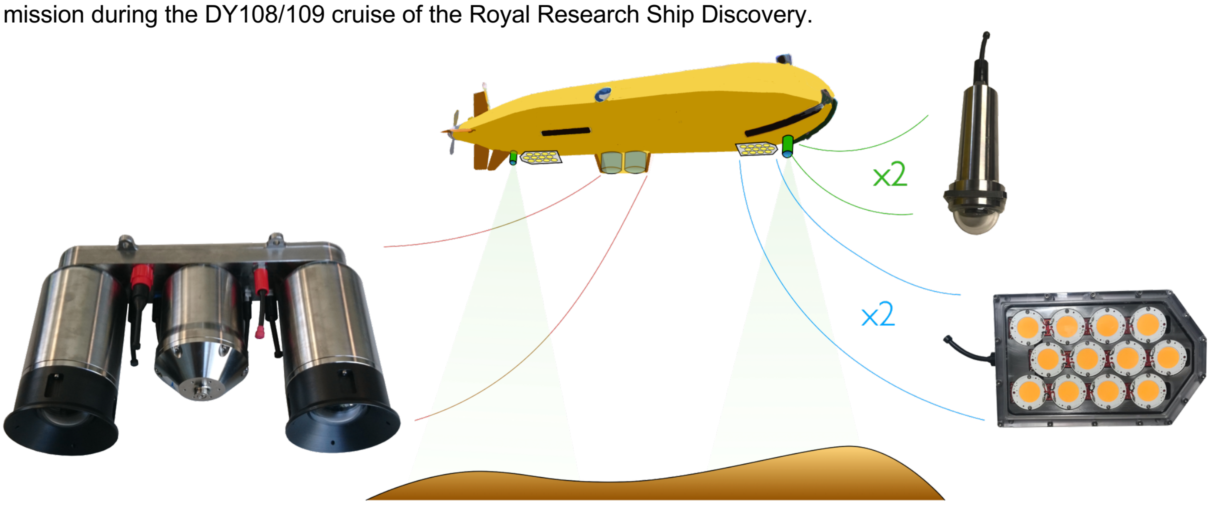

Figure 2: BioCam consists of a central unit with a stereo-pair of cameras and control electronics, fore and aft dual LED strobes and line lasers that are used to generate 3D colour reconstructions of the seafloor.

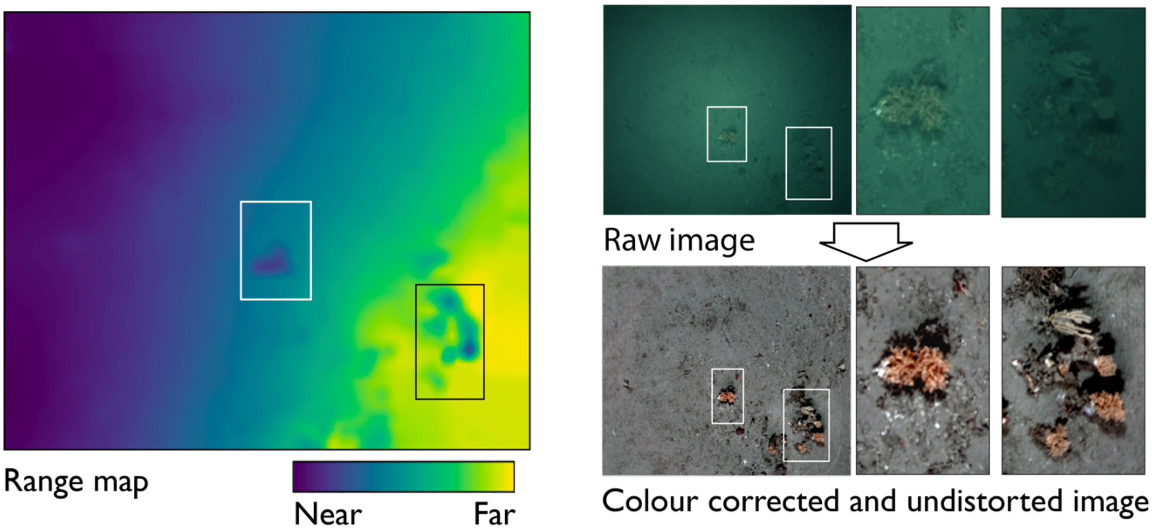

Figure 3: Laser derived 3D range information is used to rectify the colour information in the images. Physics-based image formation models use the range maps to compensate for the wavelength dependent attenuation of light in water. This allows the darkening effects and the blue-green hue seen in the raw images to be rectified even over rugged terrains.

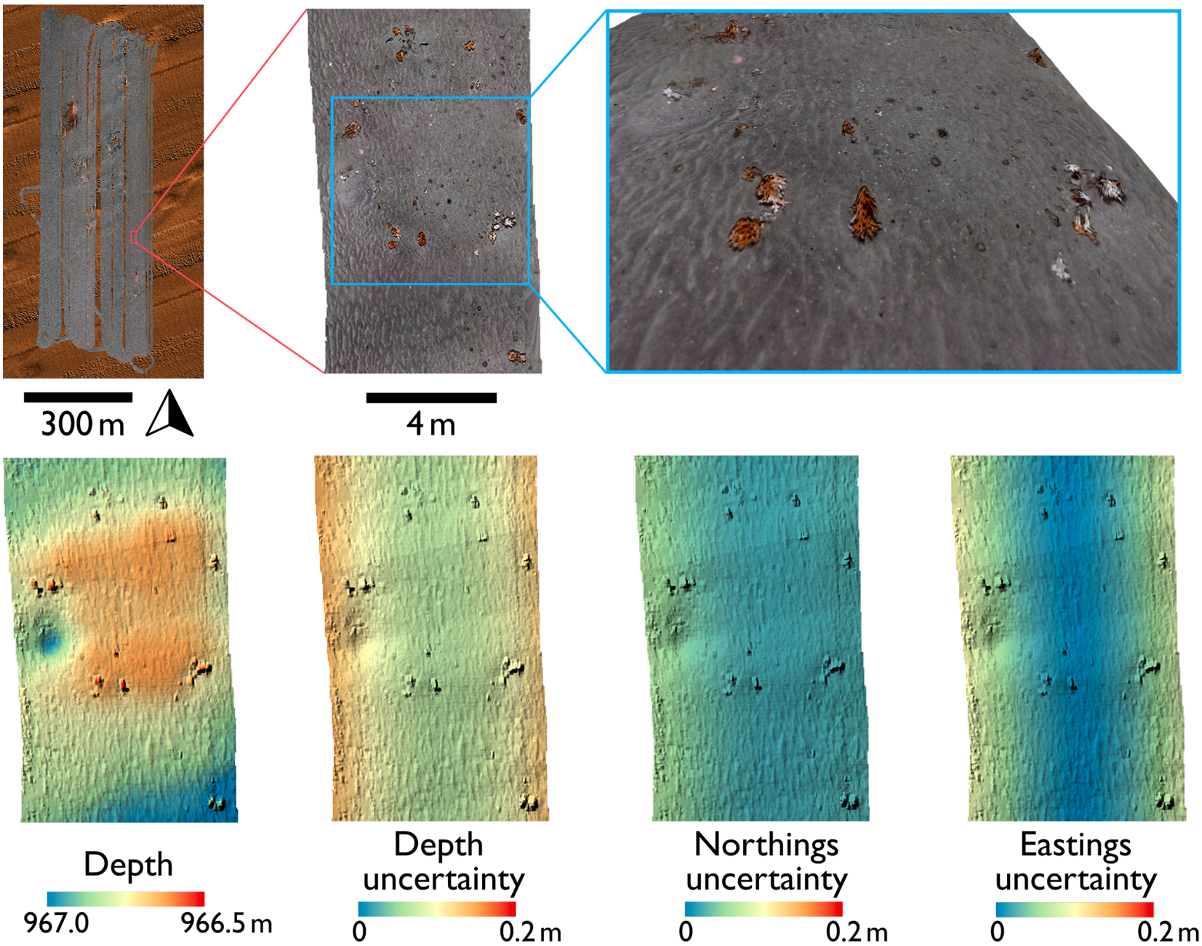

Figure 4: 3D visual mapping data gathered at the Darwin Mounds MPA. The top left panel shows a 30 ha area mapped using BioCam mounted on the Autosub6000 AUV, which has been overlaid on side-scan sonar data. The expanded detail (indicated by red lines) shows a small micro-mound with corresponding laser bathymetric measurements and the full-field dimensional uncertainties shown along the bottom row. The micro-mound has a diameter of approximately 5 m and is 20 cm high. The smaller, individual

protrusions that form a ring around the mound are cold-water-coral colonies consisting mainly of *Desmophyllum pertusum* and *Madrepora oculate*. These can be seen more clearly in the expanded isometric view indicated by blue lines. The individual colonies have diameters of between 20 to 50 cm and are between 10 and 30 cm high in the area shown.

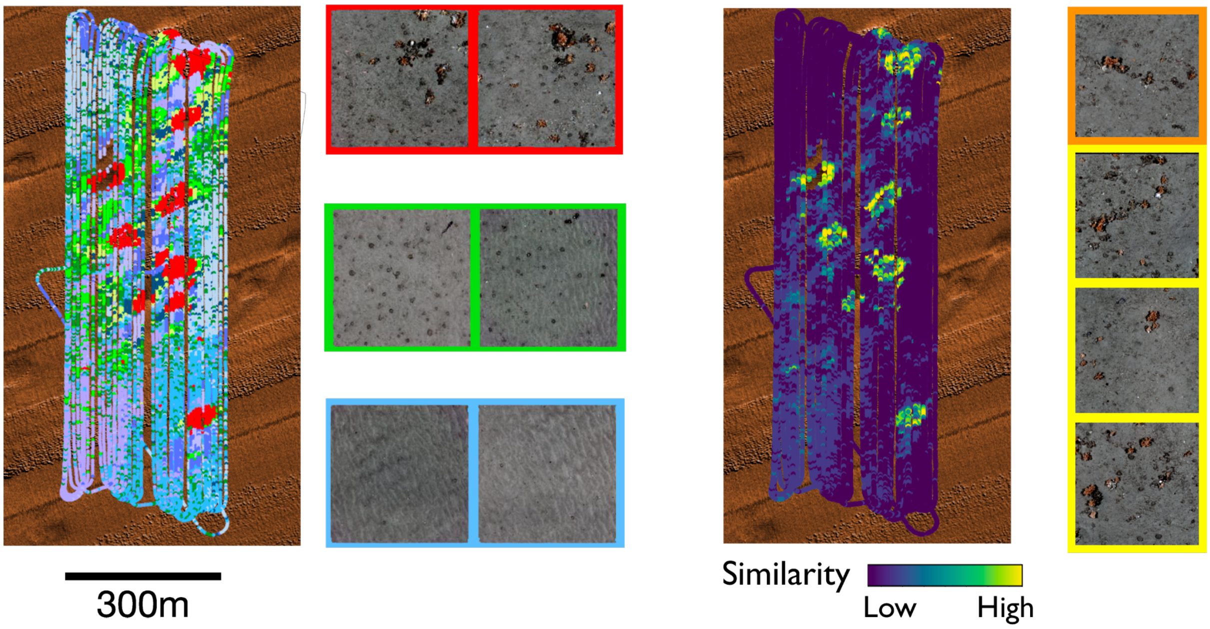

Figure 5: Unsupervised clustering outputs and examples of automatically identified cluster representative images on the left show the distribution of cold-water-coral and coral rubble (red), xenophyophores (green) and rippled sand (blue) in the region. The light green, green and dark green clusters on the left map show dense distributions of xenophyophores in the tails of the mounds, where the mounds themselves are characterised by the presence of coral and coral rubble (red). The content-based query ranks images in order of their similarity to an input image, where the example on the right is for a query image showing branched corals (indicated by an orange outline) with some examples of returned images (yellow). The distribution of similar images form a ring around the base of the mounds in this region.