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Surveying Noctural Cuttlefish Camouflage Behaviour using an AUV

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Abstract— **This paper describes a recent study in which an Autonomous Underwater Vehicle (AUV) with a high resolution stereo-imaging system was used to document nocturnal camouflage behaviour in cuttlefish at a well known spawning site in Whyalla, South Australia. The AUV's ability to fly at low altitude during day and night while closely following a desired survey pattern provided improved data collection compared to divers and previous work with a small ROV. Over the course of the week long expedition, the AUV Sirius was deployed on 38 dives at three sites in the survey area and collected tens of thousands of stereo images. Of these, nearly a thousand were seen to contain cuttlefish during post cruise analysis, with a large proportion showing evidence of camouflage. The distribution of images containing cuttlefish suggest that the animal concentrations were substantially higher closer in to shore in shallow waters, where the flat rocky substrate occurs; females lay their eggs on the underside of these rocks. Results demonstrate the strengths of using an AUV for surveying near-shore benthic habitats of ecological interest, with a particular emphasis on the ability to operate during both day and night time operations.**

I. INTRODUCTION

Animal camouflage is widespread throughout nature, yet curiously it is poorly studied and has rarely been quantified. Cephalopods (squid, octopus, cuttlefish) have the most diverse and quick-changing camouflage known. In recent work, it has been suggested that there are only 3-4 basic camouflage pattern types in cephalopods, and possibly in all animals [Hanlon, 2007]. Recent laboratory experiments by the Marshall and Hanlon labs demonstrated that cuttlefish are color blind [Marshall and Messenger, 1996], [Mäthger et al., 2006], yet their camouflaged body patterns seem to be well color-matched to a wide array of natural backgrounds. In 2006, a project began with the objective of accumulating an inventory of high-resolution digital photographs of camouflaged cuttlefish under natural lighting conditions (i.e. at different times of day and weather conditions, and with no flash). A small Remotely Operated Vehicle (ROV) featuring a low-resolution but high sensitivity camera obtained the first evidence of adaptive camouflage by cuttlefish at night [Hanlon et al., 2007]. Each animal's camouflage pattern appeared to be tailored to its immediate microhabitat, demonstrating that cuttlefish as well as predator vision is exceptional at night.

The ROV was equipped with a red filter to limit the possibility of disturbing the animals with a flash. This red filter worked effectively, as judged by the nonreactions of the cuttlefish. However, it limited the amount of light available to the system. Another drawback was that this particular Little Benthic Vehicle was not equipped with a high-resolution camera. Thus, the image quality was restrictive in terms of generating descriptions of body patterns or performing image analysis relative to background patterns.

Despite these limitations, the ROV proved to be a valuable tool that allowed more objective data acquisition under difficult night diving conditions. By flying the ROV about a meter over the bottom, images were obtained in which the cuttlefish filled approximately one fifth to one tenth of the frame, providing a good perspective for assessing camouflage. It was fairly practical to mark non-overlapping, 100 m transects with a global positioning system (GPS) on the surface vessel. Repeating the exact transect, however, would have been quite difficult with the GPS unit available on the small vessel used during the ROV trials. Night operations obscure visual landmarks near shore, currents are running in this area, and there is wave action, all of which influenced the ability to position transects with any degree of confidence.

This paper describes follow-on work in which an Autonomous Underwater Vehicle (AUV) with a high resolution stereo-imaging system was used to document nocturnal camouflage behaviour in cuttlefish at the same site in Whyalla, South Australia. The hope was that the AUV's superior imaging system and ability to designate particular track lines would provide improved data for analysing the camouflage behaviour of these animals at night.

Our aims were to survey a temperate rock reef and assess the cuttlefish pattern match against highly variable visual microhabitats, both during the day and at night. In addition to the stereo cameras, the AUV was equipped with a suite of navigation sensors. The imagery collected will be used to analyse cuttlefish colour and pattern using algorithms that emulate predator vision to identify how the patterns may appear to predators. During the day, we anticipated close - but not exact - color and contrast matches between

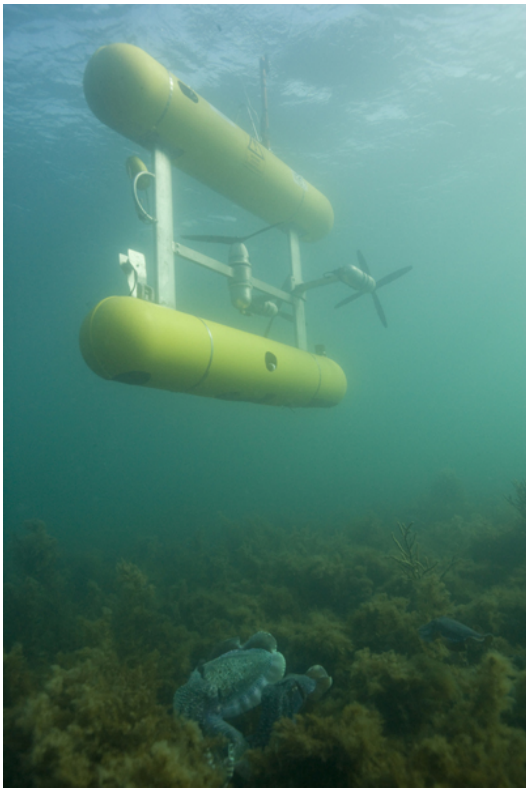

Fig. 1. The AUV *Sirius* surveying cuttlefish spawning grounds at Whyalla, South Australia.

pattern components of the animal and surrounds. At night, we anticipated less of a color match but more of a contrast match, since color vision is generally not used at night. This paper highlights some of the methods used, describes the scope of the study and presents preliminary outcomes of the analysis undertaken as part of the project.

The remainder of this paper is organized as follows. Section II describes the AUV and discusses its role in this study. Section III outlines the relevance of the study site while Section IV shows results of these activities, relating the AUV outcomes to the objectives of the project. Finally, Section V provides conclusions and an outline of on-going and future work.

II. AUV-based Benthic Habitat Mapping

One of the key features of the present cruise was the availability of a high resolution optical imaging AUV. This vehicle's primary role was in collecting large numbers of nighttime images of cuttlefish to assess their distribution and camouflage behaviour. The high spatial resolution and capacity to geo-reference the resulting imagery provides an invaluable mechanism for observing the extent and composition of particular benthic habitats. In this case, these data allow for post cruise analysis to show the position and relative abundance of cuttlefish seen during the dives.

AUVs are becoming significant contributors to modern oceanography, increasingly playing a role as a complement to traditional survey methods. Large, fast survey AUVs can provide high resolution acoustic multibeam and sub-bottom data by operating a few tens of meters off the bottom, even in deep water [Grasmueck et al., 2006] [Marthiniussen et al., 2004]. High resolution optical imaging requires the ability to operate very close to potentially rugged terrain. The Autonomous Benthic Explorer (ABE) has helped increase our understanding of spreading ridges, hydrothermal vents and plume dynamics [Yoerger et al., 2007] both using acoustics and vision. The Seabed AUV is primarily an optical imaging AUV, used in a diverse range of oceanographic cruises, including coral reef characterization [Singh et al., 2004a] and surveys of ground fish populations [Clarke et al., 2006]. Recently, the related AUVs Puma and Jaguar searched for hydrothermal vents under the artic ice [Oceanus, 2008], [Kunz et al., 2008]. Other AUV systems have been used to explore biophysical coupling, including mapping Harmful Algal Blooms [Robbins et al., 2006] and characterising upwelling around canyons [Ryan et al., 2005].

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 [Williams et al., 2008]. This platform is a modified version of a mid-size robotic vehicle *Seabed* built at the Woods Hole Oceanographic Institution [Singh et al., 2004b]. This class of AUV has been designed specifically for relatively low speed, high resolution imaging and is passively stable in pitch and roll. The submersible is equipped with a full suite of oceanographic sensors including a high resolution stereo camera pair and strobes, multibeam sonar, a depth sensor, Doppler Velocity Log (DVL) including a compass with integrated roll and pitch sensors, Ultra Short Baseline Acoustic Positioning System (USBL), forward looking obstacle avoidance sonar, a conductivity/temperature sensor and combination fluorometer/scattering sensor to measure chlorophyll-a and turbidity. The on-board computer logs sensor information and runs the vehicle's low-level control algorithms. *Sirius* is part of the NCRIS Integrated Marine Observing System (IMOS) AUV Facility, with funding available on a competitive basis to support its deployment as part of marine studies in Australia.

Navigation underwater is challenging because electromagnetic signals attenuate strongly with distance. Ubiquitous absolute position estimates such as those provided by GPS are therefore not readily available. Acoustic positioning based systems [Yoerger et al., 2007] can provide absolute positioning but typically at lower precision than that provided by the instruments on-board the AUV. Using a naive approach, the mismatch between navigation precision and sensor precision results in 'blurred' maps. A more sophisticated approach uses the environment to aid in the navigation process. Simultaneous Localisation and Mapping (SLAM) is the process of concurrently building a feature based map of the environment and using this map to obtain estimates of the location of the vehicle. The SLAM algorithm has seen a considerable amount of interest from the mobile robotics community as a tool to enable fully autonomous navigation [Dissanayake et al., 2001] [Durrant-whyte and Bailey, 2006]. Pioneering work in the deployment of the

SLAM algorithm in reef environments has been reported following trials with the ACFR's Unmanned Underwater Vehicle Oberon and the AUV *Sirius* operating on the Great Barrier Reef in Queensland, Australia [Williams and Mahon, 2004].

Our current work has concentrated on efficient, stereo based Simultaneous Localisation and Mapping and dense scene reconstruction suitable for creating detailed maps of seafloor survey sites. Methods for stereo-vision motion estimation and their application to SLAM in underwater environments have been proposed by Mahon [Mahon, 2008], [Mahon et al., 2008]. These novel approaches, based on the Visual Augmented Navigation (VAN) techniques proposed by Eustice [Eustice et al., 2006], enable the complexity of recovering the state estimate and covariance matrix in a VAN framework to be managed. This has allowed these algorithms to run on significantly larger mapping problems than was previously feasible. These techniques have been used to provide accurate navigation using the data collected for this paper.

A typical dive will yield several thousand geo-referenced overlapping stereo pairs. While useful in itself, 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 [Williams et al., 2008]. 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, even before any automated interpretation is attempted. Examples of the output of the 3D reconstructions for dives undertaken on this cruise are included in the Results section below.

III. Geographical relevance

An ideal study site is the well-known spawning aggregation of giant Australian cuttlefish, *Sepia apama*, in temperate waters of southern Australia as shown in Figure 2 [Hall and Hanlon, 2002]. Specifically, there is an 8-km stretch of rocky shore along which ca. 250,000 cuttlefish aggregate during austral fall; the nearest town is Whyalla, South Australia. This is an amazing spectacle not only for the intensive visual signaling by dense aggregations of large cuttlefish during the day but for the widespread camouflage used by animals not directly involved in sexual selection, and by all animals throughout the night [Hanlon et al., 2007]. Such an aggregation is unique in the world; moreover, this location is under consideration for designation as a marine park.

IV. Results

During the course of a week long expedition, the AUV *Sirius* was deployed on 38 dives, predominantly at night, capturing on the order of 38,000 stereo image pairs. The vehicle was programmed to maintain a height of between 1.5 m and 2 m above the ground (with the lower altitude missions yielding higer resolution of the subject animals). Given the proximity to the shore and the shallow operating conditions (many dives did not exceed 5 m in depth) the dives were kept short. The AUV covered in excess of 15 km over the course of the 6 nights of operation, with an average mission covering 569 linear metres and lasting on the order of 20 minutes. The AUV was piloted into the near shore study area and then conducted lawnmower style surveys parallel to the beach, moving out into slightly deeper waters away from shore during the course of each mission.

Fig. 2. The survey tracks showing the dive locations relative to the Whyalla peninsulla. The inset shows the location of the study site at the mouth of the Spencer Gulf near Whyalla in South Australia.

At night, previous studies have shown that the cuttlefish typically descend to the bottom and blend in with their surrounds [Hanlon et al., 2007]. Three particular sites were targeted during the deployments described here. Figure 3 shows details of the AUV dives, with the white lines showing the estimated vehicle path during each dive. The markers designate the position at which an image captured by the AUV was seen to contain cuttlefish during post cruise analysis by a human expert. Figure 4 illustrates the distribution of cuttlefish observed in the imagery as a function of depth of seafloor. The distribution of images containing cuttlefish suggest that the animal concentrations were substantially higher closer in to shore in shallow waters, where the flat rocky substrate occurs; females lay their eggs on the underside of these rocks. This supports anecdotal evidence provided by SCUBA divers working in the area. SCUBA diving activities were, however, predominantly restricted to daytime operations as night diving can be difficult to manage even in these relatively sheltered conditions.

Sample images showing cuttlefish during the day and night are shown in Figure 5. As can be seen, both day and night images show evidence of camouflage. Of 931 images showing cuttlefish during these dives, 771 were camouflaged. Since one aim of the study was to see if cuttlefish have color-

(a) Black Point

(b) Fenceline

(c) Stony Point

Fig. 3. The survey tracks showing the dive locations relative to the Whyalla peninsulla. Tracklines undertaken by the AUV are shown in white. Individual images containing cuttlefish were identified by a human expert during post cruise analysis and are marked with the circular symbol. As can be seen, the concentration of cuttlefish appear to increase as the AUV worked nearer to shore in shallower waters.

coordinated camouflage both night and day, we strived to get comparable numbers of camouflage images (even though we know that more animals are camouflaged at night, and more are signaling in the day during sexual selection behaviors). Of the 771 camouflaged images, 435 were day and 336 were night. Initial results suggest that color matching at night may

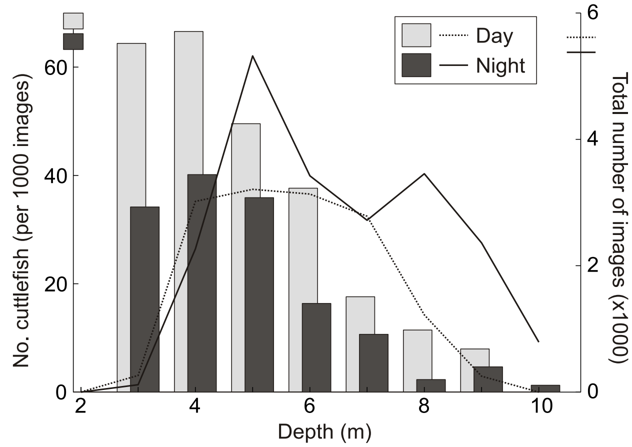

Fig. 4. Distribution of cuttlefish in relation to water depth. Bars indicate the number of individual cuttlefish observed per 1000 images during the day (light grey) and night (dark grey), according to the leftmost axis. Observation effort is represented as the total number of images taken within each depth bin during the day (dotted line) and night (solid line), according to the rightmost axis.

not be as good as during daytime. We note here that the daytime AUV trials do not accurately relfect the number (or proportion) of displaying cuttlefish, which is very high, because the display aggregations are very concentrated in small areas (and thus missed by the AUV) while camouflaged animals are more evenly distributed.

Details of a 3D reconstruction from one of the dives can be seen in Figure 6. Here we see examples of 3D stereo meshes blended and texture mapped using imagery captured by the vehicle's stereo imaging system, illustrating the increasing detail with which the meshes can be viewed. These meshes aggregate hundreds or thousands of texture mapped 3D stereo meshes, allowing the scientist to zoom out to examine the habitats at a broad scale or zoom in to examine particular features in detail.

V. Conclusions and Future Work

This work has demonstrated the strengths of using an AUV for surveying near-shore benthic habitats of ecological interest. The phenomenon of cuttlefish camouflage at night is very difficult to document using traditional techniques such as SCUBA diving and can be very labour intensive. The use of remote instrumentation, such as ROVs and AUVs, provides a means of quantitative surveying in these areas and can yield accurate geo-referencing of the resulting observations.

On-going work is looking to compare night and day time camouflage behaviour in the animals observed in the imagery collected by the AUV. Factors such as colour and spatial patterns are being examined to establish a better understanding of how cuttlefish adapt their camouflage patterns to different microhabitats both at day and night.

Acknowledgements

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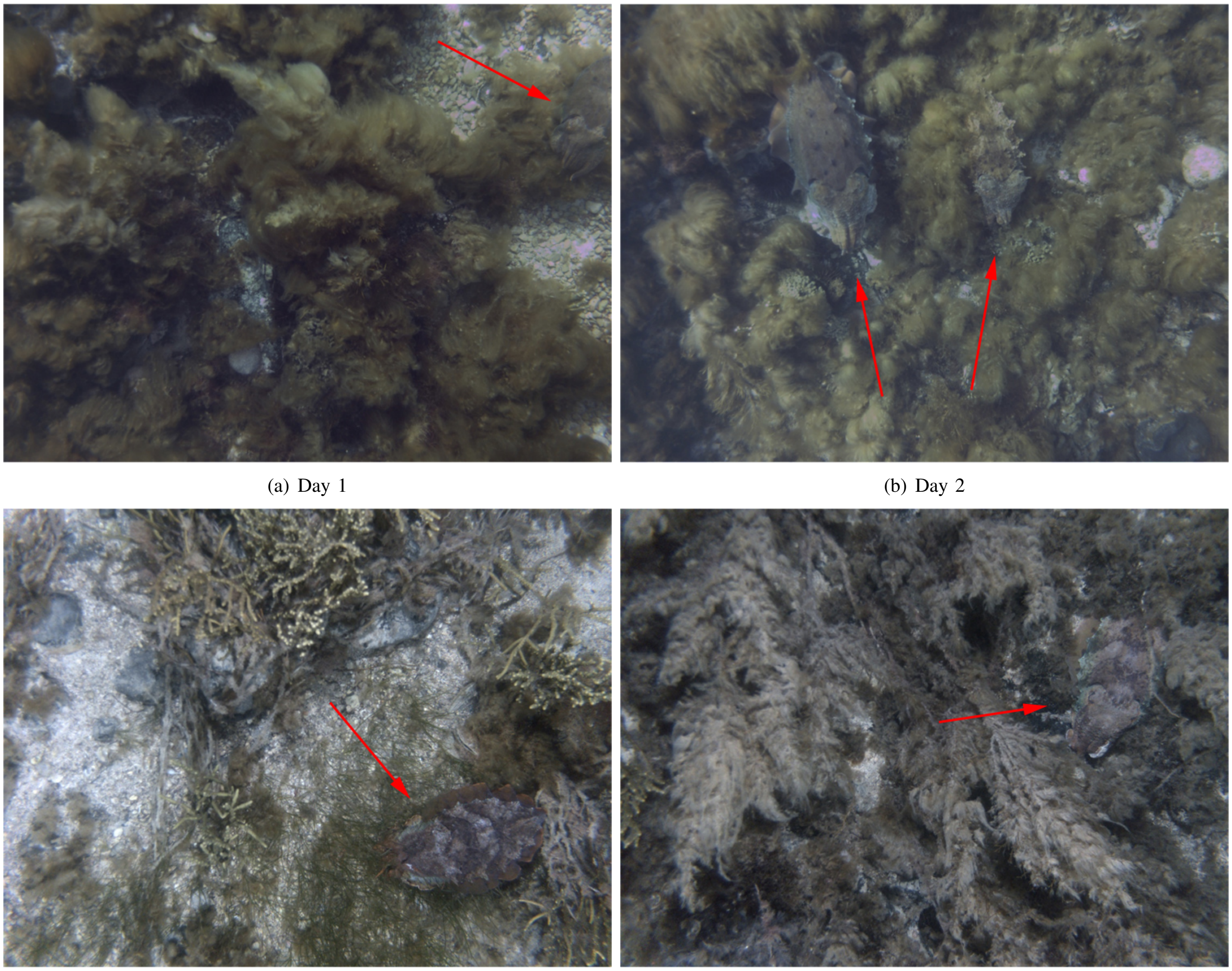

(a) Day 1

(b) Day 2

(c) Night 1

(d) Night 2

Fig. 5. Sample images of cuttlefish in various states of camouflage as captured by the AUV. (a) and (b) show examples of images captured during daytime dives while (c) and (d) were from night time dives. These are a small subset of the 951 images in which cuttlefish were identified. Note that these images have been downsampled from the original 1380 x 1024 images captured by the AUV.

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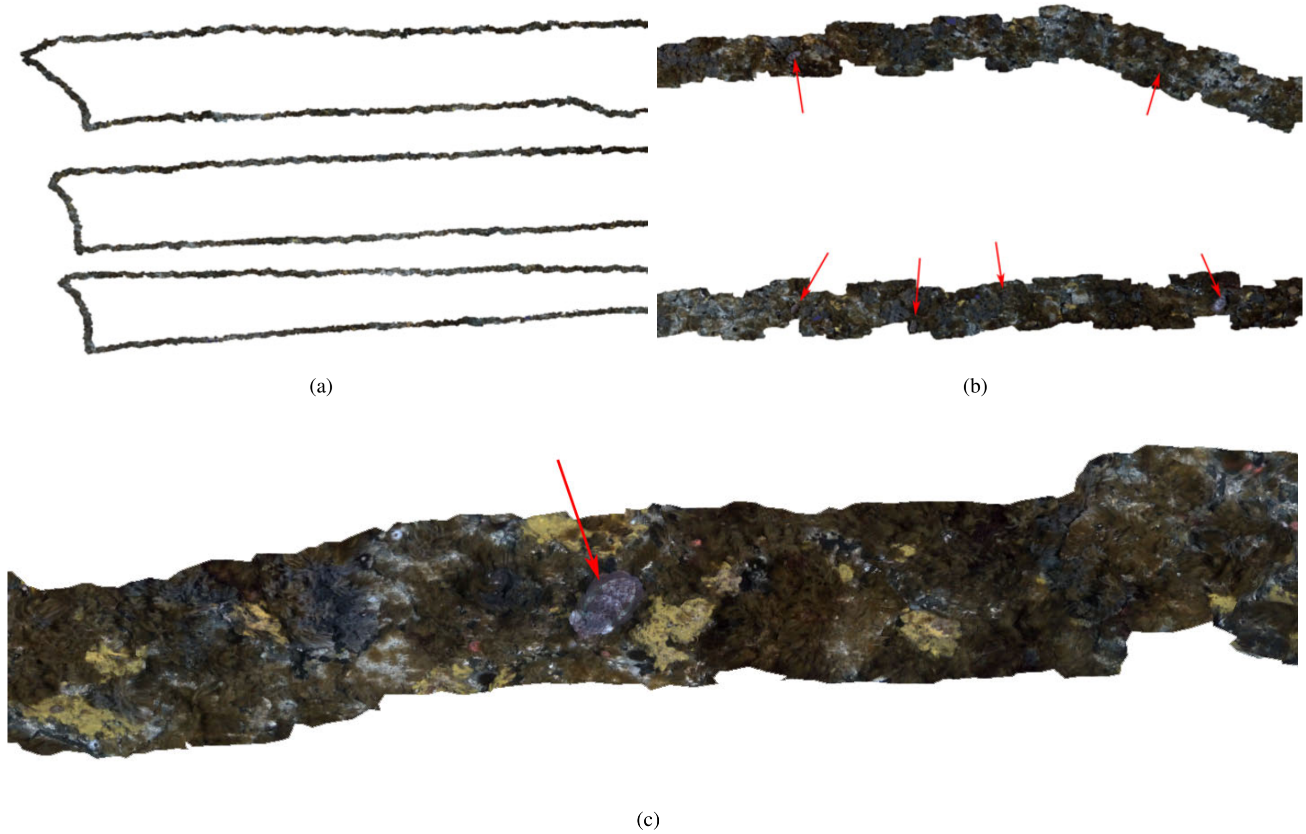

Fig. 6. A 3D photo reconstruction of one survey showing cuttlefish locations. (a) An overview of parts of the survey legs. Each leg of this dive was 100 m long with a spacing of approximately 10 m between legs. The vehicle flew at an altitude of 1.5 m resulting in an image footprint of approximately 1.2 m $\times$ 1.0 m (b) Two parallel tracklines with cuttlefish locations marked with red arrows. These are difficult to see at this resolution but the user can zoom in to inspect the cuttlefish. (c) A close-up view of one of the study animals against a portion of trackline. This segment represents an area of 1.0 m $\times$ 7.0 m, integrating numerous overlapping images projected onto a 3D mesh generated using the stereo imaging system.

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