CONTROLLING THE EXPANSION OF HALIMEDA INCRASSATA IN THE CABRERA NATURAL PARK USING MARINE ROBOTS AND PHOTO-MOSAICS

Francisco Bonin-Font, Bo Miquel NordFeldt Fiol, Caterina Muntaner Gonzalez, Antoni Martorell Torres

Abstract: Marine invasive macroalgae alter the environment in which they settle, changing food chains, generating structural variations and, sometimes, displacing native species. *Halimeda incrassata* (*H.i.*) is a tropical seaweed that settles mostly on sandy substrates and that has expanded almost sevenfold in the Balearics from 2011 to nowadays. Measuring its coverage is crucial to estimate its expansion rate and plan effective eradication actions. In the last years, the Marine Robotics team of the Systems, Robotics and Vision group (University of the Balearic Islands) has collaborated actively with biologists in the observation of sensible marine habitats using an Autonomous Underwater Vehicle to get data and image processing techniques to infer information of biologic interest. Several marine areas of Cabrera National Park were surveyed by our robot for *H.i.* video recording. Images of videos were used to form photo-mosaics, mark all *H.i.* shoots and calculate automatically its coverage with software. Time, extension and depth of data collection campaigns increase, offering measurements more accurate, and with higher temporal and spatial resolutions than those obtained with traditional techniques based on divers and quadrat frames.

Keywords: *Halimeda incrassata,* Autonomous Underwater Vehicles, Photo-mosaics.

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Introduction

Marine invasive macroalgae are one of the biggest problems in the Mediterranean because, although their colonization is normally due to human activities, once a species is introduced, it is difficult to eradicate [4]. *Halimeda incrassata* (Bryopsidales, Chlorophyta) (*H. incrassata*) is a tropical alga that settles mostly on sandy substrates colonizing seagrass habitats between 0 and 60 m depth. *Halimeda* species have calcareous (calcium carbonate, aragonite, CaCO3) thallus forming flattened segments. When the alga dies, the chips inside their segments become seafloor or shoreline sediments. The native distribution of this seaweed comprises the Western Atlantic and Indo-Pacific tropical and sub-tropical Oceans. But, in the last two decades Halimeda has expanded to Madeira, Canarias Archipelago, and the Balearic Islands. *H. incrassata* was detected in 2011 in Mallorca, and from then to nowadays it has expanded almost sevenfold in the south-west of the archipelago. Potential harmful impacts of *H. incrassata* on the Balearic ecosystem communities have been already reported [6][12]. However, some authors focus their attention on the positive effects that, until now, *H. incrassata* might be producing when settled, such as, increasing the abundance of fish diversity and the epifaunal assemblages on certain habitats formed on seagrass meadows [13][7]. When dealing with invasive species, controlling their expansion rate is crucial to understand their behavior and to plan effective eradication actions. To control this expansion, coverage turns out to be one of the most important bio-indicators, specially when evaluated along successive seasons. *H. incrassata* coverage has been mostly obtained *in situ* by divers measuring the shoot (i.e. individual plant) density. To this end, cover quadrats (usually 40 x 40 cm or 50 x 50 cm) are set, either along transects or at random sampling locations [7][11]. Then, the number of shoots within them are counted, extrapolating these measurements to greater surfaces.

In general, all diver-based underwater data gathering methods entail similar problems, namely: a) immersions are restricted by the capacity of the scuba air tanks and by the security measures, and limited in depth, time, coverage and extension, b) measurements collected by divers are usually partial, requiring further extrapolations which generate uncertainties [7], c) data geo-referencing becomes really challenging as the depth of missions increases, being inexact or fairly inaccurate; since Global Position Systems (GPSs) work exclusively in air, receivers need to be attached to floating devices and pulled, or, alternatively, GPS reference points need to be created in advance to measure the divers displacement with respect to them [9]. Furthermore, to cover extensive areas many dives of short effective working times have to be performed, increasing human risks and costs. All in all, a good compromise between accuracy and dive effort is required.

Accordingly, innovation in *H. incrassata* studies has to be focused on: a) increasing the spatial and temporal extension of missions, b) enhancing the amount of data collected in each immersion, c) monitoring habitats in deeper areas, d) increasing the accuracy of coverage estimates, and e) georeferencing missions with sufficient precision, in such a way that they can be repeated in successive seasons or times of the year.

Recently, the Marine Robotics team of the Systems, Robotics and Vision (SRV) Group (University of the Balearic Islands - UIB) has collaborated with biologists in the study of sensible marine habitats [2] [8], as one of the strategic lines for research and innovation. Work has been focused on evolving traditional diver-based methods into technology and automated processes, based on marine robotics, software and Artificial Intelligence (AI). Some of these activities included the estimation of *Halimeda* coverage variations at increasing depths, getting images of the sea bottom from an Autonomous Underwater Vehicle (AUV) and building photo-mosaics used to calculate the density of shoots. Advantages of this novel methodology include: a) increasing time, extension and depth of campaigns, b) augmenting the temporal and spatial resolution of data obtained with the AUV with respect to the data obtained with traditional techniques based on divers and cover quadrat frames, and c) increasing the accuracy of the coverage estimations since our method includes all alga shoots in a region with no extrapolations or approximations.

Materials and Methods

The sub-archipelago of Cabrera was one of the prior scenarios for the study of *H. incrassata* expansion in the Balearics [6][7]. Cabrera is a protected National Park located in the south-east of Mallorca and a representative location with a well-defined plan to minimize anthropogenic activities and their impact on the environment. Several marine areas located in Cabrera colonized with *H. incrassata* were surveyed during 2023 and 2024, by an AUV model Sparus II [3], property of the UIB, performing trajectories between 50 m and 70 m long, and between 10 m and 20 m wide. The vehicle moved at constant speeds around 0.18 m/s, altitudes between 1 and 1.5 meters and depths between 13 m and 20 m. Some sample spots of Halimeda located in Cabrera are shown in Figure 1.

Figure 1 – *H. incrassata* pictures courtesy of Fiona Tomás (group Ecology and Marine Resources, Instituto Mediterráneo de Estudios Avanzados, IMEDEA)

Our AUV is torpedo-shaped, submersible up to 200 m, it is 1.6 m long, it has a diameter of 32 cm, and it weighs 60 kg. It is propelled by 2 surge and 1 heave thrusters and it has 8 hours of autonomy. The vehicle incorporates a pressure sensor, a bottom-looking stereo rig, a GPS, a Doppler velocity log (DVL), an inertial measurement unit (IMU), an acoustic modem an eco-sounder pointing down and, finally, two led bulbs (see Figure 2). This robot can be either teleoperated or pre-programmed to perform automatically geo-referenced trajectories of any shape and extension with the unique limits of its own self-power autonomy and its maximum operation depth. Its localization module is formed by a double EKF (Extended Kalman Filter) [15] that integrates all outputs of all the aforementioned instruments. When the vehicle is submersed, it calculates the UTM (Universal Traverse Mercator) geo-location for each point of the trajectory, composing the GPS (latitude and longitude) of a surface reference point with the self-computed vehicle displacement. This capacity of geo-referencing itself enables the vehicle internal system to associate each position to an image. This feature is essential to re-evaluate the evolution of the inspected ecosystems in consecutive months, seasons or years.

Figure 2 – On the left, the AUV schema. On the right, a view of the robot in the sea.

The process per mission can be detailed as follows: a) the AUV records images continuously, at a constant altitude and at a customizable frame rate adequate to guarantee a minimum overlap among successive images or images of adjacent transects, b) in order to reduce the size of the resulting mosaic, original resolution of images is reduced by 4, c) down-sampled images are stitched together accordingly to the AUV self-estimated trajectory, d) zones with image overlapping are homogenized using a Multi-band blending strategy [1], e) all *H. incrassata* shoots are hand-labeled in each image with a graphical image annotation tool [14], f) labeled images are binarized, coloring bounding boxes containing *Halimeda* in black, and the background in white (see Figure 3), g) the same photo-mosaic is built again but with the binarized images, h) margins and zones of the mosaic not included in any of the images are excluded for the coverage because they are neither *Halimeda* nor seabed, i) the coverage is computed as the proportion of black pixels with respect to the total number of pixels (sum of black and white pixels); that is, the proportion of *Halimeda* with respect to the total surface of the surveyed area, excluding margins or zones in between images.

Results

Some illustrative results obtained from three datasets recorded in Cabrera national Park are presented next. Figure 4 shows the trajectory of the vehicle corresponding to the first experiment with 8 transects, all parallel and spaced 1 meter to each other. It is approximately 2 meters wide, 60 meters long, and it was recorded at a constant altitude of 1.5 meters and at a depth of 17 m. The geo-coordinates of the initial point are: (39.1490931024º N, 2.9331163042º E).

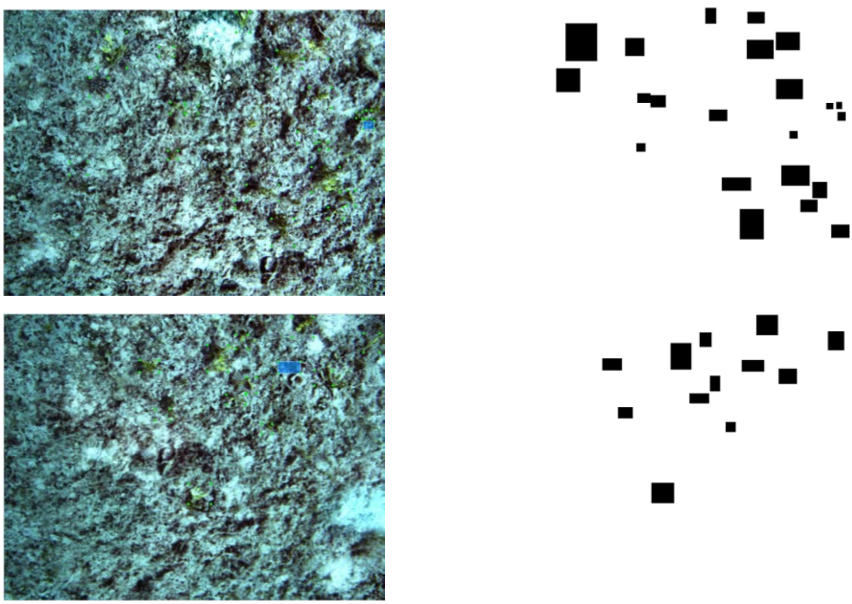

Figure 3 – Left column: two sample images hand-labeled. Right column: their corresponding binarized counterparts, with the *Halimeda* bounding boxes marked in black.

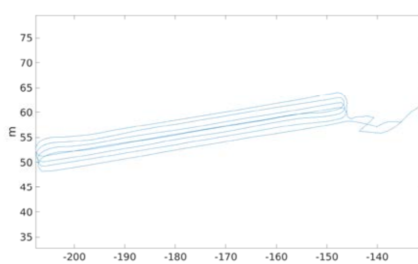

Figure 4 – Trajectory of the vehicle followed in mission 1.

On the top, Figure 5 shows the color photo-mosaic of mission 1, and on the bottom, figure 5 shows its binarized counterpart, where black spots indicate the *Halimeda,* white zones the background*,* and blue zones show the parts of the mosaic that do not correspond to any image. Both mosaics were built with 562 images each one. Let us highlight the correspondence between the trajectory of the vehicle (Figure 4) and the resulting mosaic, as expected. *Halimeda* coverage estimated as explained in the previous section was 0.0033494916 (0.3349 %).

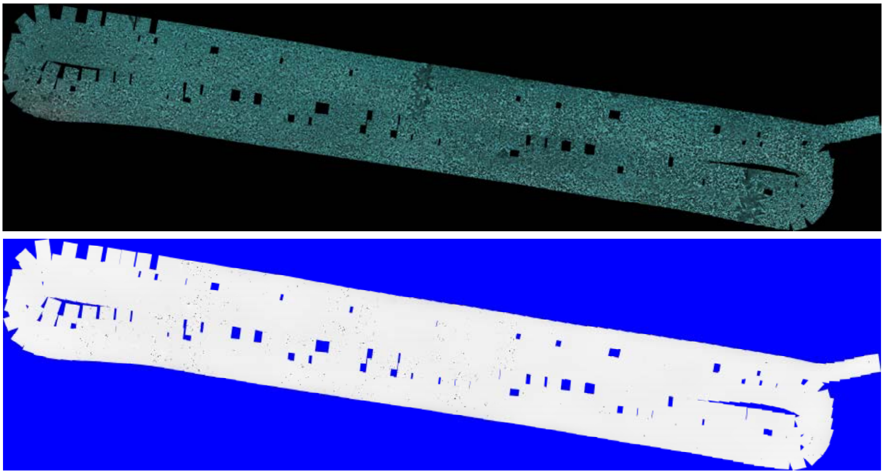

Figure 5 – Mission 1, 16÷17 m depth, recorded from a constant altitude of 1.5 m.

Figure 6 shows, on the left, the trajectory of the vehicle corresponding to mission 2, estimated by the AUV navigation module. This trajectory has a single transect, is 60 meters long, and the AUV tried to navigate at a constant altitude of 1 meter, in an area at a depth of 40 meters. Figure 7 shows, on the top, the color mosaic of this mission 2, with its initial point located around the geo-coordinate (39.1494490903ºN, 2.93431985096ºE). On the bottom, figure 7 shows its corresponding binarized mosaic, where black spots indicate the *Halimeda* and the blue zones indicate the parts of the mosaic excluded from the coverage. Both mosaics were built with 76 images each one. Note how the mosaic presents the same form as the vehicle trajectory. *Halimeda* coverage estimated from this mosaic was 0.0227 (2.27 %).

Figure 6 shows, on the right, the trajectory of the vehicle for mission 3, with 8 parallel transects, each spaced 1 meter apart. The mission was located around the coordinates (39.149410247802734ºN, 2.933732986450195ºE). The trajectory is, approximately, 6 meters wide and 60 meters long, and the AUV navigated at a tentative constant altitude of 1.5 meters, on an area at a depth of 14 m.

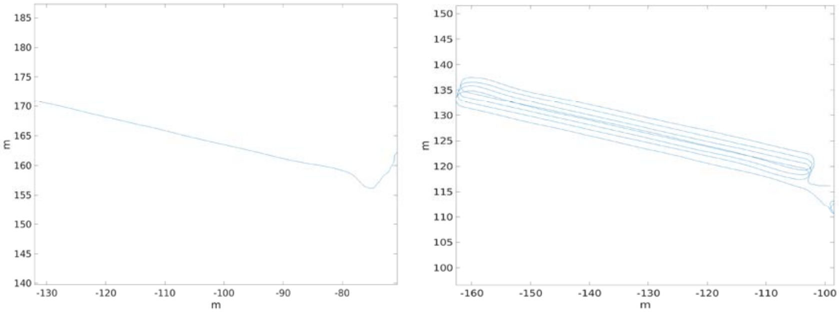

Figure 6 – Trajectories of mission 2 (left) and mission 3 (right).

Figure 8 shows, on the left, the color mosaic of mission 3, and, on the right, its binarized mosaic. Both were built with 333 images each one. *Halimeda* coverage estimated for this dataset turned out to be 0.0253 (2.53 %).

Discussion

According to the obtained results, the method explained in this paper to estimate the density of *Halimeda* in a certain region is suitable if the manual labeling is done by an expert observer, and all spots are market appropriately in all key frames that have to be included in the photo-mosaics. Results show coverages no greater than the 2.5 % in all datasets, which shows a tendency in the whole zone. This process can be run periodically in the same areas and at the same locations, in order to see the progress of coverages in successive seasons.

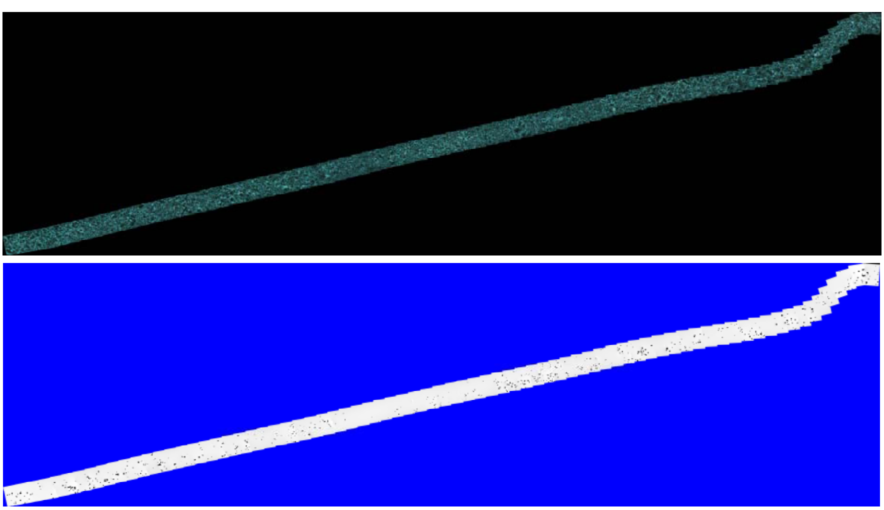

Figure 7 – Mission 2, at 10 m depth, and recorded from an altitude of 1 m.

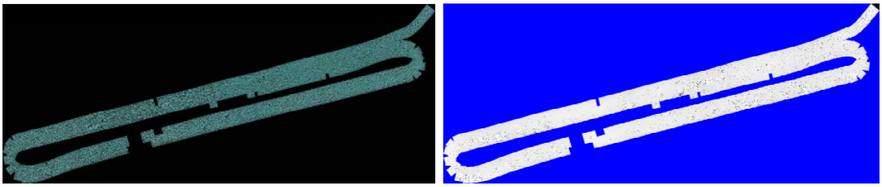

Figure 8 – Cabrera mission 3, 6 meters wide, 60 meters long, recorded at a constant altitude of 1.5 meters and an approximate constant depth of 14 m.

The most challenging aspects of the process can be summarized as: a) images need to be recorded from a mobile platform equipped with a camera that needs to be geo-localized continuously, b) the platform must navigate at an approximately constant altitude, and c) a subsequent process of manual labeling of, in many cases, hundreds of images. Image recording using AUVs solves some of these challenges, since they offer: a) The capacity to program trajectories of any shape that will be executed autonomously at constant altitude or at constant depth, b) The possibility to geo-localize precisely all images recorded during each mission, c) High autonomy to operate during hours in areas as extensive as needed, d) To get depths, in some cases, unreachable by divers without any physical link to any mother-ship or structure. Additionally, all coverages have been estimated without approximations, taking all elements of all images that are identified as *H. incrassata*. This is a clear advance with respect to classical coverage estimations based on divers, manual sampling and data extrapolation. However, this method presents several problems to be taken into consideration before missions are designed: 1- the autonomy of the AUV is limited by the capacity of its battery, 2- a complete disconnection of the AUV from any support vessel or ground station avoids operators to check the evolution of the mission and the state of the vehicle until it emerges, and 3- *Halimeda* spots are quite small, and the vehicle needs to move close to the sea floor (around 1,5 m) for them to appear in the images with sufficient resolution and clarity; the closer the vehicle gets to the sea bottom, the longer needs to be the mission to cover the same area at the same speed, 4- the method, as it is described here, requires the manual labeling of thousands of images making part of the process long and tedious.

Conclusions

Measuring the coverage and expansion rate of invasive marine species, in general, and *H. incrassata* in particular, has become crucial to understand their adaptability to the environment and the affectation to the native habitats. This information is absolutely necessary to plan effective eradication actions or to take advantage of their invasions. Although the benefits of using submarine robots and image processing techniques surpass the problems, the type and the location of the environments or habitats to be evaluated will impose the application of either traditional methods or novel methods like the one described here. This approach, in its current form, enables us to go one step forward in the use of artificial intelligence for submarine habitat assessment. However, our on-going work does even another step ahead, adapting, re-training, validating and testing a specific Convolutional Neural Network (CNN) [10] to be applied in the images recorded by the AUV. The objective is to detect, automatically, all *Halimeda* spots in all key frames used to form the mosaics. This approach replaces the visual identification and manual labeling by a process that can be run in a computer in batch mode, saving a lot of time and human resources, and solving one of the problems mentioned in the *Discussion* section. Although this work in still in progress, it is already giving encouraging results, reducing considerably the human effort necessary to label, frame by frame, the alga. Figure 9 shows 2 images with the *H. incrassata* detected and labeled automatically by one of the first CNN trained models. Finally, let us remark that this method can be applied (and, in fact, it is applied) [5] to study other submarine species. The only difference lies in the target: if it forms larger and more visible or dense structures, such as, for instance, *Posidonia oceanica,* then, its identification on images is easier than *Halimeda* and the AUV can fly at larger altitudes reducing mission times to cover areas with similar extensions.

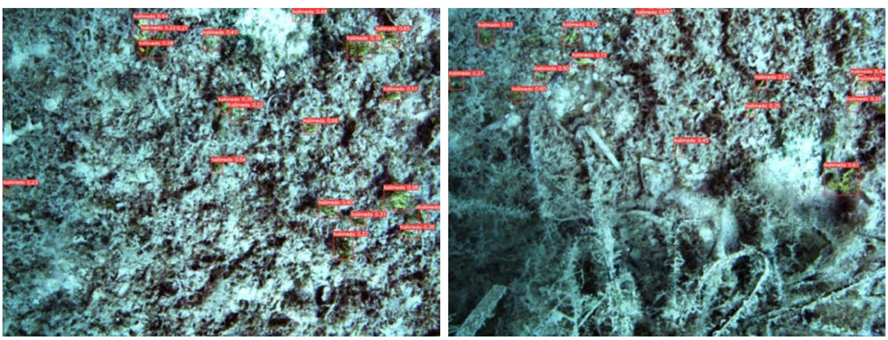

Figure 9 – Two sample images with *Halimeda* inferences output by a CNN trained model.

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