

# Shallow Coral Reef Surveying by Inexpensive Drifters

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**Abstract**—Coral reefs exhibit the highest biodiversity in the ocean and are an extremely vulnerable ecosystem. Monitoring the state of the reefs is a tedious process performed by human divers which can be automated. This paper presents the use of several inexpensive drifting sensor nodes in order to reconstruct a visual mosaic of a shallow coral reef. The drifters produce geo-referenced visual data from a downward facing camera while floating above a shallow-water coral reef. The vision is augmented with inertial data enabling the recovery of the drifter's attitude. A brief description of the drifters together with a framework to produce visual mosaics are discussed. Experimental results from a deployment over the Folkestone Marine Reserve in Barbados demonstrating the utility of our approach are presented.

## I. INTRODUCTION

Coral reefs are crucial for the environment, as they are hosts to a large variety of animals, exhibiting great biodiversity. Monitoring coral reefs, understanding the dynamic [1] and habits [2] of the animal population, and estimating the reef's health [3] is crucial but a time consuming task [4]. In the past, teams of heterogeneous robots have been deployed for monitoring small areas of the reef [5]. As an alternative a set of inexpensive drifters was created which can collect visual data as they drift over the coral reef propelled by the currents and the wave action [6]. The primary functionality was for the drifters to measure the Eulerian water currents, and as a secondary goal to collect inertial and visual information of the environment. Preliminary experiments conducted in January 2015, confirmed that even using an inexpensive setup based on the Raspberry Pi technology, enabled the collection of high quality data. An upgraded version was deployed in January 2016, resulting in a dense randomized coverage of the shallow coral reef of the Folkestone Underwater Park and Marine Reserve, Barbados; see Fig. 1. The collected data include monocular visual data, inertial information from the IMU in the form of 3D accelerations and 3D angular velocities at 100Hz frequency, and positional data from the GPS at 1Hz.

Producing large scale visual mosaic of the coral reef is important for monitoring the health of this fragile ecosystem. Historically, data collection involved divers swimming a camera over the area of interest and then stitching the images together, a process that is tedious and very time consuming. The developed drifters use the ocean currents to move over the coral reef recording images. In addition, the bobbing motion of the drifter changes randomly the orientation resulting in a wider field of view over time; see Fig. 2. It is worth noting,



Fig. 1. A single drifter floating over the coral reef.

the availability of rough positional information from the GPS signal enables the assembly of the visual reconstructions from multiple drifters, over different days, even when there are no commonly observed areas. In addition to the shallow coral reef applications, the developed drifters can also be used to assist in marine archaeology exploring submersed sites such as Pavlopetri in Greece [7].

The next section discusses related work. Section III outlines the hardware and software setup of the drifters. The framework for producing a visual mosaic is discussed in Section IV. Experimental results are presented in Section V. The paper concludes with lessons learned and a discussion of future work.

## II. RELATED WORK

The interest on monitoring underwater environments autonomously starts back in 1953, when the first cameras for deep-sea exploration [8] and the first AUVs [9] made their appearance. Since then, many different marine vehicles have appeared over the years [10] and they can be separated in two categories: AUVs that operate mostly underwater and drifters that operate by floating on the surface [11]. Drifters have been used passively [12]–[14] as in this paper, and actively by controlling them [15]–[17].

Many studies used them to monitor oceanographic features with some ad-hoc sensor. Rossby et al. [18] and Michini et

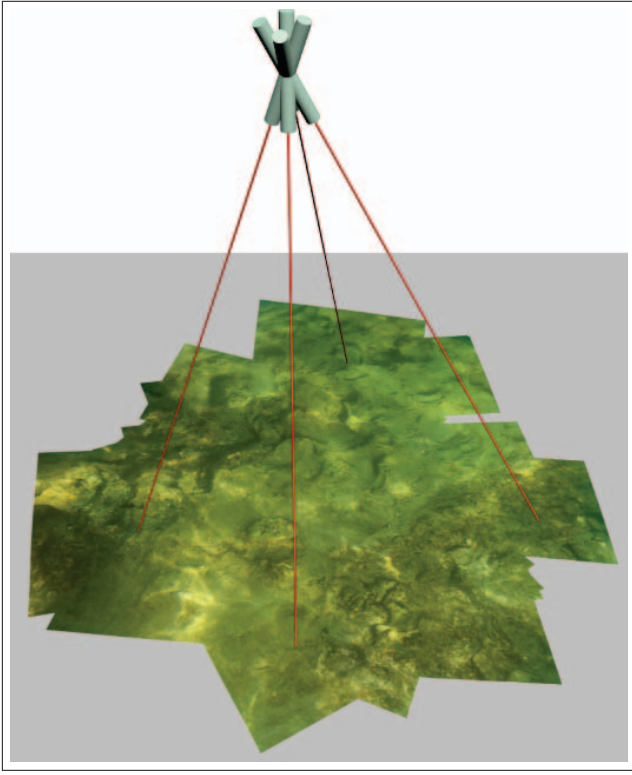


Fig. 2. The bobbing motion of each drifter results in an expanded field of view.

al. [19] analyzed the underwater dynamics; Ryan et al. [20] monitored Intermediate Nepheloid Layers (INLs) that have a strong effect on the plankton ecosystem; Das et al. [21] observed advection features. Mallory et al. [22] deployed a swarms of homogeneous robots in gyre flows and kept them in formation.

An important problem to deal with in order to develop autonomous marine robots is state estimation. Cameras and inertial sensors have been shown to be a reliable source of data to localize, create a map of the environment, and path planning, by many researchers, such as Mourikis and Roumeliotis [23], Kelly and Sukhatme [24], and Jones and Soatto [25]. Shkurti et al. [26] presented a state estimation method for the Aqua robot using visual and inertial information. Johnson-Roberson et al. [27] developed a stereo SLAM algorithm for underwater applications. Meghjani et al. [28] used an AUV with camera and IMU to search for a drifter, a problem termed underwater rendezvous.

Furthermore, research has been done on the reconstruction of underwater objects or environments. Ferrer et al. [29] provide accurate mosaics of the bottom of the sea by using a AUV that was localized locally with a bottom moored transponder network (LBL) and applying off-line bundle adjustment. McKinnon et al. [30] presented a method for a 3D reconstruction of a single coral using a single camera. A 3D reconstruction of a coral reef was done successfully using bi-objective bundle adjustment by Warren et al. [31]. The work of Friedman et al. [32] included a stereo camera for improving

the 3D reconstruction.

To the best of our knowledge, creating consistent mosaics is still an open problem in underwater domains, given the challenging setting.

### III. SYSTEM OVERVIEW

The primary goal of the drifting sensor node design is to keep the cost down so the drifters can be affordable for large scale deployments. Each of the drifters is built around a Raspberry Pi computing unit, and are equipped with a camera, an Inertial Measurement Unit (IMU), a GPS receiver, and a WiFi adapter. The software is based on the ROS [33] open source framework, enabling data collection in a standardized format. The electronics are enclosed in a PVC tube; one end of the tube is fitted with an acrylic window for the camera and the window is sealed with waterproof cement. The other end of the tube is fitted with an easily removable, splash-proof, cap; see the top part of Fig. 4. Lead weights are attached at the bottom part of the tube to ensure an upright position in the water; the buoyancy is adjusted so the top part of the drifter stays above the water to enable GPS signal reception.

#### A. Hardware

The first prototype was constructed using a long PVC case (0.56 m length and 0.12 m diameter), and employed a Raspberry Pi B computer. The low computational power of the selected CPU restricted the image acquisition at 2Hz frame rate [6]. The current version of drifters utilizes a shorter case (0.4 m length), thus enabling easier transportation. The current implementation uses an upgraded computing unit (Raspberry Pi 2). The more powerful CPU allows 10Hz frame rate image capture, which resulted in more accurate reconstructions. A 64GB micro-SD memory card is used for storing the software and the data. Each drifter is equipped with a Raspberry Pi camera which is a 5 Megapixel camera with fixed focus<sup>1</sup>. Its field of view is approximately 30° by 40°. Camera calibration is performed employing a water-proof calibration target, using the related ROS package<sup>2</sup>. An Adafruit Ultimate GPS receiver with an antenna, and a Pololu MinIMU-9 V3 Inertial Measuring Unit (IMU) are used; see Fig. 3 for the setup of the sensors. Finally the WiFi adapter, with a USB interface, is utilized for communication between nodes and with the ground station.

The original design used a 10,000 mAh battery, which was barely fitting in the enclosure. As currently most of the deployments performed have one to three hours duration, a 5,000 mAh battery is more than adequate. The battery, see Fig. 3, is inexpensive and can easily fit on the opposite side of the Raspberry Pi; see Fig. 4. On-the-bench tests indicated that the battery lasts for eight hours of full operation on a single charge.

#### B. Software

The main software package running on the drifter consists of a collection of different ROS nodes handling raw data

<sup>1</sup><https://www.raspberrypi.org/documentation/hardware/camera.md>

<sup>2</sup>[http://wiki.ros.org/camera\\_calibration](http://wiki.ros.org/camera_calibration)

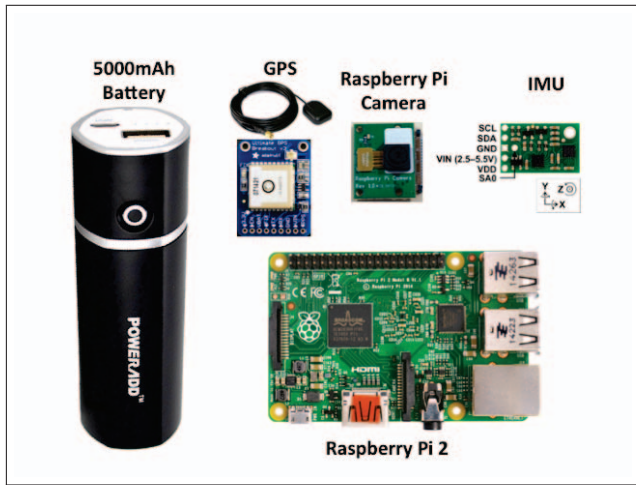


Fig. 3. The hardware employed in the drifters.

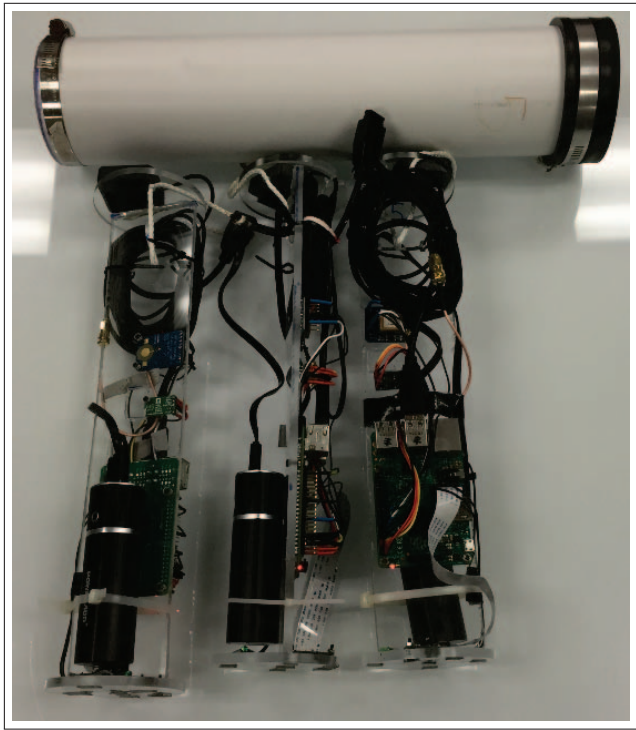


Fig. 4. The inside of three sensor nodes, and the splash-proof container.

coming from the WiFi, camera, GPS and IMU sensors, and publishing ROS messages that are saved in rosbag files for post-processing. Each of the nodes is independent of each other so that, even if for some reason one sensor becomes unresponsive, still other data are collected.

For fast-prototyping, the Python programming language was used when either the supporting driver interface was provided in Python or was supported by a general communication model. For example, the camera is provided with Python APIs<sup>3</sup>. Some extra care has been taken regarding the setup

<sup>3</sup><http://picamera.readthedocs.org/en/release-1.10/>

of the camera. Before starting publishing the camera images – which are compressed in order to reduce the size of the images and account for the limited space on the micro-SD card – a process has been implemented to fix the camera parameters, including the shutter speed, exposure gains, white balance, and the ISO. In this way, images are captured consistently over time. A laptop is required to connect to the drifter, and the steps depicted in Figure 5 are followed. A user supervises the process, as the Raspberry Pi camera driver does not allow to manually fix the exposure gains. It is worth mentioning that some recovery mechanisms are in place so that if some faults happen, e.g., loss of connection, after a timeout, a default configuration is loaded and the camera is started. The GPS interface, instead, is a third-party process that delivers the raw data through a TCP/IP socket, and to which the implemented ROS node is connecting.

The node handling the IMU instead has been written in C++, given the fact that some C++ APIs were already available. Calling directly the driver APIs allows to have minimal overhead between the generation of the message and the actual publishing in ROS.

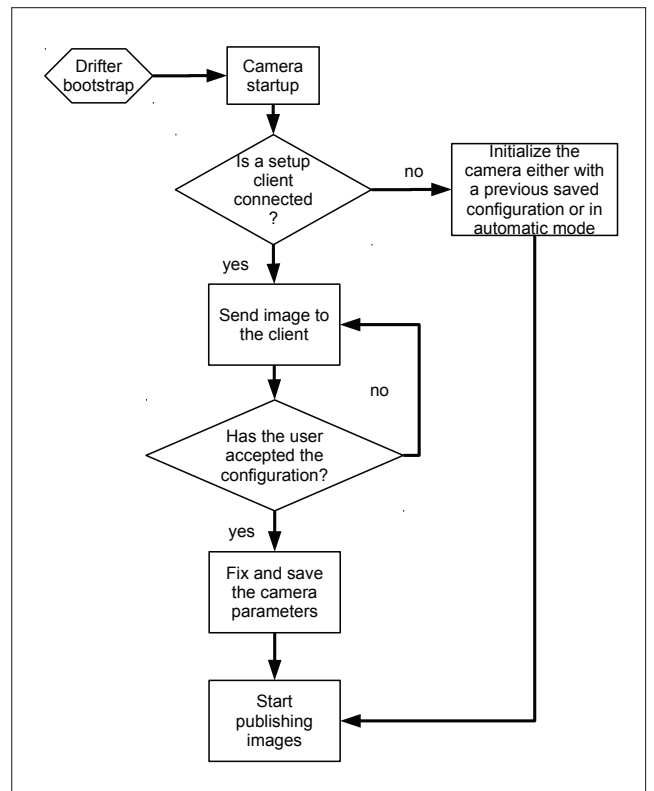


Fig. 5. Initialization of the camera.

#### IV. VISUAL DATA PROCESSING

Different steps are necessary in order to create a mosaic from a set of images. The pipeline is shown in Fig. 6.

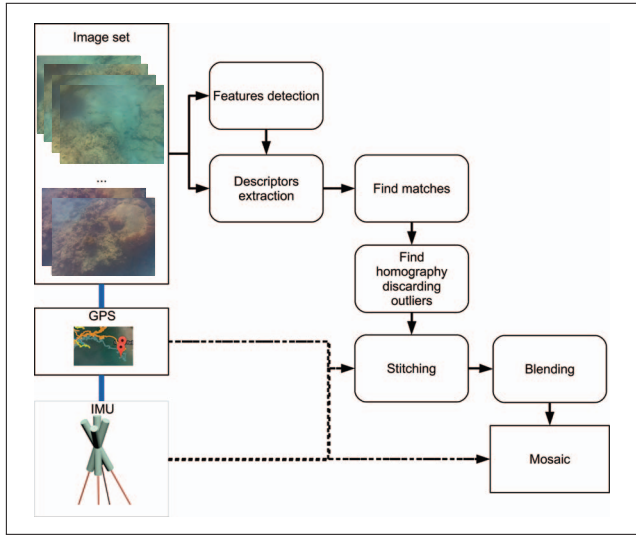


Fig. 6. Pipeline to process the data in order to create the mosaic of the coral reef.

The developed system uses the OpenCV library<sup>4</sup> and is modular enough that it is possible to change the methods used for the different modules in the pipeline.

The input to create a mosaic is a set of images and optionally GPS and IMU data, synchronized with the images. First, features are detected and related descriptors are extracted, such as ORB [34], SURF [35], or SIFT [36]. As shown in Section V, it is crucial to test the performance of different features/descriptors on the specific dataset in order not to jeopardize the entire pipeline. Second, matches are searched between the images given the extracted features and related descriptors and the homography is found according to the matches. Note that it is important to filter the noise to have consistent transformations between the images; in the proposed system, RANSAC [37] is used. In order to accept a transformation between images, a threshold on the minimum number of inlier matches can be set, to improve the consistency of the resulting reconstruction. In the experiments presented here, it was set to 20. Furthermore, it is possible to reduce the computation time of finding the matches between the images, if it is known that images have been consecutively captured, and thus setting the parameters to consider matches between images within a window. Given the transformations found, a set of patches are created by combining the images with consistent transformations and by blending them together to have a nice appealing result.

GPS and IMU data can be used to improve the resulting mosaic, by discarding images captured with a large rotation that would result in a stretched mosaic, and can provide a rough estimate for the homography. Furthermore, patches are geo-referenced so that they can be placed in a global map.

<sup>4</sup><http://opencv.org>

## V. EXPERIMENTAL RESULTS

Experiments performed during the Barbados field trials, at the Bellairs Research Institute, resulted in several datasets collected over a several days. Next we are going to discuss the deployment of the drifters, followed by an analysis of the quality of different features for underwater vision-based state estimation. Finally, the visual mosaics constructed will be presented.

### A. Deployment

During the field trials six drifters were deployed. Unfortunately during the first deployment, one of the drifters disappeared. The two most probable scenarios are: the drifter was caught by a faster current and drifted much further out to sea than the rest of the team; a small leak slowly filled the drifter with water and the device sunk over the coral reef. The remaining five drifters were deployed over several days. Varying lighting condition, resulted in some runs to be overexposed and thus not useful for contributing to the mosaic. Nonetheless, the remaining trajectories provided adequate coverage of the target corral reef as can be seen in Fig. 7.

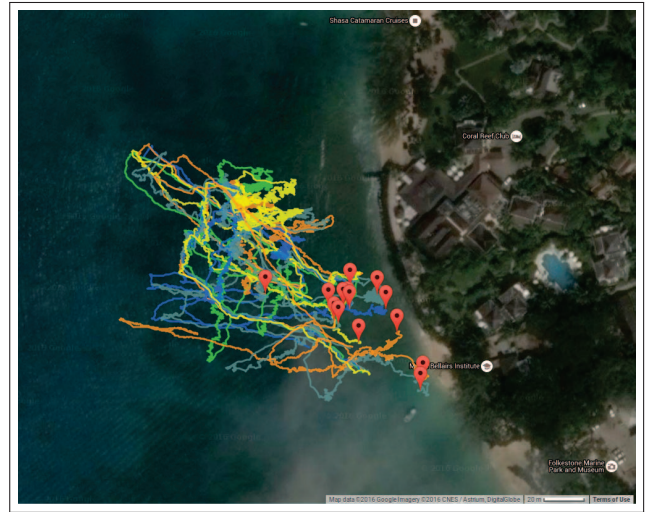


Fig. 7. The GPS traces of the deployed nodes from several days; each of the colors represents a different drifter.

In the field, observations indicated that the visibility of the seafloor at depths more than seven meters did not provide adequate information as such, when the drifters moved over the sandy area to the west of Fig. 7, they were collected and returned for another run. On January 12<sup>th</sup>, the conditions were more rough and the nodes deployed at the north part of Fig. 7 were placed further west, than before and they spend a lot more time over the same area due to the surge.

### B. Visual Feature Quality

It is fundamental to have good features to track in order to keep track of the motion of the camera and reconstruct the scene. For example, Aulinas et al. [38] use SURF for underwater visual SLAM. Some works evaluated the feature

quality in the underwater domain. Shkurti et al. [39] evaluated the goodness of some feature detectors, descriptors, and matchers for underwater robot state estimation. Oliver et al. [40] analyzed how the underwater conditions, such as blurring and change in illumination, affect the performance of feature detectors. Also, the influence of the feature detector on matchers and object detector results are studied.

Here, a more complete assessment of the feature detectors and descriptors available in OpenCV is presented, using the default parameters. The tests are run on a subset of fifty images from the field experiments. Fig. 8 shows the average number of detected features (Fig. 8a), of inliers used for the estimated homographies (Fig. 8b), and the number of images stitched together (Fig. 8c) with different combinations of feature detectors and descriptors available in OpenCV.

Even if some methods are able to find many features, such as *GoodFeaturesToTrack-SIFT* – which is basically a variant of Harris corner detector – the number of inliers is relatively low. Note also that Fig. 8(c) shows that the *ORB-SURF* combination was able to stitch more images than other combinations of methods. However, the quality of the resulting mosaic was not as good as *SURF-SURF*, the method chosen for the visual reconstruction presented in the next section.

### C. Visual Reconstruction

The drifters collected more than 100,000 images during the field experiments; covering an area of 120 m x 100 m. This section presents the visual reconstruction out of a part of the data, as the processing of all of them together is infeasible given the computation and memory constraints. It is worth noting that with the camera resolution used and considering an average depth of 3 m, a tiling covering the entire area will result into a 675 Megapixel mosaic. We are currently investigating the adaptation of an Atlas [41] framework in order to manage the collected images in a geo-referenced manner.

Figs. 9 and 10 shows patches found by matching the features between images. The result is visually appealing and showing enough textures so that, for example, marine biologists can use such images to assess the coral reef health. However, sometimes, ghosting effect can happen, as shown in Fig. 11. This can be explained by some noise in the measurements and the matching, and also the use of finite floating point numbers. It is worth noting the different colors in the two figures: deeper areas (Fig. 9) have a bluish/greener tint, as the red channel disappears [42], while shallower areas are brighter and warmer (Fig. 10). In particular it is worth looking at Fig. 10h where the deeper area at the top of the structure has a blue/green tint as it is much deeper. Several images in the dataset do not present enough features to be tracked, especially the areas characterized by sand, possibly resulting in the mosaic being interrupted. Although the GPS and IMU can provide a rough estimate about the position of the camera, the noise leads to some inconsistencies in the mosaic. More investigation is currently ongoing for globally optimizing the

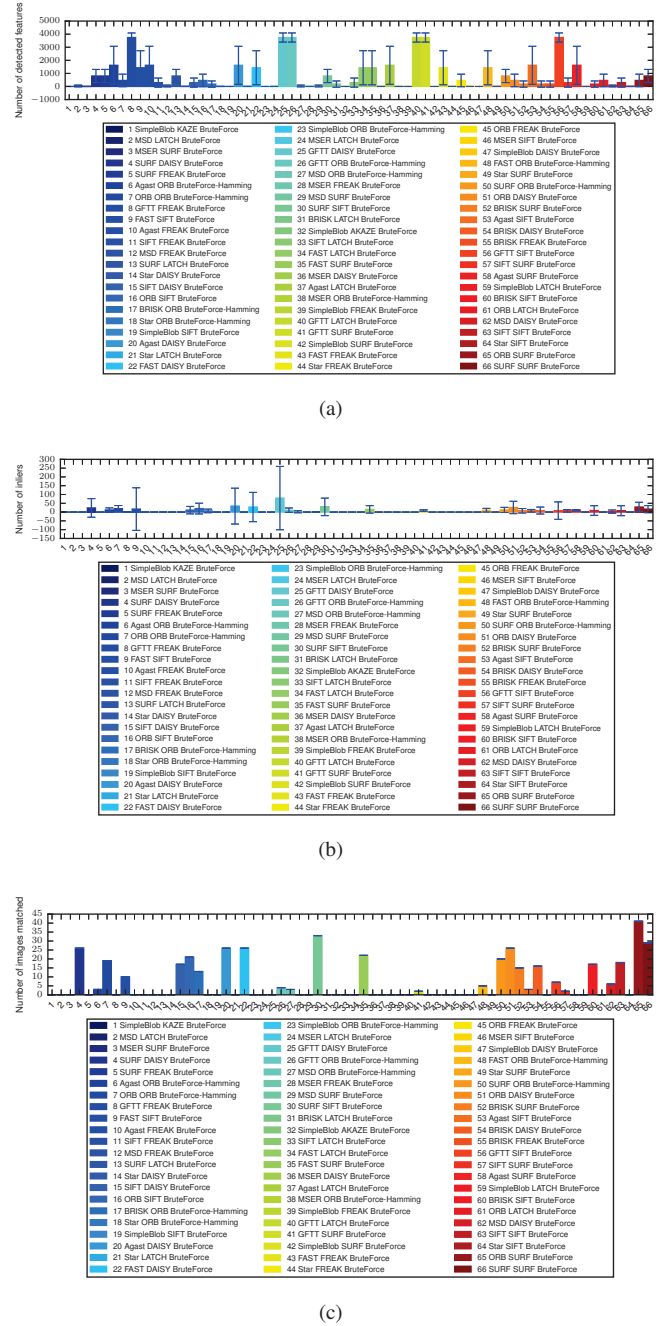
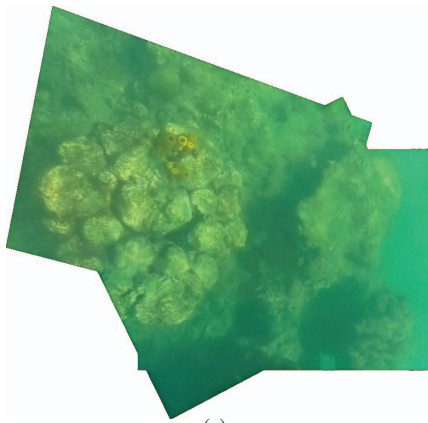


Fig. 8. Number of features, of inliers, and of images matched; in the legend, it is reported the feature detector, the descriptor, and the matcher used.

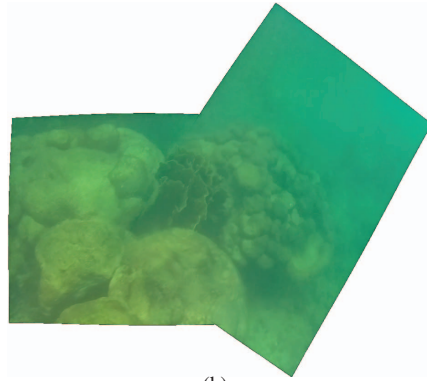
visual reconstruction and to have a more reliable estimate on the scale, degree of freedom with a monocular camera.

## VI. CONCLUSION

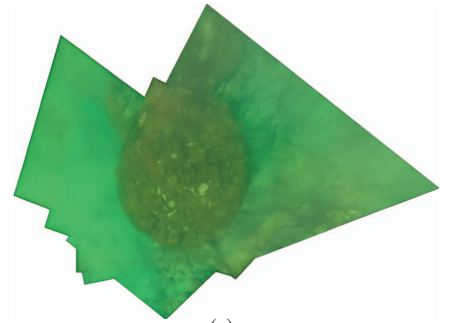
Inexpensive drifting sensor nodes were developed which enable the collection of geo-referenced visual and inertial data. Six drifters were deployed over a shallow coral reef over a period of several days, resulting in a dense coverage of the area. The visual data are stitched together using a custom framework which takes into account the orientation of the



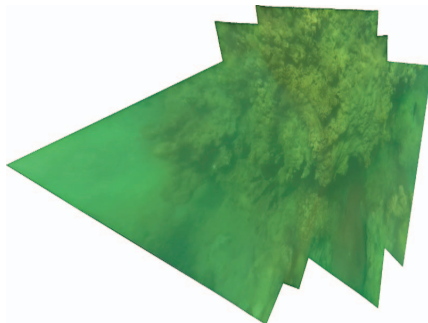
(a)



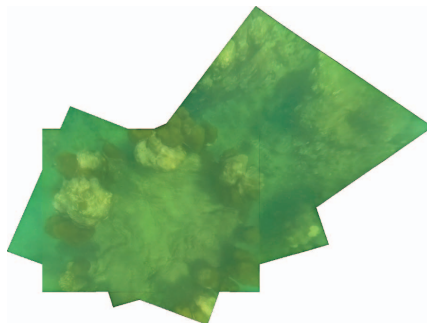
(b)



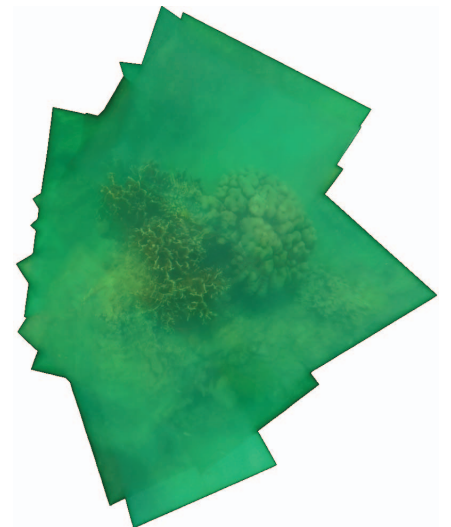
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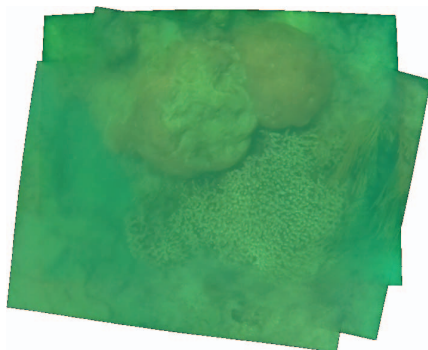
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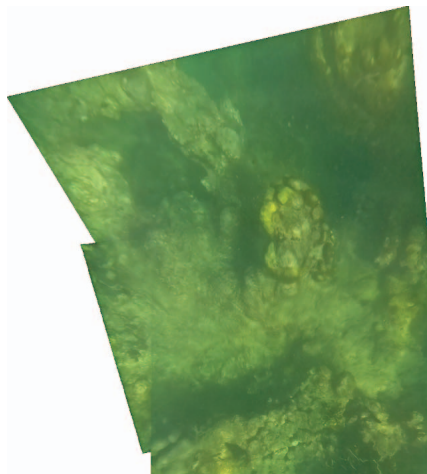
(e)



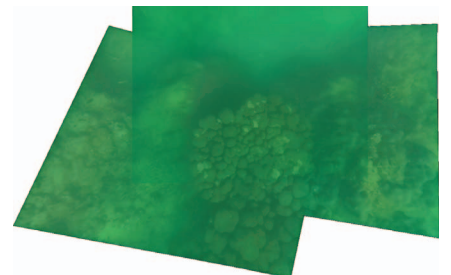
(f)



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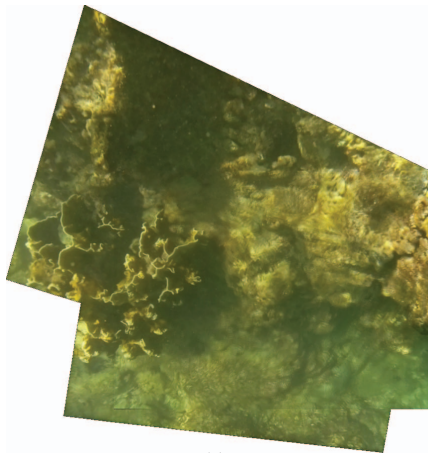


(h)

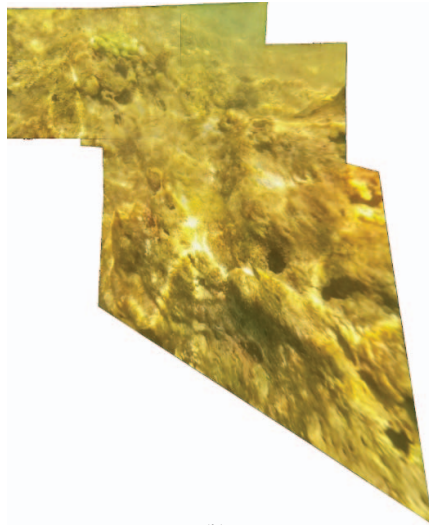


(i)

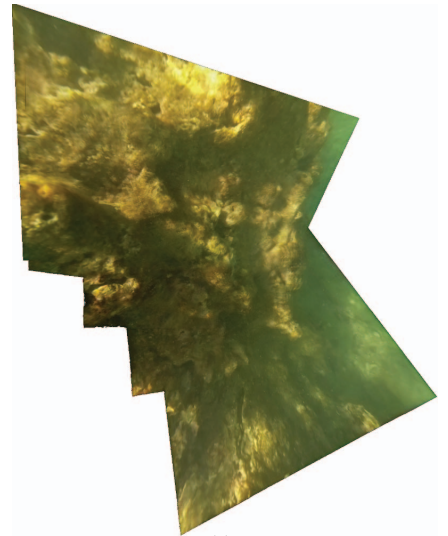
Fig. 9. Different mosaics from images taken in deeper areas, scaled down to fit in the paper.



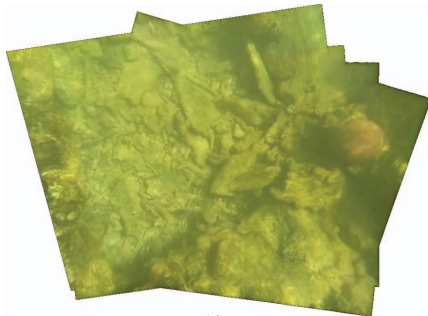
(a)



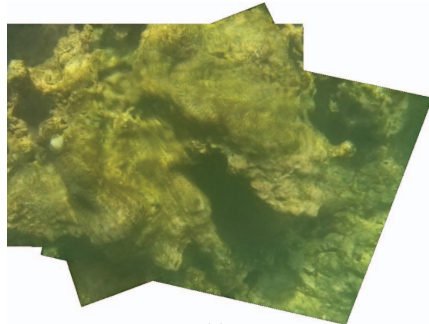
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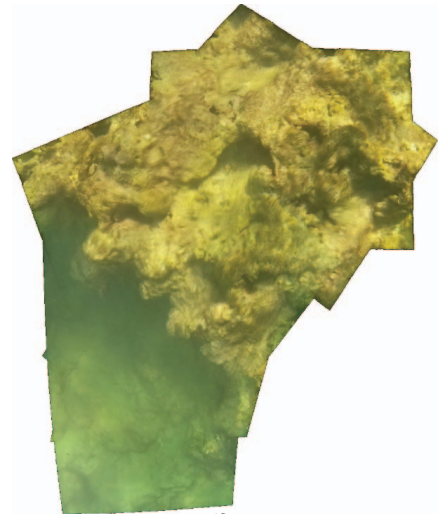
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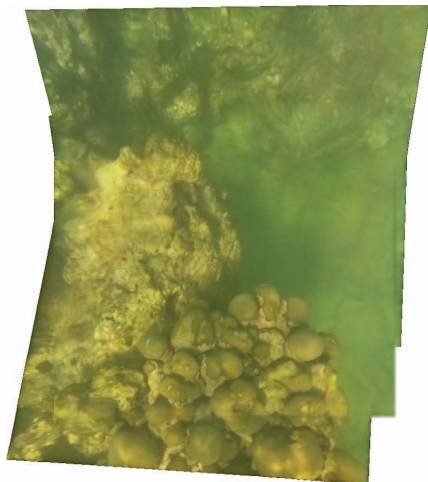
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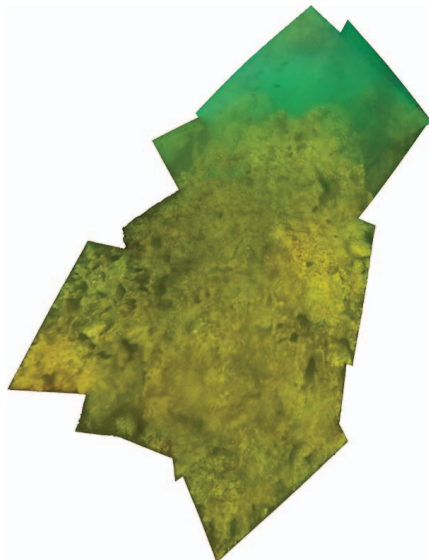
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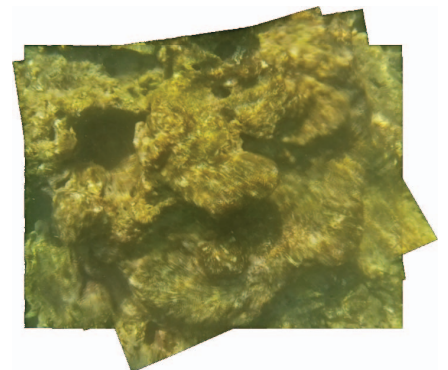
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(i)

Fig. 10. Different mosaics from images at shallow depth, scaled down to fit in the paper.

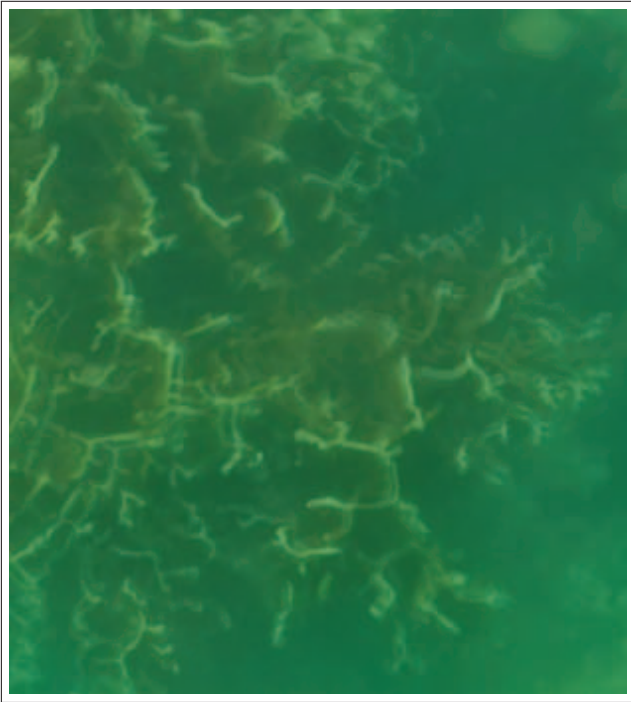


Fig. 11. Detail cropped from the mosaic of Fig. 9(f) which shows ghosting on the fire coral.

sensor as extracted from accelerometers (roll and pitch) and magnetometers (yaw) and the GPS location. From the visual data collected several different features were extracted and tracked. An analysis indicated the most suitable to be the SURF feature.

Future modifications of the drifter design will include a battery for the GPS device in order to maintain the GPS fix between deployments. It was observed that a significant amount of time was spent waiting for the GPS to acquire a satellite fix. Furthermore, a 433MHz RF transmitter will be added to each drifter in order to broadcast the GPS location over larger distances, thus enabling recovery operations if the drifter is carried outside of visual contact. The loss of one of our sensors highlighted the need for persistent tracking. Last in our future plans is to use the drifters in a multi-robot exploration scenario, utilizing the Wi-Fi signal to enable cooperative localization [43].

For more in-depth studies, the topography of the seafloor has to be reconstructed in 3D [32]. Future work will employ the Bundle Adjustment package named *Ceres* [44] using the SURF [35] feature detector in order to produce a globally optimal estimate of the trajectory of the camera, and the 3D position of the features. The resulting maps will enhance the autonomy capability of underwater robots [45], enabling them to localize on a geo-located visual map.

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