Towards a new Methodology to Evaluate the Environmental Impact of a Marine Outfall Using a Lightweight AUV

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***Abstract*—This paper describes a new methodology to analyze the effect of a marine outfall and its toxic waste on the surrounding submarine ecosystems, combining divers and a lightweight *Autonomous Underwater Vehicle* (AUV) deployed and controlled from a small recreational boat. The innovation here is twofold: a) the relatively low cost equipment and human resources used in the overall process and the subsequent minimization of human risks, b) the application of all the technology that implies the use of an autonomous vehicle in this particular application, (automatic geo-localization, accurate mission programming and execution, increasing mission time or diverse sensorial data recollection). The process intends to go one step beyond the current methods employed to inspect marine industrial infrastructures, shipwrecks, geological or benthic zones of special interest, based on the participation of divers and, in some cases, *Remotely Operated Vehicles* (ROVs). The case study presented in this paper corresponds to the inspection of the sewage outfall in Palma de Mallorca, started after the detection of *Cyanobacterium* on the surrounding seafloor, a living organism which appearance indicates elevated concentration of nitrates and pollution in the water.**

I. Introduction

Industrial, touristic, nautical and sanitary marine and submarine infrastructures are a very important part of the social and economic development for all the cities that are located on the sea coast. The inspection and the corresponding preventive maintenance of many of these infrastructures is not always made with the needed regularity, and the repairs are only made after the consequences of a problem arise. The current methods usually used to inspect marine and submarine infrastructures or areas of special interest are based on divers and, sometimes, ROVs. Depending on the dimensions of the infrastructure, or the area to be inspected, and the depth at which it is located, the number of divers, the number of immersions or the security measures must increase to complete the mission. The use of divers is costly for several reasons: a) the security conventions obligate to operate divers in groups and to follow strict protocols, b) the missions are limited in time by the capacity of the scuba oxygen tanks, making necessary to conduct several immersions. Since using human divers is not feasible for operations at great depths, companies and research institutions usually use ROVs (Remotely Operated Vehicle) or crewed vehicles, increasing operational costs and human security protocols. In the last decades, several types of advanced submarine vehicles have been used to inspect underwater infrastructures, trying to provide some added value to all these processes. The OceanRINGS [9] is a suite of technologies for sub-sea operation based on the use of mini-ROVs to inspect offshore sub-sea oil and gas installations. Authors claim that the early detection of defects in the infrastructures using this new technology can save up to a 20% of their operational and maintenance costs.

Conversely, the use of AUVs can reduce the mission complexity and cost minimizing the human resources, automatizing as many procedures as possible, and untying the robot from the support vessel. Palomeras *et al* used an AUV to inspect and collect images from a dam to find cracks in the concrete at a certain depth. Some systems are focused on solving the sewage pipe inspection problem from inside, either using *Remotely Operated Vehicles* (ROVs) [4] or micro AUVs [5]. This later work is mainly focused on urban infrastructures. Other projects were focused on inspecting underwater pipes from outside. For instance, Ortiz *et al* [6] proposed a new visual approach to detect and track the pipe outline in a video sequence. The tracking data was used to guide the AUV over and along the pipe to inspect it visually. C & C Technologies [10] are dedicated to the offshore survey industry, being the deep sea pipe inspection one of their specializations. However, the dimensions and size of their autonomous vehicles are considerable and their operational costs are only affordable by big customers.

One of the important problems in coastal medium-big towns is the spill of the sewage plants purified waters into the sea. The European Law specifies in its directive 91/271/CEE the obligation of all towns with more than 15000 inhabitants to purify the urban sewage to contain less than 35mg/L of suspended solids. If any plant has a failure or it is insufficient to treat all the incoming sewage, the unpurified waters are spilled into the sea, and, in consequence, the European law is breached. The literature is plentiful in analysis of the beneficial effects in the marine ecosystems that a reduction of sewage emissions can cause [7]. Sewage sea spills can be detected and identified using the appropriate sensors on an AUV. For example, Ramos and Abreu [11] used an AUV equipped with a Sea-Bird Electronics 49 FastCAT CTD sensor to measure conductivity, temperature and depth. The sensor data was used to build geo-referenced maps of sewage dispersion, measuring anomalies in the temperature and salinity of the water. However, in this solution, images were not used for any analytical purpose.

Due to the increase of permanent population in the city of Palma de Mallorca and the general overexploitation caused by the tourism, in the last years the capacity of the main sewage plant is under the current necessities. The water coming from the city rain sewer joints to the sewage infrastructure, all going to the plant, which overloads it when there are big storms with heavy rain (something quite common in the Mediterranean after the summer). In these situations, and in order to avoid an overflowing of the plant deposits, its floodgates are opened releasing all the unpurified water to the sea. The sewage plant was build 42 years ago, according to the current national regulations, with a drainpipe 1km long into the sea. The length of the pipe has revealed insufficient to avoid spreading all the undesired material over the closest coast, being all the infrastructure clearly obsolete.

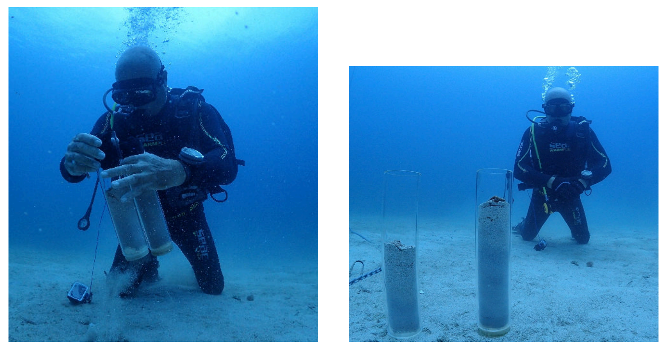
The number 172 of the journal Gaceta Nautica [1], appeared in October 2016, published the discovery made by a group of divers of several harmful effects caused by the emission of unpurified water in an area of 400m^2 and 15 meters depth, around the mouth of the aforementioned sewage pipe. The area was completely empty of fish, and the bottom clean of Posidonia Oceanica (P.O.). P.O. is a slow growing seagrass endemic from the Mediterranean and with a great ecological value. Posidonia can colonize vast extensions of the seabed forming dense meadows, from shallow waters up to 40 meters depth. The formation of the meadows takes long time, but if the water conditions are optimal its progress is continuous. P.O. meadows are declining at the alarming rate of a 34% in the last 50 years [14], but mostly due to an accumulation of local impacts. There are multiple local stressors that affect the Posidonia survival, but 2 important causes are the pollution caused by the human activity inherent to the coast super-urbanization or fish farming, and the climate change [16]. Taking into consideration that the Palma bay is mostly occupied by P.O. in all the colonizable areas, any regression of this seagrass (its absence, low density or the presence of dead matte spots) can be, most likely, one of the consequences of the outfall and a good indicator to evaluate the state of the affected zone. A first visual inspection conducted by the divers permitted to detect also some red spots over the sand, which, after several biological analysis, revealed to be fermented *Spirulina*, a *Cyanobacterium* that proliferates in presence of high concentrations of nitrates, phosphates and lack of oxygen. The lack of life in this area, except the *Spirulina*, is a strong indicator that the effect of the sewage under the sea is being devastating. Figures 1-(a) and 1-(b) show two photos of the discovered *Spirulina* and figures 2-(a) and 2-(b) show the divers taking column-type samples of sand and water *in situ*.

During the same immersion, some photos of the Palma sewage pipe revealed the existence of several holes in it, from which part of the water flow was flushing out without arriving to the mouth filters. Figure 3 shows two different views of two lateral holes in the sewage pipe. The recollection of this type of images is important to determine the state of the infrastructure and to prepare maintenance actions.

Due to the limitations of inspecting the sewage pipe and the affected area by divers and the lack of a ROV, the *Systems Robotics and Vision Group* (SRV) of the University of the

(a) (b)

Fig. 1: Two images of the Spirulina found in the sea bed of Palma near the sewage pipe mouth. courtesy of Juan Poyatos Oliver *et al*



(a) (b)

Fig. 2: Two images of the divers taken samples of sand and a water column *in situ*. Courtesy of Juan Poyatos Oliver *et al*

Fig. 3: Two images showing the Palma sewage pipe with two holes in it. Courtesy of Juan Poyatos Oliver *et al*.

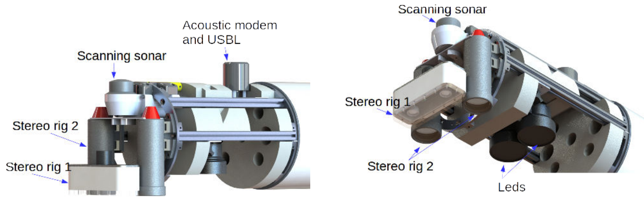


Fig. 4: Two perspectives of the vehicle payload.

Balearic Islands was required to survey the area of interest with an AUV, model SPARUS II [2].

Our purpose is twofold: 1) moving one step forward from the traditional underwater sewage pipe inspection techniques using divers or ROVs, boosting the use of AUVs for this particular application, or in general, for the inspection of any other infrastructure, to reduce costs and increase reliability, and 2) creating a methodology to observe and diagnose the state of the underwater infrastructures, and to inspect the areas surrounding them, to see their affectation on the environment.

The preliminary experiments conducted around the Palma sewage pipe are just a sample of the on-going expeditions and the start of a forthcoming series. The objective is to determine the extension and state of the total affected area around the outfall, its exact location with respect to the pipe mouth, and its progress over time. Results include the geo-localization of the areas and points of interest, the dimensions of the affected zones and some photo-mosaics of the seabed to see clearly its composition and current global state. Although this is a work in progress, the recovered information is being and will be used to warn the administration and the scientific community about the unfulfilment of the European directives and the enormous damage cause to the local marine biosphere.

II. The experimental set up

The AUV used for the inspections is a model SPARUS II. The vehicle weights, approximately 50 Kg, and it is equipped with a forward looking scanning sonar, two stereo rigs (one looking downwards with the lens axis perpendicular to the vehicle horizontal axis, and another one with an adjustable position from the frontal direction down to the downward direction - at 90° from the frontal), a DVL, an IMU, a pressure sensor and an Evologics S2CR 18/34 USBL acoustic modem which provides a communication link with a nominal transmission speed of $13.9 kbps$ in an available range up to 3500m.

Figure 4 shows two different views of the vehicle payload CAD design, where both camera pairs, the sonar, and the acoustic transducer are seen.

The USBL head was submersed 2.5 meters into the water and it was attached to the boat with a 4 meters long stainless steel stick. The top of the stick held a GPS card, and both, the GPS card and the USBL were linked to a laptop located also on board through an Ethernet cable. The GPS attached to the USBL head permitted to calculate the vehicle *North-East-Down* (NED) referenced world coordinates composing the USBL vehicle position with the USBL head global coordinates. The vehicle global position is sent back to the vehicle via the

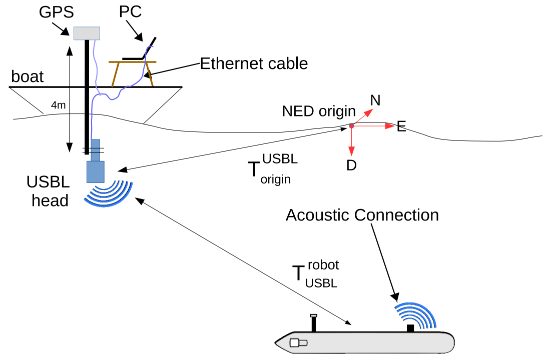
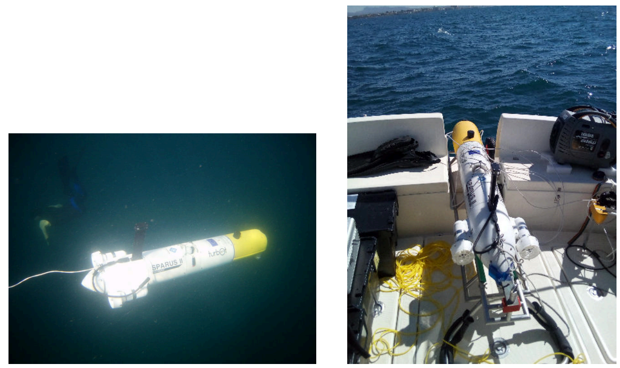


Fig. 5: Experimental setup.



(a) (b)

Fig. 6: (a) Sparus II moving underwater, (b) SPARUS II on the boat before being launched.

acoustic link, and once in the vehicle, this position is used for navigation and control. The vehicle integrates all the localization data provided by the IMU, the DVL, a visual tracker and the global USBL position in a double *Extended Kalman Filter* which returns a filtered state composed by the vehicle pose $(x, y, z, roll, pitch, yaw)$, the linear and the angular velocities $(v_x, v_y, v_z, w_x, w_y, w_z)$ and the linear accelerations (a_x, a_y, a_z) [12].

The idea is illustrated in figure 5, where T^{USBL}_{origin} is the position transform between the NED origin and the USBL position at a certain time, T^{robot}_{USBL} is the vehicle position transform with respect to the USBL frame at the same instant, and T^{robot}_{origin} is the transform between the robot and the NED origin ($T^{robot}_{origin} = T^{USBL}_{origin} * T^{robot}_{USBL}$).

The boat used for carrying and taking the vehicle to the mission area is an Astinor model 820, 8.5 meters long, with 2.85 meters wide, and a draught of 0.7m.

Figure 6 shows two additional pictures of the submarine during one of the field mission.

III. Experiments

For all the experiments, the autonomous robot SPARUS II was taken to the area of interest by boat, 400m away from the mouth pipe, and once there, it was programmed to move in 4 different trajectories at a constant speed of 0.5 m/s. Three of them at a constant altitude of 6 meters and an approximate

Fig. 7: The inspected area with some of the missions.

duration of 25 minutes each one, navigating at: (1) two lawn-mower surveys, one of $400m^2$ and the other of $1000m^2$, in order to see the state of the bottom, (2) one triangular route with two straight sides of 200m each one, with the objective of measuring the range of the damaged area. The last and longest trajectory was programmed to inspect a greater area moving away from the pipe to the south-east, in order to get additional information about the range and the type of the affected area. The length of this last trajectory is nearly 1 km, and, in order to get images of the bottom with better quality than the ones obtained in the previous experiments, the vehicle was programed to navigate at a constant altitude of 2.8 meters. This last mission lasted 1.5 hours, generating more than 100 GB of information stored in the vehicle hard disk, including images, DVL, USBL, IMU, pressure and vehicle pose data.

During all the missions, the bottom looking cameras of the vehicle recorded continuously video sequences of the seabed. Videos were grabbed at a frame rate of 10fps but key frames were extracted at 5fps, with an approximated overlap between consecutive images of a 35%, and all down-sampled to 480×360 pixels. The key frames of each mission were stitched together to form photo-mosaics of the covered areas. Since the obtained images were poor in salient features due to the nature of the bottom (Posidonia and sand) and the lighting conditions, the position of each image in the mosaic coordinate system was the vehicle global pose estimated by the navigation filter when each image was taken, but expressed in pixels. For these experiments, the navigation module only integrated the IMU, DVL, USBL and pressure sensor data. The final mosaic was composed by means of the Image Stitching OpenCv pipeline [3], which includes a previous finding seams and a later color blending processes.

The photo-mosaics permit a general view of the whole surveyed zone in one single image, facilitating the inspection and a complete diagnosis of all the affected area. Once the general view of the environment was obtained, the criteria to evaluate its state was the presence of, mainly, P.O., and also other forms of marine live. Furthermore, if these experiments are done periodically, the progression or regression of the Posidonia and other living beings observed in subsequent missions will be indicative of the expansion or regression rate of the zone affected by the spills. One of the advantages of using our AUV is the possibility to run exactly the same missions several times, starting at, approximately, the same location, depending on the precision and accuracy of the GPS samples.

Figure 7 shows the exact location of the explored area, where the cyan dot corresponds to the pipe mouth, the red star corresponds to the whirlpool caused by the emission of the wasted water, and the 4 surveys conducted by the vehicle are depicted in pink, blue, yellow and brown. All missions started at approximately 400 meters from the whirlpool. It is assumed that the sewage spill does not affect the immediate area located just by the mouth pipe, since, the pollutant material is flushed away with force, being deposited at a certain distance. The *Spirulina* was found at an approximate distance of 400 meters away from the pipe mouth.

Figure 8 shows the detail of the covered trajectories estimated by the internal vehicle localization EKF filters which integrated all the aforementioned sensors. This figure also shows a summary of the obtained data. In order to facilitate the analysis of the longest trajectory, this was divided in 7 consecutive sections. For each section, its respective photo-mosaic was build to evaluate the state of the bottom. Red circles and red squares mark the origin and the end, respectively, of the 7 different sections. Origins are labeled with the text osi and ends with fsi. For instance, the red circle labeled with *os1* indicates the origin of the section 1, while the rectangle labeled with *fs1* indicates the end of the section 1, and so forth. One of the important descriptors of Posidonia meadows is its bottom coverage [13]. A high density of seagrass in an extend area of the bottom indicates a meadow in a good condition while low coverages with disperse spots of seagrass indicate a clear regression or a high mortality. Then, blue ellipses of figure 8 mark areas with a relatively high density of P.O. while green ellipses indicate areas with a sparse presence (low density) of P.O.. The rest of the trajectory corresponds to areas with sand and fragments of dead seagrass. All these information was obtained by visual inspection, observing the video sequences and analyzing the photo-mosaics of each section and of the different datasets. Figure 9 shows the photo-mosaic of the area viewed during the pink survey. This mosaic evidences the lack of any live, neither P.O., nor other species of algae or fish, only sand and rests of dead matte.

Several important conclusions can be inferred by observing figures 8 and 9: a) the P.O. bottom coverage is irregular and disperse in the majority of the inspected areas; b) the first surveys revealed areas completely barren; c) the P.O. distribution suggests a clear regression towards the pipe mouth, but it does not permit to draw any limit, yet, between *dead* o *alive* zones; additional inspections are needed.

Figure 10 shows the photo-mosaic obtained from images taken in sections 5. This mosaic was formed by 501 key frames and covers 150 meters of trajectory, approximately. In this area, the bottom is formed mainly by sand, dead seagrass and a few spots of alive P.O., marked in red circles.

Figure 11 shows two portions of the mosaic of section 5 (from image number 269 to 373), as a sample of a *dead* zone. Both figures were build with only 14 images, covering, approximately, between 6 and 7 meters of the trajectory. The clear areas correspond to sand, while the sparse black spots

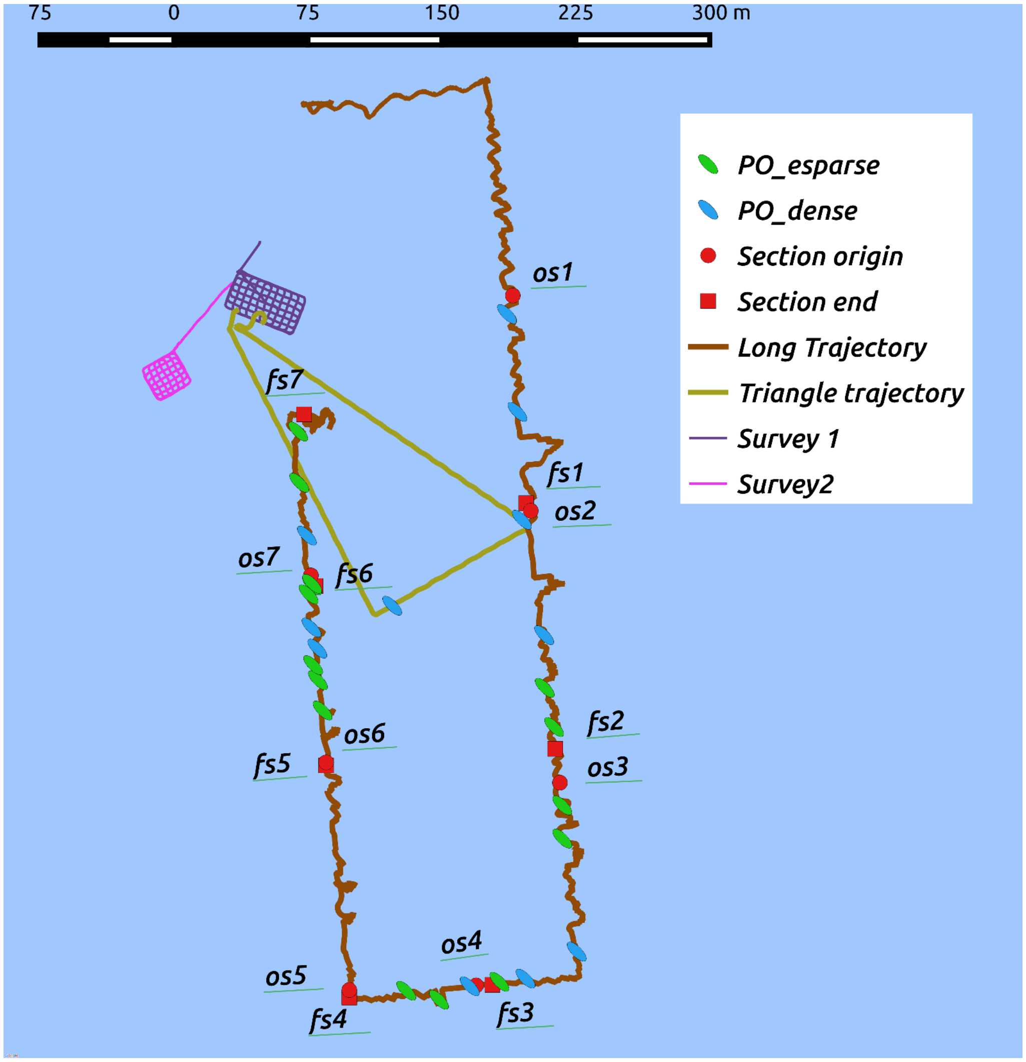


Fig. 8: Vehicle trajectories with the relevant observed data. Red circles and red squares indicate, respectively, the origin and ends of the different trajectory sections. Blue and green ellipses indicate areas with high and low density of Posidonia.

correspond to some rests of dead matte. Figure 12 shows two mosaics of two different portions of section 2, as a sample of a zone where the PO still occupies the bottom with a relatively high density. Both figures were composed with 21 images, between the number 242 and 261 and from the 303 to the 325, covering, approximately, 7 meters of the aforementioned trajectory, each one. In both mosaics, the darker areas correspond to the alive P.O. while the clearer areas correspond to sand. Although the density of P.O. is not as it is usual in healthy meadows, the presence of seagrass is quite significant here.

Finally, figures 13 and 14 show two mosaics of other two portions of section 2, where the presence of P.O. is sparse. The first mosaic was formed with 17 frames (from image 396 to 413), covering 5 meters of the second section, while the second one was build from the first 65 images of the sequence, covering 20 meters, approximately. In these mosaics, it is difficult to distinguish between the dead matte (see some samples marked in red) and the rests of alive P.O., (see some samples marked in blue).

Since P.O. usually forms very dense meadows when the environmental conditions are optimal, all the analyzed sections reveal a clear regression of this specie in a still undefined area nearby the sewage pipe. The bottom coverage of P.O. is null in the pink and blue squared surveys, and in the triangular yellow trajectory, except in both distant vertex, and so is the presence of any other living beings. However, the brown trajectory shows some more areas with sparse spots combined with areas of a denser concentration of P.O..

These observations permit to conclude that the increasing presence of P.O. towards the south-east indicates a clear progression in that direction and an obvious regression of the marine live on the way to the pipe mouth. All the inspected area corresponding to the longest trajectory reveals certain quantity of P.O. in greater or lesser extend, but in clear declination with respect a regular healthy meadow. In order to get additional data useful to delimit and evaluate the direction and range of the whole affected area, and how it is affected, further experiments are currently being and will be done in forthcoming missions, following the same procedures, in the

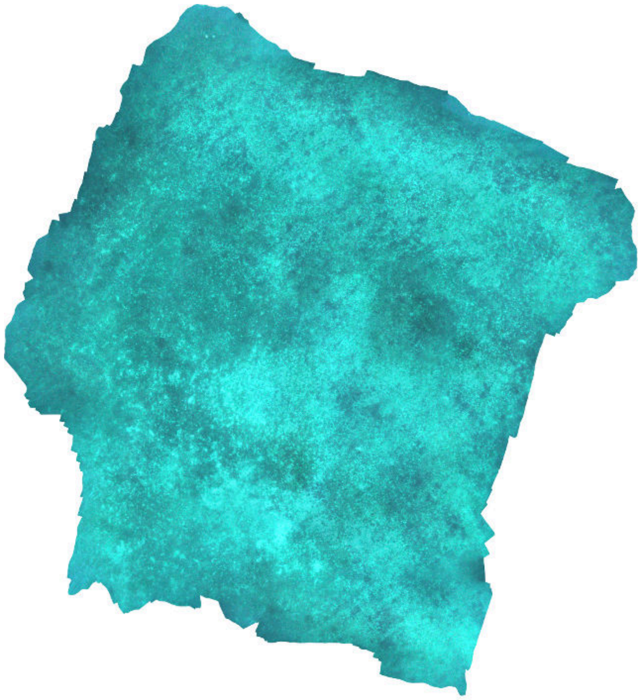


Fig. 9: Photo-mosaic of the pink squared survey.

same direction and all around the pipe.

IV. Conclusions

Anthropogenic activities in coastal urban areas affect considerably the physiology and the physiognomy of the local marine ecosystems. Sewer pipes, fish farms, recreational anchoring or fishing are some of the actions affecting the aquatic environments, and need of certain regulation and control. Nowadays, these control procedures are performed via divers combined, when longer and deeper missions are required, with ROVs. Current methodologies are expensive since require many specialized human and technical resources, which, usually withdraws all the recommended periodical or preventive actions. In the last decades AUVs have emerged as cheaper, more versatile, precise and secure systems for many underwater purposes. In this paper we present a new low cost methodology to inspect underwater areas with a lightweight AUV, a small boat and few specialized technicians. The case study presented here corresponds to the inspection of an area nearby a sewage pipe, where the biodiversity of the zone has been seriously affected by the sewage water spill. The navigation data captured by the vehicle sensors and the images grabbed during several autonomous missions permitted to see with detail the composition of the sea bottom in all the inspected areas; in particular the presence or absence of Posidonia Oceanica, a classical bio-indicator of the state of a Mediterranean marine ecosystem. The construction of several photo-mosaics from images grabbed during the missions and the inspection of the video sequences was of great utility to get some preliminary and encouraging conclusions about the state of the Posidonia meadows at a certain direction and distance to the pipe mouth. From now on, further datasets have to be extracted, in other directions and at different distances to complete the visual maps of the area, in order to deliver a

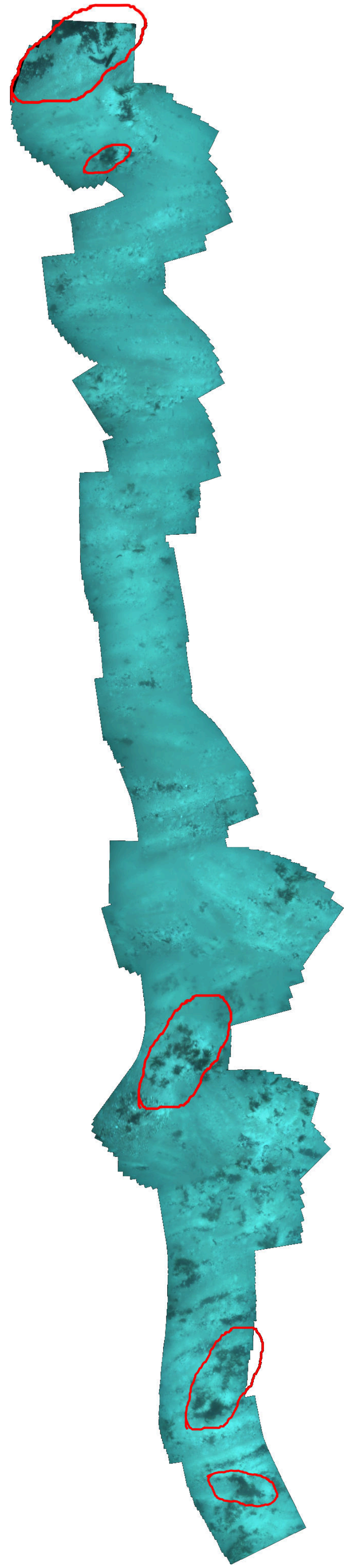
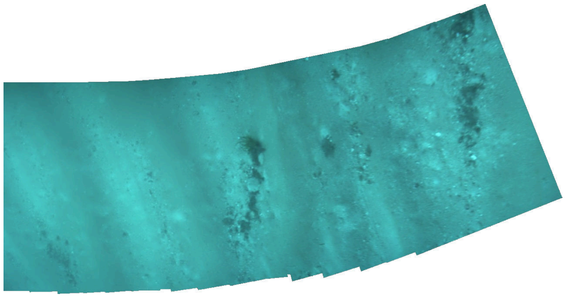
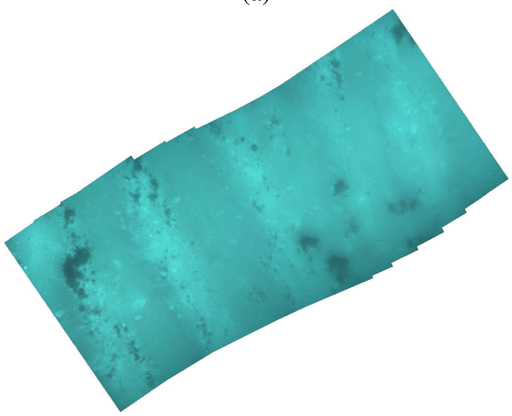


Fig. 10: Mosaic of section 5.

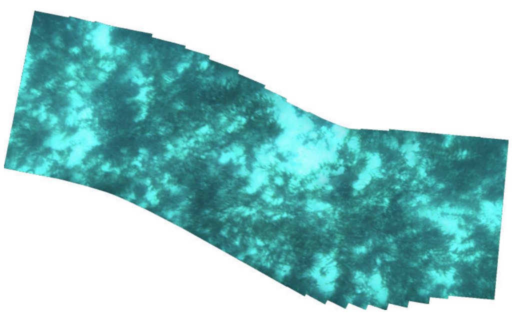


(a)

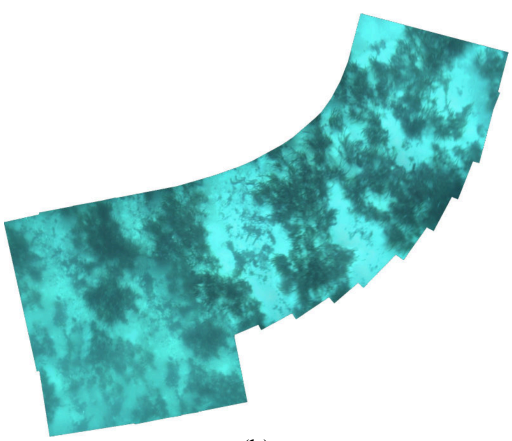


(b)

Fig. 11: Sub-mosaics of to two different portions of section 5.



(a)



(b)

Fig. 12: Mosaics of two different portions of section 2.

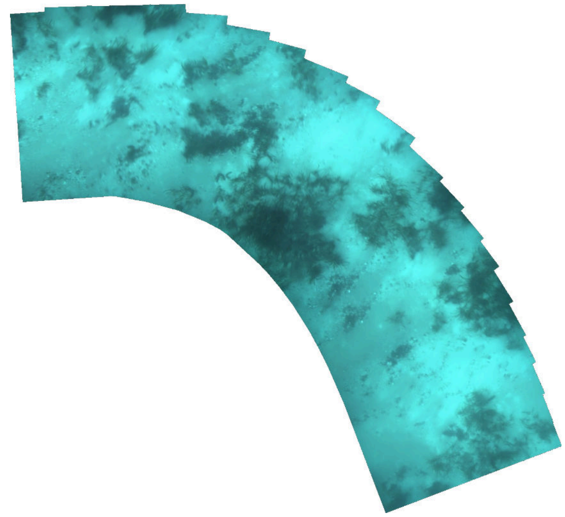


Fig. 13: A mosaic of a portion of section 2.

more complete diagnosis. Video sequences of the sewage pipe will also be taken in order to evaluate the evolution in time of its state. The same technique also permit to evaluate the state and conditions of any submarine infrastructure or wreckage. Our equipment permits to reduce operational costs without reducing the utility of the obtained data and the effectiveness of the procedures.

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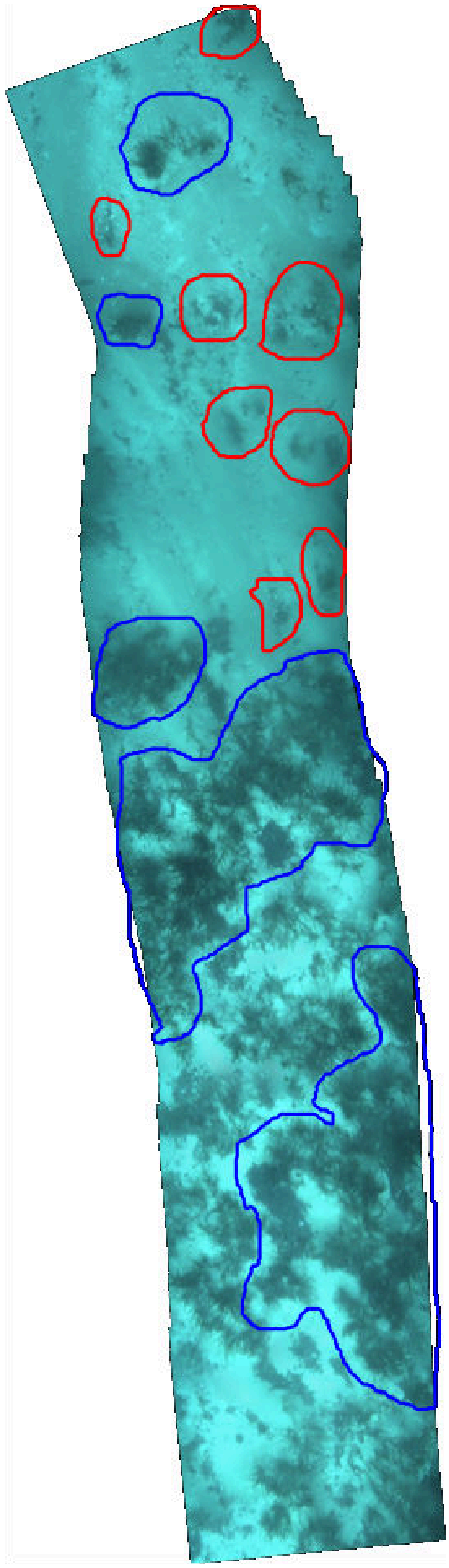

Fig. 14: A longer mosaic of a portion of section 2.

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