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The NOPTILUS project overview: A fully-autonomous navigation system of teams of AUVs for static/dynamic underwater map construction

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Abstract: Within the project NOPTILUS, a fully functional system/methodology had been developed that allows the cooperative, fully-autonomous navigation of teams of AUVs when deployed in Static or Dynamic Underwater Map Construction (SDUMC) or Dynamic Underwater Phenomena Tracking (DUPT) missions. The key ingredient of this fully functional system/methodology (called the NOPTILUS Planning, Assignment and Navigation Module – NOPTILUS PAN) is an optimal control algorithm – called Parametrized Cognitive Adaptive Optmization – (PCAO) – developed by one of the NOPTILUS partners (CERTH). PCAO is firstly tailored and modified so as to be applicable to the problem of autonomous navigation of teams of AUVs when deployed in SDUMC or DUPT missions. For this purpose, a nonlinear model is developed so as to capture the dynamics of the AUVs, their sensors and the underwater environment. More precisely, the original PCAO-based approach is revised so as to be able to efficiently handle information coming from the localization module, the underwater acoustic communication module, the situation understanding module as well as instructions from the operator. The information coming from these modules is handled by the NOPTILUS PAN module without the need to enter in tedious re-design tasks. Two real-life experiments (involving teams of AUVs deployed in static mapping or simultaneous static mapping and dynamic target taking) demonstrate the efficiency and practicability of the NOPTILUS PAN module.

Keywords: SLAM-TT, Exploration, Path Planning for Multiple Mobile Robot Systems, Trajectory Generation, Cognitive Robotics, Mapping, Marine Robotics

1. INTRODUCTION

Recent technological advances have made the usage of autonomous underwater vehicles (AUVs) more appealing in a variety of missions [1], which may include harbor security [2], [3], post-disaster infrastructure inspection [4], underwater archaeology [5], continuous infrastructure monitoring to prevent accidents [6], habitat mapping [7], etc. In all the aforementioned missions there are several factors that affect the performance of the AUV (in the case of a single vehicle) or of the overall team (in the case of a team of AUVs operating simultaneously). These are related with the technological limitations of the hardware which is used and the methodologies that process and fuse data to obtain valid conclusions related with the actual AUV performance. A key element of success in almost every mission is the ability to perform Static or Dynamic Underwater Map Construction (SDUMC) or Dynamic Underwater Phenomena Tracking (DUPT) by utilizing all the available resources.

There are, basically, two different problems that the team of AUVs faces when deployed in missions for SDUMC and/or DUPT. The first of these problems has to do with the ability of the AUVs to process their sensor measurements so as they create accurate maps of the environment. As creation of accurate maps requires the AUVs to "know where they are", such a problem is also known as the *Simultaneous Localization and Mapping (SLAM) problem*, i.e., the problem of processing the AUVs sensor measurements so as to simultaneously identify "where they are" and create the map of the external environment. The second part of the problems deals with the question "which trajectories the AUVs have to follow", i.e., the problem [1] of *trajectory generation* for the AUVs so as to maximize SLAM efficiency.

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[1] The problem of multi-robot *trajectory generation for maximizing SLAM efficiency* is also referred in the literature as *exploration* or *optimal motion strategy.* In the rest of this paper, these terms will be used interchangeably.

Most of the research work has concentrated on the problem of SLAM (in case of single-AUVs) or Cooperative SLAM (C-SLAM) in case where a team of AUVs is deployed. Very powerful SLAM and C-SLAM methodologies have been proposed recently and have successfully demonstrated in real-life situations. Despite, however, these advances, the vast majority of missions *rely on pre-specified AUV trajectories.* In other words, the trajectory the AUV has to follow is designed off-line, before its actual deployment. As the AUV is called to map a partially known or, in some cases, a totally unknown area, off-line designing of the AUV trajectories may become quite problematic: first of all, the off-line design is quite likely to "miss" areas of crucial information; moreover, it may lead the AUV to "waste" time mapping areas of little information. Thus, in practice, AUV-based mapping is accomplished by employing a costly and tedious repetitive procedure: firstly, an original trajectory is designed off-line, the AUV is then deployed and maps the area following to the off-line designed trajectory, then based on the created map a new trajectory is designed off-line again, the AUV is deployed according to this new trajectory, and so on. Apart from the fact that such a procedure is costly and tedious, it renders prohibitive the deployment of AUV in time-critical mapping missions or in cases where there are limited resources available, such as detection of sunken drums leaking chemicals or search-and-rescue missions. Most importantly, off-line generation of the AUV trajectories cannot take advantage and exploit the cooperative capabilities in case a team of AUVs is employed. Typically, multi-AUV deployment for mapping purposes employ again pre-specified trajectories with no or little interaction between the AUVs or, in the best case, the AUVs communicate with each other so as to improve their localization estimates and/or to make sure that they are moved in certain formation. However, full exploitation of the cooperative capabilities of a multi-AUV system cannot be accomplished by having the AUVs moving along pre-specified trajectories or in formation: the cooperation between more than one AUVs can speed-up considerably the overall mapping process, by having the AUVs coming closer in areas of high importance and by having the AUVs sharing sensor measurements and mapping information.

2. THE NOPTILUS APPROACH

Within the project NOPTILUS we develop and evaluate both using theoretical analysis and simulations as well as real-life experiments a new methodology that attempts to overcome the limitations described previously. More precisely:

To start with, most of the existing approaches are based on the assumption that the sensor characteristics are linear affected by Additive Gaussian White Noise (AGWN). Such an assumption is far from being realistic especially in underwater environments. Typically, the result of such an assumption is that the SLAM accuracy deteriorates as time goes by, leading to poor mapping and failure of the overall mission after a while. In our approach, we first develop a realistic model for the sensor characteristics which takes into account all the nonlinearities and other limitations of the underwater sensors [**[8]**, **section 2**]. What is really important to mention is that *our goal is not to use such a nonlinear sensor model in the underlying SLAM approach used: the NOPTILUS PAN module is intended to be used with a variety of existing and well accepted SLAM methodologies; the nonlinear sensor model is used by the NOPTILUS PAN module so as to make sure that the AUV trajectories are calculated so as to minimize the effect of nonlinearities and any other phenomena that contribute to the deteriorating SLAM efficiency.* In other words and given any SLAM methodology the AUVs may be using, the NOPTILUS PAN module is designed so as to make sure that it minimizes the effect of nonlinearities and other factors that contribute to the divergence of the SLAM accuracy.

One of the most severe limitations of multi-robot trajectory generation for maximizing SLAM efficiency is the fact that such a problem is an NP-hard optimization problem. Most of the existing approaches employ one-step-ahead optimization or relaxed versions of the NP-hard trajectory generation optimization problem to overcome such a limitation. Such approaches, however, may end-up being quite problematic. Initially, the calculation the closed-form (i.e., analytical mathematical form) that relates the SLAM efficiency to the overall multi-robot team dynamics is not trivial. However, calculating of the analytical form of SLAM efficiency is the least of the problems encountered: the most important problem is due to the fact that optimizing the SLAM efficiency may lead to severe *deadlocks* or, mathematically speaking, to getting stuck into local maxima. As a matter of fact, as we reported in the NOPTILUS Deliverable D4.1, one-step-ahead optimization of the SLAM efficiency can lead to situations where the AUVs get stuck to deadlocks even after they have accomplished only 10-20% of their mapping mission. A similar situation arises in case of relaxations of the original NP-hard problem.

The approach adopted for the development of the NOPTILUS PAN module is to use an alternative to one-step-ahead optimization or relaxations of the original problem. More precisely, the NOPTILUS PAN module is based on a recently introduced *approximate optimal control* methodology – abbreviated as Parametrized Cognitive Adaptive Optimization (PCAO) [9, 10] – specifically tailored to the problem of multi-AUV exploration. PCAO, instead of relaxing the original NP-hard problem, *it does the best it can so as to approximate its optimal solutions by a computationally tractable decision making mechanism.* In simple words, the PCAO approach solves the following problem: given a parametrized decision making mechanism whose real-time implementation is practically feasible (for a fixed set of its parameters), find the set of the decision making mechanism's parameters that optimally approximate the – non-practically feasible – optimal solution. The exposition and development of the PCAO-based methodology is presented in [**[8]**, **section 3**].

It must be emphasized that PCAO possesses three very significant advantages over alternative approximate optimal control methodologies that may also be applied for the solution of the problem at hand. The first of these advantages of the proposed approach is the fact that instead of attempting to optimize a measure related to the SLAM efficiency, it optimizes an equivalent measure that is based on the well known in optimal control and dynamic programming Hamilton Jacobi Bellman (HJB) equation. The use of such an HJB-related measure *embeds the NOPTILUS PAN module with fault-tolerant characteristics: whenever one or more AUVs are added or removed, no tedious re-design is required as the NOPTILUS PAN decision making mechanism needs to just switch to a new set of parameters* that are already available [**see [8], section 3.3**]. It is worth emphasized that the switching to this new set of parameters does not have any effect to the approximately optimal nature of the overall scheme: whenever one or more AUVs are added or removed, the decision making mechanism is switching to a new one that automatically does the best it can given the new team's configuration.

The second of the advantages of the proposed approach is that is can straightforwardly incorporate additional constraints, requirements and objectives other than mapping efficiency. More precisely:

• In the original approach for the NOPTILUS PAN module described in [8], both the performance criterion as well as the information provided in the multi-AUV decision making mechanism depend on the mapping efficiency at the different locations of the area to be mapped. As it is seen in the NOPTILUS [**11**], the use of *a transformed version of the mapping efficiency can significantly assist any navigation scheme* that attempts to optimize such a transformed version in avoiding deadlocks and in speeding up the accomplishment of the overall mapping procedure. In [**see [12], section 3.1**], we revise the transformed version of the mapping efficiency of [**11**] by incorporating a more accurate model for the sensor noise characteristics as well as terms that can significantly improve the navigation scheme (as compared to the original transformed version presented in [**11**]). This new transformed version depends not only on the mapping efficiency at the different map locations and the effect of nonlinear sensor noise characteristics but also on the "importance" of each different map location for the efficiency of the overall mapping procedure (in simple words, the introduction of the "importance" of the map locations is used in order to avoid situations where the mapping procedure leaves "holes" in the map). In [**see [12], section 3.2**] we show how such a transformed version can be incorporated in the originally developed algorithm.

• The original or transformed versions of the mapping efficiency do not directly incorporate information regarding the *localization accuracy* of the overall scheme. As a matter of fact, the PCAO-based approach presented in section D7.1 has been developed under the assumption that the locations of the AUVs are perfectly – or, with satisfactory accuracy – known. Such an assumption, apparently, is not realistic especially in cases of long-duration experiments where the localization accuracy of the AUVs drifts as time goes by. Working similarly as in the case of the transformed version of the SLAM efficiency, we extend the original methodology so as to remove such an assumption. More precisely, we incorporate direct information coming from the *cooperative localization module* developed by the partner TSI. [**see [12], section 4**]: both the performance criterion as well as the multi-AUV decision making mechanism are extended/revised so as to incorporate information not only of the mapping efficiency but also on the localization accuracy. Simu-realistic experiments indicate that the NOPTILUS PAN module operates quite efficiently when the assumption on perfect – or, at least, satisfactory – localization are removed.

• Similarly to the transformed version of the mapping efficiency and the localization accuracy, information can be directly incorporated regarding *underwater acoustic maps* in which case, the AUVs are navigated – simultaneously to optimizing mapping efficiency and localization accuracy – to locations that optimize the probability of successful communications [**see[12], section 5**]. The underwater acoustic maps produced by the NOPTILUS partner TUDelft can be thus directly incorporated within the NOPTILUS PAN module.

• Finally, the NOPTILUS PAN module can directly interfaced to the *situation understanding* module developed by the partner TSI as well as to the *mission operator*. In essence, the PCAO-based approach used within the NOPTILUS PAN module allows to incorporate *rules and objectives* that can be sent – on the fly, during the mission – either by the situation understanding module (in case this module identifies an event that calls for specific rules or objectives to be met) or the operator (in case she/he decides that additional rules or objectives to ones already incorporated in the NOPTILUS PAN module are needed). This is made possible by incorporating within the NOPTILUS PAN module an approach – developed in the ICT FP7 project AGILE [13] – which allows, additionally to the performance requirements that related to mapping efficiency, localization, communications, etc, to also incorporate any type of "if-then-else" rule in the PCAO approach: such an "if-then-else" rule can be activated during the mission, in which case PCAO automatically takes care of the requirements of this rule without the need for redesigning the NOPTILUS PAN module. A large variety of rules and objectives introduced by either the situation awareness module or the operator can be thus incorporated within the NOPTILUS PAN module. The overall approach for incorporating rules and objectives is described in [[**12**], **section 6**].

Last but not least, the third of PCAO's advantages has to with the fact that *PCAO can efficiently deal with problems of very large dimensions*: as the problem of finding the set of the decision making mechanism's parameters that optimally approximate the – non-practically feasible – optimal solution is essentially transformed into a static optimization problem of *thousands* of parameters, it is really important to apply a methodology that can deal with such a large number of parameters. Simulation experiments performed for the multi-AUV mapping of complex seabed areas demonstrate that the PCAO-based approach adopted for the development of the NOPTILUS PAN, significantly outperforms well-established alternative methodologies [**see [12], section 7**].

We finally demonstrate that the NOPTILUS PAN module can be deployed in real-life Static or Dynamic Underwater Map Construction (SDUMC) or Dynamic Underwater Phenomena Tracking (DUPT) missions. More precisely, as we report in [**see [12], section 8**], two different real-life experiments were conducted in the port of Oporto employing a team of AUVs. In the first of the experiments

, three AUVs are deployed to explore/map an underwater area with the one of these AUVs becoming non-operational (stopped to operate) at some point during the mission. As we report in [**see [12], section 8**], the overall mission was quite successful with the AUVs being able to accomplish the mission when one of them left the team. The second of the missions involves two AUVs that are deployed to simultaneously map the seafloor and track a dynamic event (track a target given only distance measurements). Again, the operation of the team was quite successful.

3. INFORMATION FLOW THROUGH THE NOPTILUS PAN MODULE

The NOPTILUS PAN (Planning, Assignment and Navigation) module constitutes the backbone of the NOPTILUS PAN, and has been extensively described in [**8, 12**] Figure 1 illustrates the way that the available information flows from the other modules, in order to be produced the new waypoints commands.

• Initial the designer has to specify a pool of possible scenarios that may include a variety of different number of AUVs, with or without target tracking, etc. Sequentially, and still in an offline fashion, the designer has to run each one of them, inside the NOPTILUS PAN simulator [**8**] and to produce the corresponding control matrix P, using PCAO algorithm(for more information see [**8**]). The results of that process are stored in the Storage Module so as to be accessible, not only at the beginning but even during of the experiment. *It is worth highlighting that, in this step we do not solve all possible problems that may be occurred, in order to just apply the appropriate solution afterwards in the real experiment, but we found for each abstract class of them, the best possible way to translate the real-time data into new waypoints.* Moreover, something like that would be impossible due to infinite combinations of problems but mainly because we can't know the morphology of the operation area (and hence the sensors' measurements) or/and the dynamical target's movement.

• As soon as we have completed the building of the storage module, achieving satisfactory minimization of error term for each scenario [[**12**] **section 3**], we are ready to operate. At any time step of experiment the new waypoints are produced using the following procedure:

(1) When the AUVs reach their new destinations, they employ their sensors and transmit back *raw measurements.* At the same time, the localization algorithm ([**14**]) makes an *estimation about the current position* in x-y plane of the AUVs, using the AUV-to-AUV distances both with the navigation commands. This two inputs are used, at first, in order to compute two key elements:
(2) The current *tiles estimation*, which is a metric about the mapping quality at every tile and the *mapping efficiency* which corresponds to the calculation of some terms which have been proven to be helpful([[**12**] **section 3**]) for the efficiency of navigation task.
(3) Simultaneously, a measure about the quality of the underwater communication, for the AUVs positions, is available via *Received Signal Strength* abbreviated as RSS([**15**]).
(4) In the sequel, the appropriate scenario is selected from the storage module. If any changes has arisen, regarding to the number of AUVs (addition/removal) or/and the module from situation understanding or/and some arbitrary operator's command, the appropriate scenario will be found and the corresponding control matrix P will be returned.
(5) According, to the methodology of the [[**8**] **section 3**] with the extension of [**12**], the new near-optimal waypoints will be produced, by the control matrix P and the values from a) *Tiles Estimation* b) *Mapping Accuracy* c) *Pose Estimation* d) *RSS*. In other words, the control matrix P, is going to be used as a "translator" of the available information.
(6) But before we actually send the AUVs to that new waypoints, we must make sure that they are valid, in the sense that do not violate any of the operational constraints. If it is necessary we project the navigation commands so as to meet the constraints, and send them to the AUVs as new directions.

4. REAL LIFE EXPERIMENTS

In real life experiments apart from the task to build a detailed map of a sub-area of the Oporto's harbor the AUVs were called to a) continue to operate in case where one of the AUVs has some malfunction and eventually stops and b) simultaneously track the movements of a dynamic target. The experimental environment can be described as follows:

- In both cases the map is a square area with dimensions equal to 240 × 240 meters.
- The AUVs (Noptilus-1,Noptilus-2 and Noptilus-3) that are available belong to the class of LAUVs.
- The number of AUVs is equal to $N_R = 3$ for the first scenario and $N_R = 3$ for the second one.
- The AUVs are moving within the terrain's limits, i.e., within $[X_{min}, X_{max}]$ and $[Y_{min}, Y_{max}]$ in the x- and y-axes, respectively. Each AUV remain in constant z so as to neglect any collision possibility.
- The duration of each experiment is $T = 450$ time-steps (where by a new time-step is defined whenever new waypoints are sent to the AUVs).

4.1 Experiment 1: One AUV is out, but the mission has to continue

In this experiment we started the mapping task using a squat of 3 AUVs. The proposed algorithm, as described is Deliverable D7.1 and extended in this Deliverable, was starting to produce waypoints in such a way to fully exploit the 3 AUVs capabilities and dynamics (installed sensors, maximum speed, etc.). [2]

Figure 2a illustrates the progress of 3 AUVs (blue lines) until the time-step 90, with the current AUVs' positions (magenta color) at this time-step. The black tiles corresponds to ones that have not ever been measured by any of AUVs, while the colorful ones correspond to the areas

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[2] The readers are kindly referred to `https://www.youtube.com/watch?v=WnTSBBKFrLI&feature=youtu.be` , where they can watch the whole progress of operation in a two minutes video.

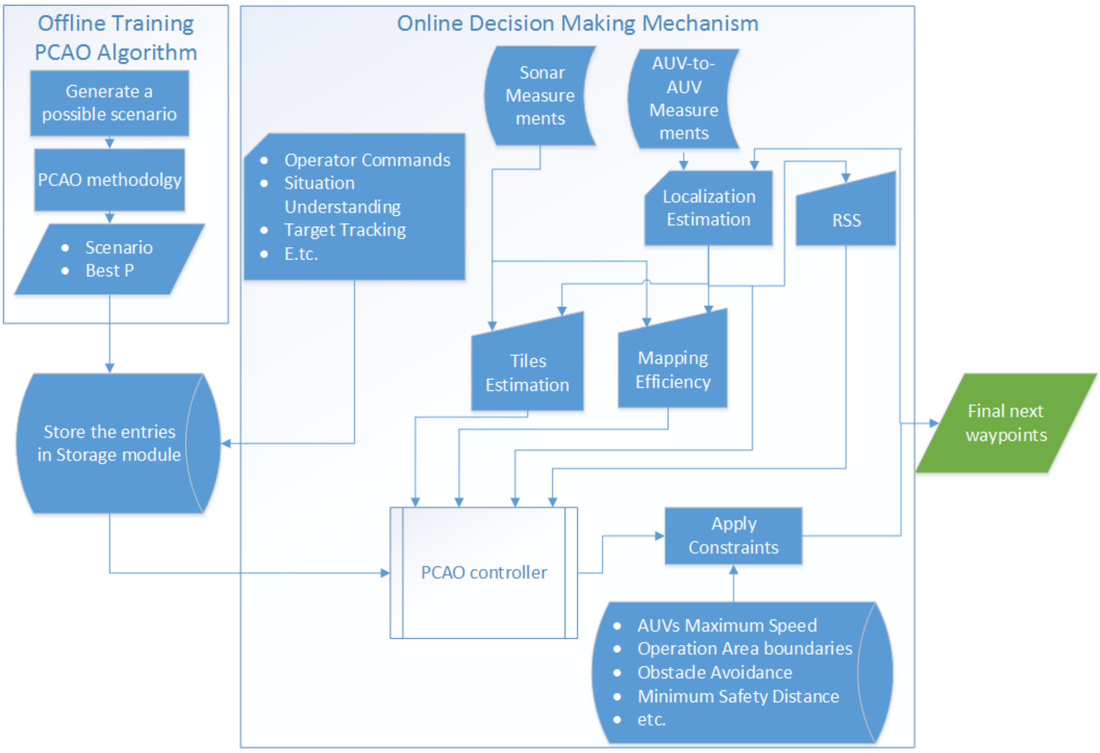


Fig. 1. Flowchart of the Navigation/Exploration Algorithm

where the AUVs have started (and may completed) their estimation process. The color in each one of them is an error index that varies from dark-blue, in case where the AUVs have acquired a perfect match from the ground truth, to dark-red in case where the measurements doesn't have any correspondence with the actual surface that underlines the specific tile. Final, these error indices per tile have been applied to the real surface(ground truth map) so as to be able to evaluate the efficiency of the proposed approach

At time-step 100 we assumed that the Noptilus-1's propeller didn't corresponds to our control commands and the AUV is considered from now on, unable to move (Figure 2b, red thick sphere). Under these new circumstances, the algorithm is called to do the best it can be done with the remaining properly working infrastructure. Please take into consideration that, this kind of incident will make the majority of today's approaches to fail, because they can either stop the remaining AUVs for a trajectory redesign or continue their predefined trajectory leaving an important part of the operation area uncovered.

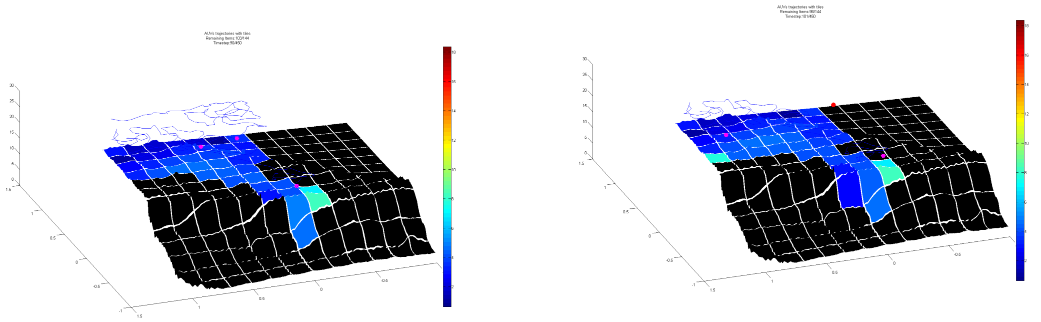
As it is presented in Figure 2c, the two remaining ready-to-operate AUVs adjust their navigation decision making mechanisms to the current infrastructure. More specifically as it is exhibited in Figure 2c the Noptilus-2 has started to "sweeping" the tiles, that would have been normally assigned to the Noptilus-1. The mapping process is terminated after 450 time-steps where the AUVs covered the majority of the operation area, estimated 136 from 144 tiles. It is worth noticing that in the majority of estimated tiles, the AUVs acquired a satisfactory number of bathymeter measurements, different in each case, since it is highly dependent on the actual morphology that underlines the tile (*the higher the height variance the higher the number of measurements*).

4.2 Experiment 2: Performing Target Tracking simultaneously with the mapping task

In this case, track a moving target while, concurrently, construct a map of the seafloor area visited by the moving target. Two AUVs were employed for this purpose, while a third AUV was used as the moving target. The information regarding the moving target that is available to the two AUVs is the AUV-to-moving target distance. In other words, *the two AUVs do not know the position of the moving target, but they are using their AUV-to-moving target distance measurements in order to estimate the – dynamic – position of the target.*

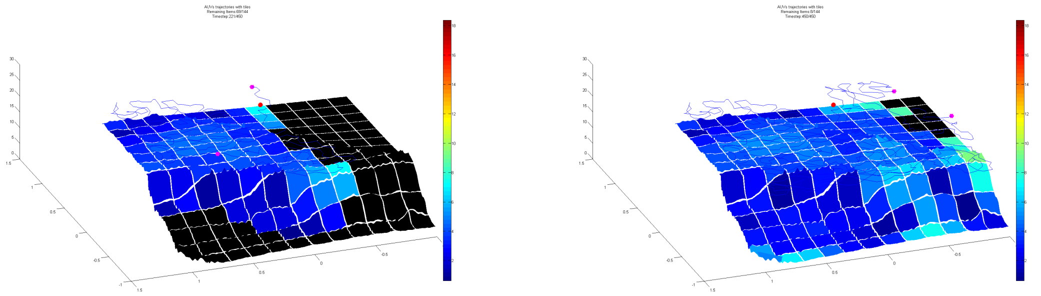
The difference from the previous experiment is evidential, even from time-step 18 (Figure 3a), where one AUV (Noptilus-3), chooses to approach almost directly the target in order to minimize their Euclidean distance. The navigation algorithm automatically assigned the task of target tracking to one of the AUVs (Noptilus-3) and the task of mapping for this AUV becomes a secondary objective, while the other AUV (Noptilus-1) tries to build an accurate map of the underwater surface in an efficient way, correcting in many cases the incomplete estimates for the Noptilus-3 (Figure 3b).

In the sequel, and more specific at time-step 139 (Figure 3c), it can be observed an another feature of the algorithm. At this time-instant, the distance between the target and any of the two AUVs in more or less the same, so the algorithm, in order to achieve a more efficient information about the sea-bottom, applies a "switch". This switch



(a) Proposed Approach - Exploration time-step 90

(b) Noptilus-1 has stop its exploration process(red thick sphere), Exploration time-step 100



(c) Noptilus-2 undertakes the tiles of Noptilus-1, Exploration time-step 221

(d) Completion of the experiment, Exploration time-step 450

Fig. 2. First experiment's key snapshots

is achieved by assigning the task of target tracking to Noptilus-1 and correspondingly relieves Noptilus-3 of the "burden" of target tracking. Please note that such a "switch" allows to the AUV (Noptilus-3) that is "easier for it to explore more unexplored area" to dedicate itself to the mapping subtask.

The Noptilus-3 now can perform any arbitrary trajectory, in order to cover the tiles that are underneath of it, in the best possible way (Figure 3d). The aforementioned switching process is performed many times during the experiment [3] , in cases where the AUVs have more or less the same distance from the target and there is a clear advantage for the specific switching. *It is worth highlighting that, the algorithm chooses to make the transitions only when the AUVs have more or less the same distance from the target, in order to avoid a sudden increase in the estimation error of targets motion.*

5. CONCLUSIONS

A new method for dealing the problem of exploring an unknown area and building a detailed map of the environment using multi-AUV teams under environmental and operational constraints, while simultaneously keep track of moving targets, has been proposed. In this paper we extend the basic PCAO-based methodology so as to incorporate a revised version of the mapping efficiency as well as to incorporate information coming from other the NOPTILUS modules that can significant either assist the multi-AUV team in accomplishing its mission or to perform secondary tasks simultaneously with the mapping procedure. Our approach is ideal for *real-life implementations using heterogeneous vehicles and independent of the SLAM methodology* employed since it is based on the approach "to the best it can be done" based on the current configuration, given the communication/sensing/SLAM system, allowing even cases where the multi-robot team comprises of vehicles with mutually different sensing capabilities or operating different SLAM algorithms without the need for a preparatory work that will render the vehicles "compatible". The efficiency and applicability of our approach is demonstrated through two real-life underwater sea-floor mapping and target tracking experiments, under severe weather conditions and infrastructure malfunction, in the Leixes port, Portugal using three LAUVs.

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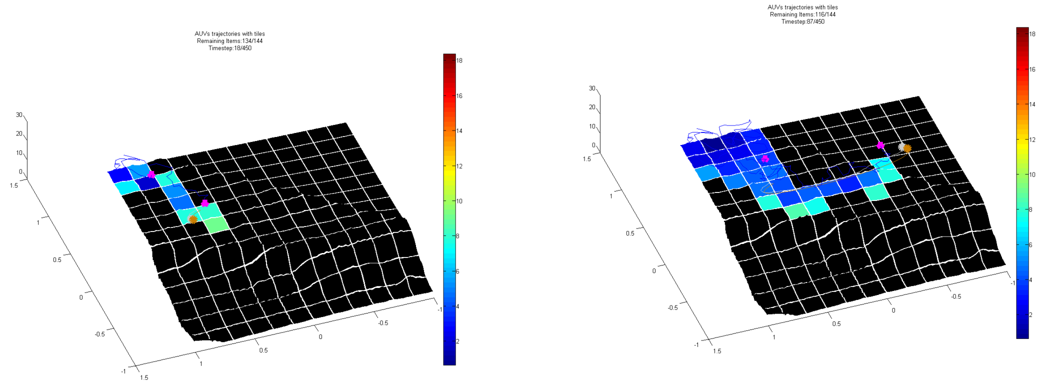
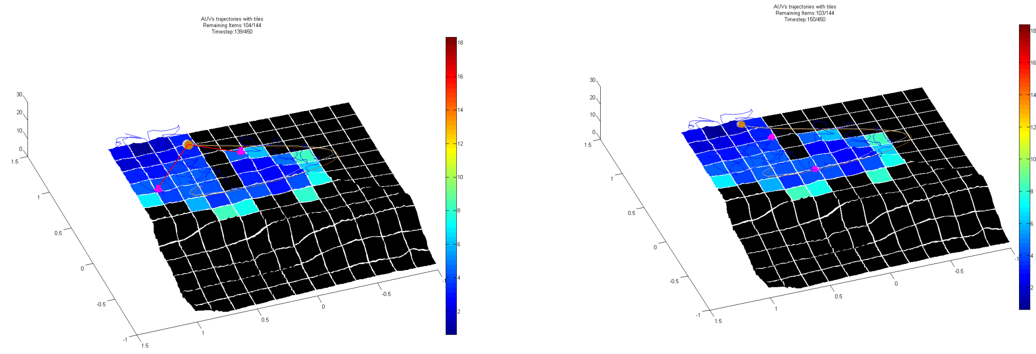
[3] The interested reader is kindly requested to watch a two minutes video with the experiment via `https://www.youtube.com/watch?v=IPGsSnVRyFU`



(a) Noptilus-3 approach target in order to improve its estimation, Exploration time-step 18

(b) Noptilus-3 keeps tracking of the target, while the Noptilus-1 take measurements in order to produced a detailed map, Exploration time-step 87



(c) The target tracking task is assigned to Noptilus-1, Exploration time-step 139

(d) Noptilus-3 is re-sensing the underestimated tiles, while Noptilus-1 keeps tracking of the target. Exploration time-step 150

Fig. 3. Second experiment's key snapshots

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