Coordinated Navigation of Surface and Underwater Marine Robotic Vehicles for Ocean Sampling and Environmental Monitoring

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***Abstract*—Water pollution generated by accidental spill of hazardous materials is a growing problem worldwide. There is an urgent need for a tool that would help environmental response teams perform rapid understanding of the location and the extent of the spill to effectively establish an appropriate response. This paper presents a cooperative robotic system for environmental monitoring consisting of an autonomous underwater vehicle (AUV) and an autonomous unmanned surface vehicle (USV). The main contributions of the paper are a systematic description of the design and implementation of the proposed cooperative robotic system, a novel human-on-the-loop (HOTL) approach applied on the system for environmental monitoring, and demonstration of the results of the open-sea experiments on pollution deliberately caused by harmless Rhodamine water tracing (WT), carried out in Cartagena, Spain, in June 2015. The proposed HOTL system provides near real-time pollution measurement data, while not consuming a significant amount of human time and effort. It supports decision-making and allows the operator to initiate the most adequate mission in a current situation, i.e., ensures mission change on-the-fly. While the AUV samples the ocean, the USV maintains the localization and communication data transfer to the control center and corrects the AUV's dead reckoning error.**

***Index Terms*—Autonomous underwater vehicle (AUV), environmental monitoring, human-on-the-loop (HOTL), unmanned surface vehicle (USV).**

I. Introduction

TOOLS for subsurface environmental monitoring have generated increasing public interest during the last decade, especially after the tragic Deepwater horizon disaster in 2010. The existing remote-sensing techniques are efficient and well-developed for surface disasters, but underwater pollution requires other, mainly *in situ* measurement and sampling techniques. Our targeted application to develop a rapidly deployable system for *in situ* detection and quantification of pollutants in the water column defines a set of the selection criteria. From the functional viewpoint, criteria for an efficient and effective system include near real-time measurements, capability to detect a pollutant in the water column with low detection limit and low false detection rate and to work in adverse weather conditions. From the operational perspective the system should preferably be portable (i.e., small size and light weight), quick and easy to deploy and with low power consumption.

An autonomous underwater vehicle (AUV) with an integrated specific environmental sensor is a logical choice for subsurface monitoring. AUVs are technologically mature, commercially available and able to sample large areas in a reasonable time span. There are a number of scientific and practical studies in which AUVs automatically and based on *in situ* measurements, e.g., on pollution chemical signature and internal mission re-planning script, trigger missions such as source localization or boundary tracking. In [1], real-time sensor information was used to track a hydrothermal plume to a hydrothermal vent and to localize the vent based on the moth-inspired chemical plume tracing strategy. One of the pioneering works [2], reviewed instances of biological plume tracing and strategies for an AUV-based plume tracing. The paper [3] presented an innovative model for the real-time assessment of pollutants on the sea surface based on a network of AUVs. The AUVs, equipped with an electronic noselike system, sailed the sea surface detecting volatile organic compounds produced by hydrocarbons.

In complex, rapid response operations, AUV is usually not the only data providing tool. The decision-making process is based on a number of different inputs from weather forecast to data provided from different sources or vehicles, e.g., aerial vehicles or buoys. Real-time availability of an AUV acquired data becomes priority enabling us to feed the pollution numerical model, support decision-making and re-plan and launch the most appropriate mission in a timely manner. Provision of real-time data from an AUV is still a challenging task that would definitely open up new prospects in managing rapid response

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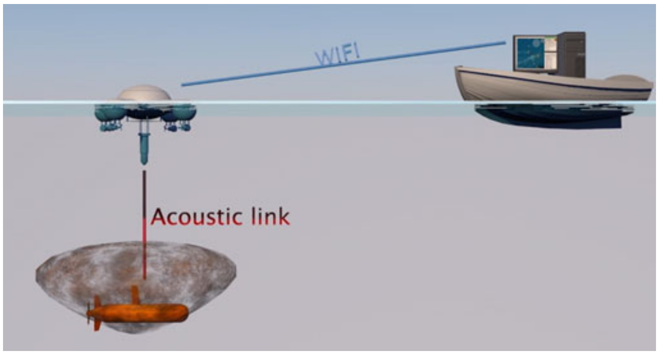

Fig. 1. HOTL system. AUV (via USV) continuously feeds the operator with measurements through acoustic and WiFi links. Using the same links in the opposite direction the operator is able to abort or change the AUV mission or request some specific data.

operations and improve the efficiency of an AUV application. Currently, the only functional way to transfer data from underwater, is to use an acoustic link. There are two main limitations concerning this approach: Low bandwidth of the acoustic communication channel and necessity to keep the support vessel nearby within communication limits of an AUV mission area, in order to maintain an acoustic link with an AUV.

In this study, we propose the introduction of another robotic vehicle, which would serve as a communication hub between the underwater and the surface environments. This vehicle is autonomous unmanned surface vehicle (USV) that handles acoustic communication with an AUV and WiFi communication with a control center, releasing support vessel for another concurrent tasks as shown in Fig. 1.

Advantage of such an USV-AUV fleet is that this setup ensures remote AUV mission change, very appropriate for disaster response applications in which rapid response teams can change the plan not only based on recent AUV data but also based on many other decision-making inputs. Thus, having the opportunity to reassign AUV to a different task as fast as possible and without the need for surfacing can be of utmost importance. The novelty of this work is the application of human-on-the-loop (HOTL) concept in which an operator is continuously updated with near real-time subsurface pollution data and interferes with AUV mission only upon decision based on all available data, including the AUV measurements. This setup allows the operator to visualize real-time concentration data, to use modeling and decision support capabilities of the system, and in turn change the mission on the fly. The example of the HOTL system is described in [4] where small team of operators supervised a network of automated agents operating in dynamic, time-pressured environments. The experiments demonstrated an improved system performance for a network of unmanned vehicles search, track, and neutralize mission. Valavanis and Vachtsevanos [5] elaborates HOTL versus human-in-the-loop concept, and specific technical challenges and levels of autonomy required from unmanned vehicles in order to execute a mission without significant human intervention. The concept promises to enhance UAV deployment in many application domains.

While being underwater, an AUV does not have access to GPS or any other reliable source of absolute localization information. An AUV relies on dead reckoning for navigation with serious drawback that position error grows with time that AUV spent submerged. Therefore, an AUV needs to surface periodically to acquire GPS signal and correct dead reckoning error. This maneuver requires some time to execute, time that can be valuable in rapid response operations. In our proposed scenario USV plays the role of AUV's "private" satellite and ensures ultra-short baseline (USBL) localization information all the time. Although USBL absolute position information is not as accurate as the one provided by the GPS, fused together in navigation filter with other dead reckoning information and supported with a kinematic and dynamic model of the vehicle, it keeps the localization error bounded. A similar system was elaborated in [6]. A dual system composed of USV and a fleet of AUVs in tandem navigation strategy was proposed to achieve a good communication link between the onshore station and individual underwater vehicles in order to avoid costly satellite communications.

The concept of HOTL means that the human is in the overall executive control to call in or call off the vehicles rather than being in control of each individually [7]. Although the unmanned vehicles are essentially autonomous, they need to be upgraded with the communication system, control system supporting HOTL and adequate sensing for a required task in order to effectively cooperate and be part of the HOTL system.

We can now summarize our motives for proposing the described system and emphasize the benefits that this system brings forward. In comparison to applications where AUV automatically re-plans a mission based solely on the *in situ* measurements, one of the benefits of the proposed system is that it ensures mission re-planning by using a variety of information available to the operator. The benefits of adding USV to the fleet are enabling an AUV to stay underwater for a prolonged period of time and providing near-real-time communication link between AUV and surface control center. Furthermore, the HOTL system unlike human-in-the-loop system does not consume a significant amount of human time and effort for the operation.

The main contribution of this paper is the systematic description of the design and implementation of the proposed cooperative robotic system for ocean sampling and underwater environmental monitoring. The demonstration of the system was carried out in Cartagena, Spain in June 2015 and this paper presents the results of field experiments with pollution created by harmless Rhodamine WT.

The paper is organized as follows. The system used in this study is introduced and elaborated in Section II, which describes the robotic vehicles, communication channels, and visualization techniques. A detailed description of experiments is provided in Section III, whereas corresponding results are provided and discussed in Section IV. Finally, Section V summarizes the work presented in the paper.

II. System

The complete cooperative robotic system for ocean sampling and underwater environmental monitoring consists of USV and AUV, acoustic and WiFi communication links and control center with the visualization and decision support interface. The

Fig. 2. AUV (orange vehicle at the bottom of the image) and USV used during the experiments in Cartagena.

goals of the proposed system were to ensure near real-time availability of underwater measurements and to provide almost instant control over the AUV from the control center. Although both agents had their own roles, they were not fully independent of each other and needed to cooperate to the certain extent. The AUV's task was to independently scan the area based on last loaded mission. The USV served as a communication link between the underwater agent and the control base or other surface or airborne systems. This means that USV had to be in the acoustic range of the AUV all the time.

A. Autonomous Underwater Vehicle (AUV)

An AUV is an untethered vehicle that requires much less complicated logistics and has significantly larger area coverage than, e.g., a remotely operated vehicle [8]. Its capabilities make AUV ideal underwater agent for environmental monitoring application requiring *in situ* water sampling.

The AUV used in this study is the light autonomous underwater vehicle (LAUV)-LUPIS, lightweight, one-man-portable vehicle shown in Fig. 2, developed at the Underwater Systems and Technology Laboratory (LSTS) of the University of Porto [9]. It is an affordable vehicle that can easily be launched, operated, and recovered making it highly effective surveying tool. Using a motor connected to a 3 blade propeller, it can travel with speed up to 5 kn for 6–8 h in the most common configurations. An off-the-shelf AUV is equipped with WiFi communication, basic navigation sensors, and control system to perform preplanned missions. Therefore, a mission can be generated only according to the information available prior to the mission. For proposed application, the AUV needed to be substantially modified with water sampling, acoustic communication and mission planning, and supervising abilities. The AUV capabilities were built up by adding and integrating required payload modules and extending the vehicle's control system. New capabilities provided us with an opportunity to change mission on-the-fly based on real-time concentration measurements.

From mechatronics viewpoint, the vehicle was modified mechanically and electronically to accommodate the new payload. The vehicle was also upgraded with new acoustic communication and localization system, and expanded control system.

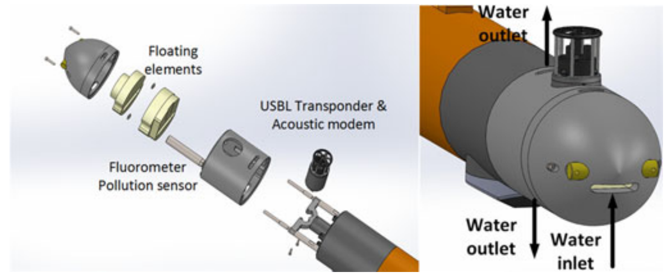

Fig. 3. Modification of the off-the-shelf LAUV. Extension of the original flooded nose of the vehicle for integration of the fluorometer and acoustic system.

1) AUV Customizations: The fluorometry is a proven technology for detection of the presence of pollutants in the water column [10]. The *in situ* submersible Turner Designs Cyclops 7 fluorometer [11] was chosen for our application due to its small size, low power consumption, affordable price, good measuring range, and resolution. The sensor supported three sensitivity configurations 0–10, 0–100 and 0–1000 ppb. The implemented automatic gain control function adjusted the sensitivity according to the voltage output from the sensor. If sensor output was saturated, concentration range increased. If the output was low, the opposite occurred. The initial experiments showed that approximately 3 s were needed for reading to stabilize after the gain change. It presented a serious problem in nonhomogeneous plumes due to frequent range changes and consequent measurement stabilization period.

To address this issue, automatic gain change was initiated only after a longer period (20 s) of sensor output saturation. Maintaining the static middle-range gain setup as a tradeoff between the range and sensitivity was an alternative method to ensure continuous measurement. Fluorometer facing forward and acoustic USBL transponder/modem were installed [12] into the specially designed and manufactured new nose, the wet section of the vehicle, whose exploded view is given in Fig. 3. The size and shape of the new nose section was approximately the same as the original one, with built in floating elements to keep it neutrally buoyant. As a result the vehicle preserved the same dynamic properties, meaning that there was no need for tuning of controllers or modification of the original navigation filter. Such an installation also ensured adequate flow of water around the sensor for reliable measurement, protection from the ambient light that may cause false positive measurements in shallow water applications and firm attachment to the vehicle in order to withstand AUV movement. Installed devices were supplied from the vehicle power management system.

2) Control System: Although HOTL concept does not assume automatic triggering of a new mission, in our study replanning, i.e., generating a new mission plan, was automated. There are two important reasons in favor of the automated mission planning: Operators workload should be kept as low as possible, and manual mission planning for both vehicles is time-consuming. However, AUV is always in motion, it cannot stop and wait. For example, if a very efficient human mission planning takes 5 min, an AUV at average speed used in the experiment of 3 kn would be already 500 m away from the point

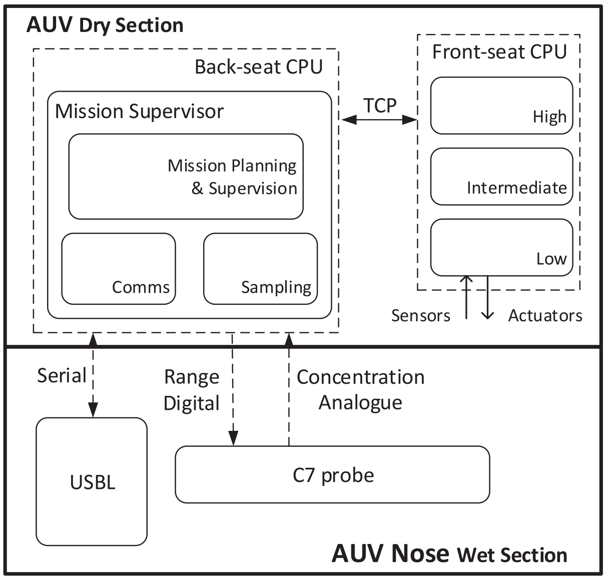

Fig. 4. Control architecture of the AUV with the new control level running at the back-seat CPU.

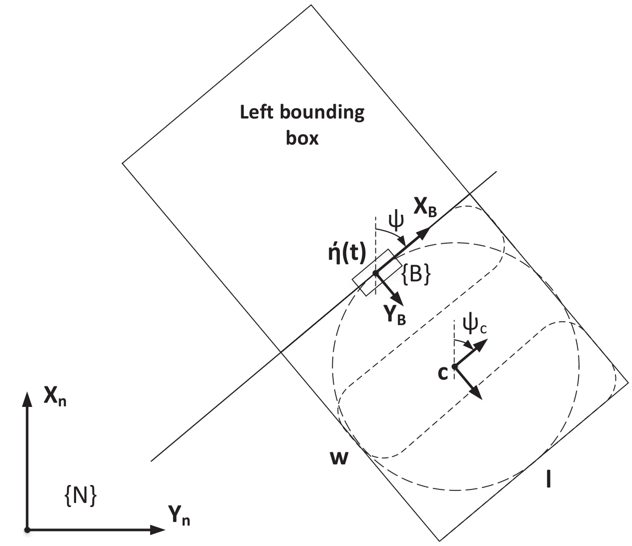

Fig. 5. Example of loiter or lawn mower mission, planned in a right bounding box.

of detected pollution. In order to significantly accelerate the mission change process, a new mission was generated instantly on operator's request onboard the AUV. The goal of the adaptive mission could be pre-set in order to achieve the mission objectives such as to find the source, to monitor the plume (stay in the plume) or as it was in our case, to scan the area close to positively detected pollution thoroughly. Following the new mission request, a mission was planned and transferred to the mission execution levels.

AUV operations are generally risky. For coastal AUV operations carried out from small boats in shallow waters, with possible uncharted obstacles or intense surface traffic, the probability of losing an AUV could be as high as 0.3 to 1.9% [13]. Therefore, all modifications related to the operation and control of an AUV must be handled with great care. So how to modify and extend the operational capability of an AUV, and at the same time maintain original safety standards?

A vehicle motion control system [14], can be conceptualized to involve at least three levels of control in a hierarchical structure: strategic (high), tactical (intermediate), and execution (low) level [15]. The similar architecture but with different level nomenclature, mission (deliberative), control, and reactive, is presented in [16]. In order to preserve the original control capabilities and safety standards of the vehicle, we decided not to modify the existing control system but to introduce a new level on top of the original structure as presented in Fig. 4. Furthermore, the new level, mission supervisor level was physically separated and managed by the back-seat, second CPU, while original vehicle control system was handled by the front-seat, primary CPU. The introduced level handled environment awareness by measuring pollution concentration *in situ*, online mission planning, the vehicle remote access, i.e., acoustic communication, essential for any multivehicle cooperative task and logging of both raw and processed data.

Since the information flow decreases from the bottom to the top of the hierarchy, low bandwidth data exchange between supervisor level and front-seat was required. It consisted of AUV position measurement from the USBL system (once every 2 s) and generated new mission file (occasionally) to the front-seat CPU. The position estimate from the navigation filter was transferred back from the front-seat CPU to the back-seat CPU and further to the USV and control center.

The vehicle's navigation filter estimates the vehicle's states such as position, orientation, velocity, by fusing the observations with models of the vehicle [17]. Due to the fact that original navigation sensor suit was used and the vehicle was modified without affecting the vehicle's dynamic, it was reasonable to keep navigation filter unchanged. Consequently, AUV position, obtained by the USBL and received through the acoustic link from the USV, was fed directly into the navigation filter instead of the nonexisting GPS measurements underwater. USBL system that provided an absolute AUV position, was essential for the bounding of the dead reckoning error [18]. However, we needed to take into account variance of the measurement error and time stamp of the received data due to slight delay caused by data transfer. The standard deviation of the localization error was estimated to fixed value of 3 m, incorporating USBL and USV GPS deviations, while time delay was estimated to 2 s. Measurement delay in the navigation filter was handled in a way that latest (last 5 s) measurement, state, and covariance matrices of the navigation filter were stored for trajectory re-calculation, if needed. When new time stamped localization measurement was received, AUV trajectory was re-calculated from the moment of the time stamp.

3) Mission Planning: The reference frames usually employed in order to describe marine vehicles motion are North-East-Down frame (NED), represented with the subscripts N, and body frame fixed to the vehicle of interest and represented with the subscripts B in Fig. 5. Using SNAME notation [19], NED-relative planar position and orientation (represented by the Euler angles) of a BODY frame attached to an AUV can be expressed by $\eta \doteq [x, y, z, \phi, \theta, \psi]^T \in \mathbb{R}^3 \times \mathbb{S}^3$.

Algorithm 1: Mission Planning.

Input Data:
$\eta \doteq [x, y, \psi]^T \in \mathbb{R}^2 \times \mathbb{S}$, - planar AUV pose
z - AUV depth
Data transferred through the acoustic link to the AUV:
$Mission.type$ ="lawn mower" (default) or "loiter," 1 b
$Mission.side$ ="right" (default) or "left," 1 b
$Mission.depth$ ="fixed" (default) or "yo-yo," 1 b
$Mission.size \doteq [l, w]^T$ (custom) or $[100, 100]^T$ (default), 1 b
if $Mission.size$ ="custom" **then**
  if $Mission.type$ ="loiter" **then**
    $l = w$, $Mission.size \doteq [w, w]^T$, 4 b
  else
    $Mission.size \doteq [l, w]^T$, 2×4 b
  end if
end if
Result: Mission plan
$type = Mission.type$
$horizontal.step$ = 10 m - lawn mower linespace
$size = Mission.size$ - bounding box size
$speed$ = 1.5 m/s - predefined
$z_c = z$ - mission depth
if $Mission.depth$ ="yo-yo" **then**
  pitch angle (15°), depth envelope (3 m) - predefined
end if
Mission box:
if $Mission.side$ ="right" **then**
  $c^B = [0, w/2, 0]^T$ - center in $\{B\}$ frame
else
  $c^B = [0, -w/2, 0]^T$
end if
$c^N = \eta + R(\psi)c^B$ - center in $\{N\}$ frame
$R(\psi) \in SO(3)$ - rotation matrix which represents a positive rotation about the z-axis of the NED frame by an angle ψ $\psi_c = \psi$ - box orientation

We chose lawn mower and loiter (circular) mission patterns for customized AUV missions. In order to change the mission on-the-fly, supervisor level generated the mission plan on operators request. Mission plan for both missions consisted of: type of the mission information (lawn mower or loiter), a planar bounding box of the mission, mission depth setting, and desired AUV speed. The bounding box was given by its size, which was predefined (100 m × 100 m) or set by the operator, vector of the center point c and orientation ψ_c. The box was placed left or right (selected by the operator) of the AUV position with the orientation coincided with the AUV orientation. The center of the bounding box was located on the y axis of the body frame as shown in Fig. 5. For lawn mower mission plan, "horizontal step" i.e., linespace, was preset to 10 m. For loiter mission the reference circle was inscribed in a square box (the same width and length). Fixed depth mission setting ensured planar mapping of the polluted area while yo-yo setting, which was predefined, enabled variable depth mapping. Details of how all required information for mission planning were transferred to the AUV through a limited acoustic bandwidth are elaborated in Section II-C. The USV mission plan included only dynamic positioning (DP) setpoint that was the center of the AUV mission bounding box, naturally with zero depth setting. The algorithm's procedure is summarized in Algorithm 1.

Upon request from the operator, the new mission was planned by the supervisor control level and transferred to the mission control system that aborted an active mission and started a new one. The proposed system also supported manual mission planning, meaning that complete mission could be planned by the operator and then transferred to the AUV through the acoustic channel. Transfer of the manual mission plan was rather slow and required a number of acoustic communication cycles.

Note that the same mission planning process can be used for different tasks, e.g., automatic source finding. In that case, mission planning is an automatic iterative process where center of the next mission polygon becomes the area of the highest observed concentration from the previous mission. Although the procedure does not provide the optimal solution, it is feasible and represents an interesting area for further research.

B. Unmanned Surface Vehicle (USV)

The autonomous USV, shown in Fig. 2 is named after its initial application, Platform for Dynamic Positioning (PlaDyPos). For this particular study, PlaDyPos was equipped with the payload for navigation, SeaTrac acoustic system for USBL localization and communication with underwater agents, and WiFi for communication with the control center. The navigation sensor set consisted of a 9-axis Inertial Navigation System and high precision GPS. The USV could also be equipped with a variety of other instruments such as mono or stereo underwater camera systems, multibeam sonar, Doppler velocity log or sensors for water quality or environmental monitoring, e.g., Cyclops 7 fluorometer.

The surface platform was developed at the Laboratory for Underwater Systems and Technologies, University of Zagreb Faculty of Electrical Engineering and Computing, Croatia, and it has been used for a number of different applications from diving support [20] to underwater archaeology [21]. It is overactuated with four thrusters forming the X configuration. This configuration enables motion in the horizontal plane under any orientation. PlaDyPos has diagonal length of 1 m, it is 0.35 m high and weighs approximately 30 kg with payload configuration used in the experiments. Its maximum speed in ideal conditions is 1 m/s.

The choice of scenario generates different USV motion objectives. If USV samples the surface at the same time as AUV samples the water column, USV can be assigned to follow the underwater agent i.e., to perform trajectory tracking with the constraint that USV is not as fast as AUV especially when, unlike an AUV, it needs to fight rough sea conditions. This problem of an USV following, e.g., AUV or other USV, without having any a priori information about its path was addressed in [22]. In other scenario, USV performs independent path following

Fig. 6. LAUV-LUPIS underwater, mapping a plume. Support vessel Clara Campoamor and the USV at sea. USV and AUV at sea. Source: Universidad Politecnica de Cartagena. Images are from: http://www.upct.es/urready4os/?page_id=1181

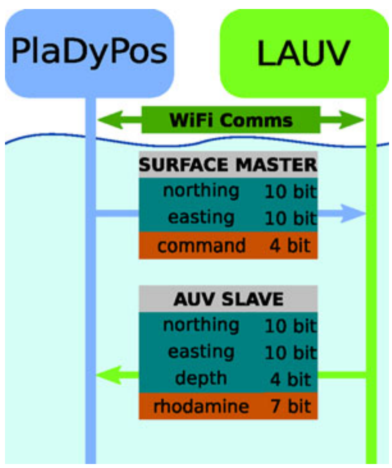

Fig. 7. Localization and communication cycle.

maintaining the range from the AUV and the quality of acoustic communication. Although the USV was capable of sampling the surface our focus was on underwater sampling and we did not use this option. Having that in mind, the most appropriate and most energy efficient mode, taking into account that range of the acoustic communication was larger than AUV mission area, was to perform DP in the middle of the active AUV mission polygon. When AUV mission changed, USV moved to the new DP position, center of the new polygon.

C. Acoustics

Acoustic localization was used to determine the AUV position underwater. The SeaTrac USBL, manufactured by Blueprint Subsea and integrated into both AUV and USV, was used for simultaneous localization and data exchange. The localization information was available exploiting two way communication. The acoustic USBL localization package was extended to incorporate user data, which introduced overhead in the ranging ping and the localization was additionally delayed. Therefore, a tradeoff between the quantity of transmitted data and frequency of localization fixes was required. During the one localization cycle, one user data package was delivered up to the USV and one down to the AUV.

Based on our previous filed experience, it was expected that localization error would be bounded to 2 m. Installed USBL system allowed simultaneously tracking of multiple underwater agents while undertaking bi-directional data exchange. But in that case, the cycle time would be increased, i.e., frequency of the localization fixes decreased proportionally to the number of tracked units.

The available data transmission rate was 100 b/s and the localization overhead was ≈ 1.3 s. Error detection during transmissions used the 16-bit cyclic redundancy check algorithm. To maintain cycle times below 2 s the uplink data, from AUV to surface, was limited to 4 bytes and downlink, from USV to AUV to 3 bytes.

The uplink data included the AUV position and the Rhodamine sensor measurement as shown in Fig. 7. The North-East information was exchanged in local (acoustic) frame of reference whose origin was center of the mission polygon, known to both vehicles. Position data occupied 10 b for North and 10 b for East coordinate of the local frame. It allowed us to encode a local plane of approximately 500 m $\times$ 500 m with fixed resolution of half a meter. In case, if AUV exits the local plane, i.e., flies more than 250 m away from the origin, then overflow information is used to ensure correct absolute positioning. Indeed, the risk of incorrect wrapping exists, especially in case of long period of acoustic dropouts. Due to favorable USV position for acoustic localization of the AUV, we did not expect, nor experienced any serious acoustic dropouts. Note that position transmissions from AUV could be avoided, since USBL measurement was available. However, the position was included in the uplink to provide an alternative in cases where USBL fixes were too noisy. Depth was encoded in only 4 b, meaning that overflow information needed to be used. Rhodamine data occupied 7 b and provided sufficient measurement resolution.

The downlink North-East information was encoded the same way as uplink information. Received downlink USBL fix position was transformed to absolute coordinates onboard the AUV to allow navigation corrections and bounding of dead reckoning error. In addition to localization, the data contained 4 command bits for transmitting mission re-planning information. If mission was planned using only default, predefined parameters (see Algorithm 1) then complete new mission data was transmitted in one communication cycle. If size of the mission box was

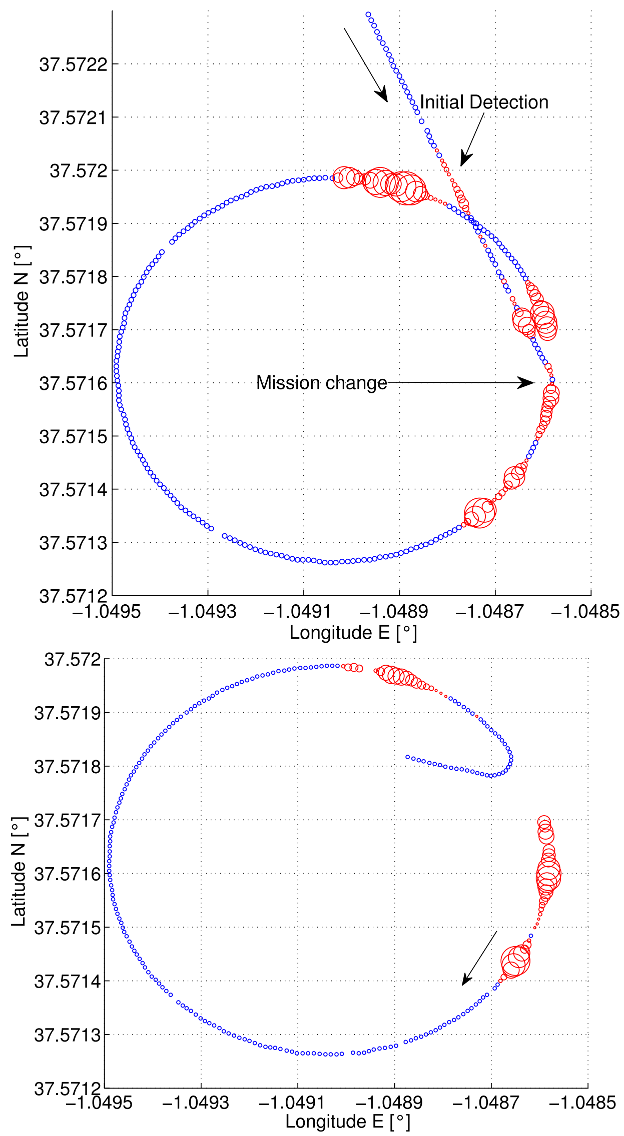

Fig. 8. Mission change and spatial concentration measurement during the two consecutive passages over the same area. Red circle indicates positive detection of the pollution. The size of the circle is proportional to the concentration measurement.

custom defined, then one additional cycle was required for square custom box, or two for rectangular box. Due to resolution of only 4 b, available mission polygon sizes were from the 10 m × 10 m, the smallest box to the 160 m × 160 m, the biggest box. Any other custom information such as new mission depth, AUV speed, yo-yo parameters, etc., would have required extra communication cycles for transmission.

Additionally, the robotic system supported inverted USBL (iUSBL) operation, i.e., mounting the USBL on AUV rather on than the USV to enhance AUV position and attitude estimation as it was shown in [23] and [24]. In iUSBL mode of operations the surface position of the USV would be transmitted.

D. Architecture and Visualization

LAUV vehicle that was used came with preinstalled software DUNE: Unified Navigation Environment. DUNE is the runtime environment for vehicle onboard software which is used to write generic embedded software and it contains all necessary control, navigation, and mission planning capabilities. On the other hand, USV navigation, control, and mission planning software is based on robot operating system (ROS) architecture. ROS is a flexible framework for writing robot software. It is a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust robot behavior across a wide variety of robotic platforms [25]. Integration of two such different software architectures was achieved through the intermodule communication (IMC) protocol used for building interconnected systems of networked vehicles, sensors, and human operators. The protocol does not impose or assume a specific software architecture for client applications. Native support can be automatically generated for different programming languages and/or computer architectures resulting in optimized code that can be used both for networked nodes and also for interprocess and interthread communication [26]. DUNE natively supports the IMC protocol while the message translator was implemented in ROS to establish communication.

NEPTUS control software was used for vehicle coordination and as a human control interface. NEPTUS [27], designed by LSTS, is a command and control infrastructure for heterogeneous teams of autonomous vehicles. This tool supports the entire mission life cycle, including planning, execution, review, visualization, and decision support. Visualization of the real-time collected data from the autonomous vehicles as well as pollutant dispersion model output provides an updated picture of the actual status in the operation field to the operator. NEPTUS presents the georeferenced color map of the pollutant concentration data overlaid on the mission map. It also uses IMC protocol meaning that LAUV is natively supported, while USV is not plug-and-play compatible. For that purpose, the team built custom adaptation layers based on ROS message translator.

III. Experiments

Work and experiments described in the paper were performed in the scope of the project "AUVs ready for oil spill—UReady4OS." The preliminary experiments were carried out in Split, Croatia, in 2014 [28].

The goal of the 2015 experiments presented in this paper was to test the fleet's cooperative performance in an envisioned and realistic spill situation. The experiments were about to provide insight into the system's capabilities, such as identification, quantification, and real-time visualization of the pollution, as well as execution of adaptive missions based on decisions and commands aided by decision support system.

The experiments were performed with the vehicles LAUV-LUPIS and PlaDyPos elaborated in Section II. The sea trials were carried out in two occasions: in Biograd na moru, Croatia, in May 2015 and in Cartagena, Spain, in June 2015. During the sea trials in Croatia, on-the-fly mission change functionality was tested in a rather controlled environment before open-water trials in Spain. All parts of the system needed for HOTL scenario were tested, such as data flow, visualization, top side initiated AUV and USV mission change.

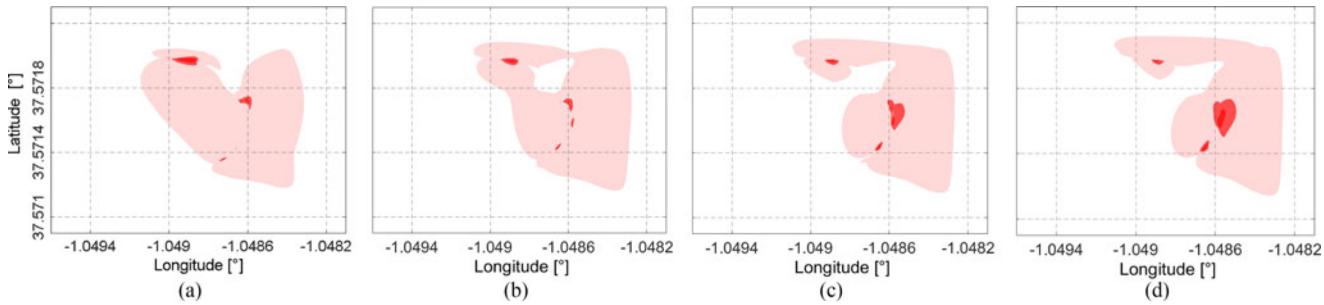

Fig. 9. Spatio-temporal progression of the plume over the period of 15 min. Pink area represents Rhodamine concentrations of 2–$10\ \mathrm{ppb}$ and red area concentrations of over $10\ \mathrm{ppb}$. (a) First scan (T_0). (b) Second scan (T_0 + 5 min). (c) Third scan (T_0 + 10 min). (d) Fourth scan (T_0 + 15 min).

The experiments in Cartagena were carried out from the support vessel Clara Campoamor (see Fig. 6), provided by Spanish Maritime Safety Agency. Control center was stationed onboard the vessel and all the vehicles were transferred to the experimental site, prepared and deployed from the vessel. The pollution was simulated with Rhodamine WT, a fluorescent nontoxic and biodegradable chemical product commonly used to track flows, clearly visible as a red plume in front of AUV nose in Fig. 6.

AUV's task was to scan the area suspected to be polluted. The initial mission was preplanned on the fixed depth according to available information at the time of deployment. Pollution concentration measurements were transmitted in real time to the control center from where eventually new adaptive mission based on most recent information regarding the fate of the plume was commanded. The AUV was kept underwater all the time and its spatial localization error was bounded thanks to USV supporting the AUV's operation. The AUV's control system was also customized to perform operator-triggered but automatically planned mission change when pollution was doubtlessly detected. To ensure continuous measurement with optimal sensitivity, the automatic gain control, described in Section II, was applied. To avoid triggering of an adaptive mission on false positive detection, positive detection was claimed only if an average value of 20 consecutive measurements was above predefined threshold. A new mission plan, in the form of a dense lawn mower or loiter, was generated online, based on the position of detected pollution and the direction of the AUV's travel. Although the automatic mission change execution was an option, the goal of the experiments was to test HOTL system in complex operations meaning that execution of any new mission needed to be triggered by the human in charge.

The USV itself was not equipped with the sensor for environmental monitoring. Therefore, its task was to maintain the communication link between the AUV and the control center and to improve AUV underwater localization using the acoustic USBL system. The initial mission of the USV was to perform DP at the center of the current AUV mission polygon. In case of degradation of the communication quality, either acoustic or WiFi, or loss of USBL localization signal, DP point was reassigned to be closer to the AUV or the support vessel. Upon the AUV mission change the USV DP point was moved again to the center of the new AUV mission polygon.

IV. Results and Discussion

Upper image of Fig. 8 illustrates spatial pollutant concentration measurements from the fixed depth mission performed by the LAUV-LUPIS vehicle. The red circle indicates positive detection, while the size of the circle represents the concentration measurement, i.e., bigger circle represents higher concentration. The figure shows the AUV performing preplanned lawn mower mission until the moment of the first positive pollution detection. Loiter mission, initiated top side and generated onboard the AUV's back-seat computer, replaced the initial lawn mower mission plan with the goal of mapping the area in the neighborhood of the detected spill.

The loiter mission was repeated a couple of times in the polluted area. Lower image of Fig. 8 shows pollution concentration measurements during the second passage. There was a difference between the concentration measurements during the first circle and during the second circle, just a few minutes later. These data illustrate dynamic behavior of the plume responding to environmental and oceanographic conditions. Consequently, response team must be able to track the movements of the plume in near real time to ensure proper action. The data acquired with the missions adapted to scan the polluted area provided us with an estimate of quantitative, spatial, and temporal distribution of the plume. Visualization in the form presented in Fig. 9 would definitely allows us to perceive the extent of a disaster and help us decide which further steps should be undertaken.

Meanwhile, the USV supported the AUV's operations performing DP in the center of active mission polygon and followed the AUV when switched to the new mission plan. The experiments showed that this USV positioning allowed improved and robust acoustic coverage in the operational area. DP error during the experiments, at sea state 3 to 4, was limited to 1 m most of the time, 2 m occasionally, evaluated by onboard high precision GPS. These DP results were in line with our previously published work [29]. The quality of communication of the integrated acoustic system was very good in the favorable open sea and low acoustic noise environment. Delivery failures were very rare $<2\%$ and occurred mostly during the near surface operation (diving and surfacing) of the AUV.

According to transmit power of the WiFi device installed on PlaDyPos, expected WiFi range was 1 km in favorable sea conditions. The range could have been further increased by having a more powerful WiFi communication system onboard the USV.

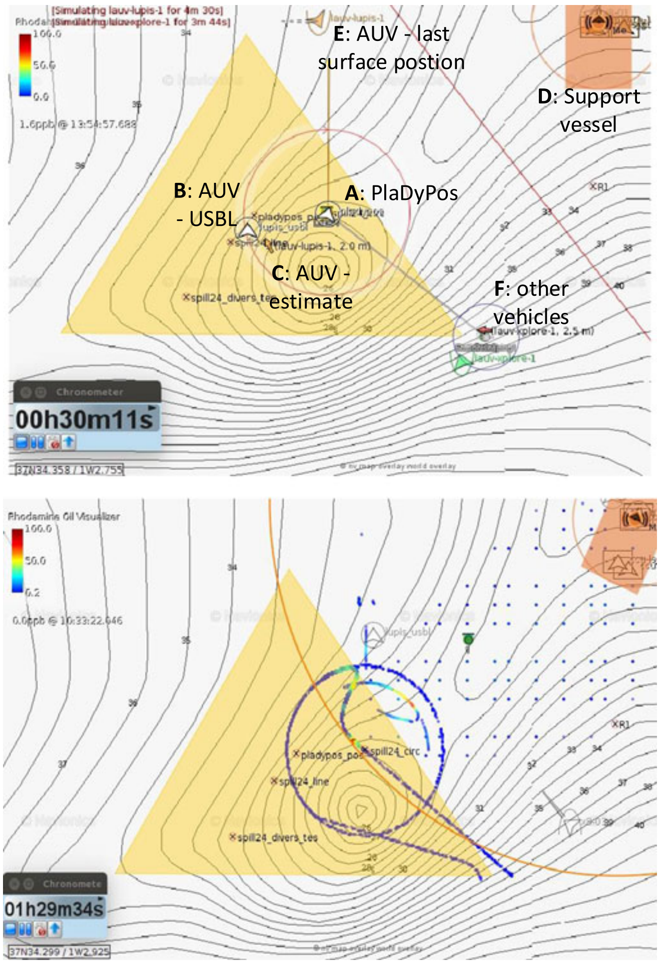

Fig. 10. NEPTUS visualization, control, and decision support software. Upper image presents position of the vehicles: A—position of the USV, B—AUV position from USBL, C—Neptus estimation/simulation of the AUV position, D—support vessel, E—last AUV surface position, F—position of an other vehicle in the experimental arena. Lower image presents color map representation of the measurements. Source: LSTS Universidade do Porto.

During the experiments, support vessel Clara Campoamor maneuvered within a 500 m range from the USV. To reduce WiFi communication dropouts due to waves and vehicle motion, USV antenna was raised above the PlaDyPos. Still, we experienced some communication dropouts during the mission, although they were not that frequent. In order to ensure packet delivery, the wireless bridge ROS node was set to acknowledge reception of data packets. During the short dropouts, packets that failed delivery were resent when possible, ensuring near real-time communication link. Generally, even if real-time package delivery would have failed completely during the long dropouts caused by, e.g., out of range operation, complete logged data would be received once a connection is re-established.

On board the support vessel the operators using the NEPTUS system monitored the position of the surface and underwater vehicles as well as the situation in their area of responsibility by watching different visualization layers. Fig. 10 shows the first layer illustrating position of the vehicles in the experimental arena, providing situational awareness for the operator, and the second layer presenting recent concentration measurement data in a color map form. Finally, these field results fused with data from other sources, fed into the numerical spill model and presented in NEPTUS demonstrated a valuable contribution to the proper decision-making process regarding the future actions.

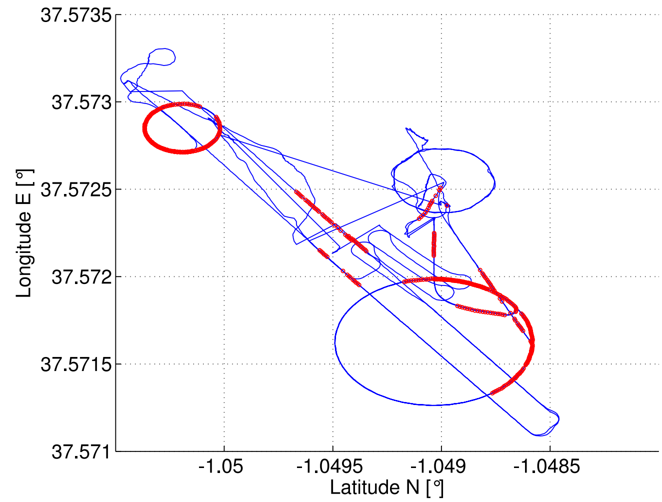

Fig. 11. Spatial concentration measurement during the series of consecutive missions initiated top side and replanned by the AUV supervisory system. Red dots indicate positive detection of the pollutant.

Being the operator timely informed about the situation in the field and giving the one opportunity to re-plan the AUV mission in order to scan the area of interest, resulted in the mission presented in Fig. 11. The mission started as a lengthy lawn mower. Once pollution was detected, series of new missions were initiated without AUV surfacing. Fig. 11 illustrates a number of top-side triggered loiter missions with different diameters, lawn mowers of different sizes, and spatial positions of positively detected pollution.

Realization of such a mission would not be possible without AUV localization enhancement. Duration of the complete mission was 57 min and although we did not have the tool to ground truth localization quality during the mission, we were able to compare the AUV's estimated position with the one of GPS once AUV surfaced. The onboard AUV's position estimate was within the GPS error standard deviation, i.e., the difference between estimated position and GPS position was only 2.5 m. The main reason for this excellent result was a good quality and availability of the acoustic USBL measurements at open sea. During the preparatory experiments held in Croatia in shallow waters and high marine traffic area, thus acoustically noisier environment, the results were somewhat worse but still localization error was bounded to less than 10 m. For comparison and based on our experience, dead reckoning error during 1-h mission with Doppler-assisted AUV, could grow up to 50 m, depending on, e.g., quality of the sensors calibration and currents in the operational field.

V. Conclusion

This paper presents the cooperative robotic system consisting of the AUV and USV for environmental monitoring and ocean sampling. The system was experimentally tested for rapid response operations in subsurface pollution scenario.

The cooperative marine robotic fleet operated by the HOTL concept provided near real-time pollution data and proved to be a very convenient tool for rapid response. The system supported decision-making and allowed the operator to decide and initiate the most adequate mission in a current situation, i.e., it ensured mission change on-the-fly, while not consuming a significant amount of human time and effort because the vehicles were not directly operated by the operator. Apart from the AUV, which actually performed the water sampling, introduction of the USV brought additional benefits. It ensured real-time transfer of underwater measurements to the control center, it substituted support vessel making it available for other tasks, and enabled infinite underwater operation by correcting the AUV dead reckoning error. This cooperative robotic fleet autonomously performed the underwater sampling while being ready at any time to be reassigned to a new task by the human in charge.

The results of experiments carried out in Cartagena, Spain, in June 2015, present fleet performance in a real-life situation with pollution created by harmless Rhodamine WT. Apart from deployment and recovery, vehicles operated independently of the support vessel. Valuable sampling data collected by the AUV were transferred in near real time to the control center via USV and visualized on the NEPTUS system. The operator fed by this information and all other available data was able to execute automatically generated adaptive AUV mission on-the-fly. The USV re-planned its own mission plan according to the new AUV task.

In order to increase capabilities of the system and improve its performance the focus of the future research should be directed toward enlarging the fleet by implementing cooperative control between a few AUVs and an USV, increasing the bandwidth of the acoustic communication channel and increasing the level of an AUV autonomy by extending a re-planning options, i.e., adding missions targeting specific tasks, e.g., find a source.

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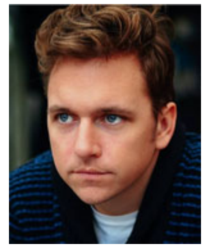

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