Heterogeneous robotic system for underwater oil spill survey

A. Vasilijevic[1], P. Calado[2], F. Lopez-Castejon[3], D. Hayes[4], N. Stilinovic[1], D. Nad[1], F. Mandic[1], P. Dias[2]
J. Gomes[2], J. C. Molina[3], A. Guerrero[3], J. Gilabert[3], N. Miskovic[1], Z. Vukic[1], J. Sousa[2], G. Georgiou[4]

[1] University of Zagreb Faculty of Electrical Eng. and Comp., Lab. for Underwater Systems and Technologies, Croatia
[2] Faculdade de Engenharia da Universidade do Porto, Underwater Systems and Technology Laboratory (LSTS), Portugal
[3] Universidad Politecnica de Cartagena, Department of Environmental Chemistry, Spain
[4] Oceanography Center, University of Cyprus, Cyprus

***Abstract*—The tragic Deepwater Horizon accident in the Gulf of Mexico in 2010 as well as the increase in deepwater offshore activity have increased public interest in counter-measures available for sub-surface releases of hydrocarbons. To arrive at proper contingency planning, response managers urge for a system for instant detection and characterization of accidental releases. Along these lines, this paper describes the application of a heterogeneous robotic system of unmanned vehicles: autonomous underwater vehicle (AUV), unmanned surface vehicle (USV) and unmanned aerial vehicle (UAV) extended with the oil spill numerical modeling, visualisation and decision support capabilities. A first set of field experiments simulating oil spill scenarios with Rhodamine WT was held in Croatia during the early autumn 2014. The objectives of this experiment were to test: effectiveness of the system for underwater detection of hydrocarbons, including multi-vehicle collaborative navigation and communication as well as visualisation of the system components.**

I. Introduction

Hydrocarbons and their derivatives comprise the largest energy source in the world. Exploration and extraction activities in the marine environment are expected to continue to grow, both at coastal and deep water sites. Therefore, it is very important to ensure effective prevention and response to oil spills, as there are significant economic and environmental costs when oil spills occur. The tragic Deepwater Horizon accident in the Gulf of Mexico in 2010 as well as an increase in deepwater offshore activity have increased public interest in counter-measures available for sub-surface releases of hydrocarbons. Available remote-sensing techniques are efficient and well-developed for surface disasters, but they are not useful for underwater releases.

The most important information needed to discover and predict oil spill fate are: type of hydrocarbon (crude or refined and the specific properties), rate and duration of release and geographic coordinates and vertical position of release in the body of water. Discharged oil responds to environmental and oceanographic conditions and consequently, response teams must be able to track the movements of oil in water in near real-time. To arrive at proper contingency planning, response managers urge for a system for instant detection and characterization. The system should be able to provide location and 3D spatial extent of the spill by integrating and accommodating multiple real-time data streams and allow quick interpretation of results.

Along these lines, this paper describes the application of a heterogeneous robotic system of unmanned vehicles: autonomous underwater vehicles (AUV), unmanned surface vehicles (USV) and unmanned aerial vehicles (UAV).

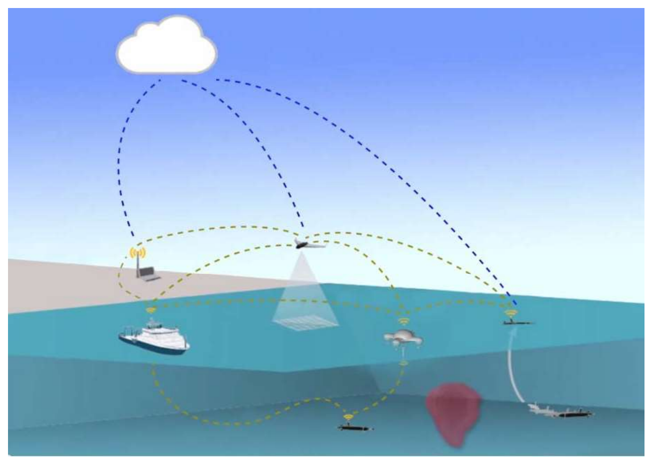

Fig. 1: Heterogenous fleet

The role of the multi-agent system, shown in Fig. 1, is to deliver timely information on sub-surface hydrocarbon concentration. The complete system includes, besides vehicles, an oil spill trajectory simulation model and a Command and Control Console to assist the man-on-the-loop Decision Support System. The underwater vehicles with hydrocarbon sensor directly measure hydrocarbon concentration while unmanned surface and aerial vehicles sense the surface and serve as a communication link to make the collected data available to a remote ground station. Once the information reaches the ground station it is merged with other useful data sources such as output from numerical spill trajectory models, aerial photographs or hydrodynamic hind- and forecast and visualised in the Command and Control software. All these information layers actively assist in the overall system mission design in order to better capture the extent and intensity of the spill.

Fig. 2: Marine agents: AUVs and USV (white vehicle shown on the right)

Fig. 3: Image of the UAV takeoff

II. Heterogenous Robotic System

A. Vehicles

1) Autonomous Underwater Vehicle AUV: In order to model spatio-temporal distribution of the pollutant, it is necessary to install the relevant sensor on a dynamic platform (or fleet of platforms). A platform should be able to cover the desired area, including the water column, accurately geo-reference measurements [1], [2] and log those geo-referenced data. Potential platforms are towed vehicles, remotely operated vehicles (ROV) and AUVs.

An AUV is an untethered vehicle which, as a consequence, does not require a support vessel or complicated logistics and has significantly larger area coverage than an ROV. Exchange of sensors of different types e.g. crude oil, refined oil or rhodamine, is plug-and-play apart from the calibration procedure, which is application specific. An AUV can perform preplanned missions, generated according to available information prior to mission or adaptive mission, modified on-the-fly, based on real time concentration measurements. The goal of the adaptive mission is pre-set in order to achieve the mission objective such as to find the source, to monitor the plume (stay in the plume) or to find and monitor the plume boundaries. For this study, two models of AUVs were used during the first set of experiments: LAUV and IVER2 vehicle (Fig. 2).

The LAUV is a lightweight, one-man-portable vehicle that was developed at the Underwater Systems and Technology Laboratory (LSTS) in the University of Porto [3]. It can be easily launched, operated and recovered with minimal operational setup. Operating it does not require extensive operators training and it is an affordable, highly operational and effective surveying tool. Starting at a basic functional system that includes communications, a computational system and basic navigation sensors, the LAUV capabilities are built up adding optional payload modules. Using a motor connected to a 3 blade propeller, it can travel with speeds up to 5 knots for 6 to 8 hours in the most common configurations. The long range configuration used in Croatia can operate for 24 hours continuously.

For the experiment, a rhodamine probe was installed facing forward, in the nose of the vehicle, and connected to an analog to digital converter inside the vehicles main hull. This converter is then connected to the main processing unit which processes and stores the data for later underway access or analysis on shore. The on-board software was configured to log both raw and processed rhodamine data, according to the calibration procedure.

The IVER2, also small one man-portable AUV, is manufactured by Ocean Server Technology, Inc. The one used in the experiment is equipped with a bottom track (Doppler Velocity Log) DVL system allowing high-accuracy underwater positioning. A Raspberry PI was installed as a backseat CPU in charge of the communication with the navigation system on the main CPU and to retrieve and geo-reference data from the pollutant sensor. The auto-gaining of the sensor and the generation of the best sampling strategy according to the measurement was performed by the backseat CPU. A Turner Designs Cyclops Integrator, consisting of an electronic sensor control board, and an optical Cyclops sensor board for crude oil, refined fuel and Rhodamine was integrated into the specifically designed and manufactured new head for the AUV by the Underwater Vehicles Laboratory of the Technical University of Cartagena (UPCT).

2) Unmanned Aerial Vehicle UAV: In order to decrease the response time of the heterogeneous systems to the spill site, a fast platform is used to make an initial survey over a large area. The UAV has this capability, with fast deployment and cruise speeds of around 18m/s. The launch is done by catapult, and recovery is done by net landing. The two-meter wingspan UAV, shown in Fig. 3 is equipped with an ethernet camera and real-time transmission capability to the base station. This allows the team to locate the spill and coordinate all the other systems in the area. Another possible configuration is a Cannon compact camera. This enables photos with better resolution but they are only saved on-board and must be analyzed after landing. The UAV also functions as a bridge, working as an Local Area Network access point between base station and the other systems deployed but out of range from the base station.

3) Unmanned Surface Vehicle USV: The autonomous USV, shown in Fig. 2 is equipped with payload for navigation, acoustic localisation of underwater agents (ultra short base line - USBL), acoustic communication with underwater agents and WiFi communicaton with aerial agents or a ground station. The surface platform has been developed at the University of Zagreb Faculty of Electrical Engineering and Computing, Laboratory for Underwater Systems and Technologies, and it is over-actuated with 4 thrusters forming the X configuration. This configuration enables motion in the horizontal plane under any orientation. The navigation sensor set, consisting of a 9-axis Inertial Navigation System (INS), and high precision GPS, provides localization accuracy within tens of centimeters.

B. Sensors

Current hydrocarbon sensors for oil spill prevention and response could be classified into two categories: in-situ and remote sensors. In-situ sensors are defined as any sensor that makes direct contact with the oil or the media in which the oil is suspended, emulsified, or dissolved. Qualitative assessments of in-situ sensor performance is provided in [4]. Our targeted application, to develop a rapidly deployable system for the in-situ detection and quantification of submerged oil in the water column, is defined with the following set of selection criteria: a) near real time results; b) easy calibration for different hydrocarbon pollutants; c) detection of oil in the water column; d) capability to work in currents up to 3 knots; e) capability to work day and night and in adverse weather conditions; f) low false detection rate; g) low oil detection limit; h) portability, small size, weight and power consumption; and i) quick and easy deployment of each component. Based on selection criteria and a state of technological maturity, in-situ submersible Turner Designs Cyclops 7 fluorometer [5] and Cyclops Integrator have been chosen for our application. Due to their small size and weight, Cyclops C7 sensors and Cyclops Integrator are suitable for integration into any platform that supplies data logging and power. Gain Control can be static, the use of only one gain setting at a time, or set for automatic adjustment of the sensitivity according to the voltage output from the sensor.

C. Visualisation and Decision support

A software package named Neptus, from the University of Porto, is used for visualization and decision support. Neptus is part of the LSTS Toolchain for autonomous systems [6] to command and monitor. LAUVs and the UAV are natively supported, meaning that Neptus can be used to plan and review data collected by these systems. IVER AUV is not compatible, so a two-way adaptation layers was built. In the IVER AUV side, the adaptation layer transforms the position and attitude data into a format that Neptus could feed from. This way the AUV is shown in the Neptus console. In order to command IVER AUV from Neptus, a translator from Neptus plans to the mission language of IVER was built. This adaptation layer translated a plan into a text file with IVER plan that could be loaded by the operator into the AUV for execution. Neptus is then used for full situational awareness in regard to the vehicles' state, as shown in Fig. 4.

In what concerns the decision support, Neptus was extended to read pollutant dispersion model output. This represents the simulation of the oil spill spreading versus time. This time stamped data field is presented in the Neptus console according with the current time by overlaying into the map a georeferenced color map data showing the density of the oil (colored grid of points). This data evolves over time and gives the operator information that is used for planning the surveys. Additionally, real-time collected data from the AUVs is also overlaid, feeding the operator with an updated picture of the actual spreading of oil. This data can be accessed at the end of a survey by each vehicle or by receiving sampled data from the AUVs through acoustics communications. Fig. 4 depicts this data overlayed into the map.

D. Oil spill simulation and modeling

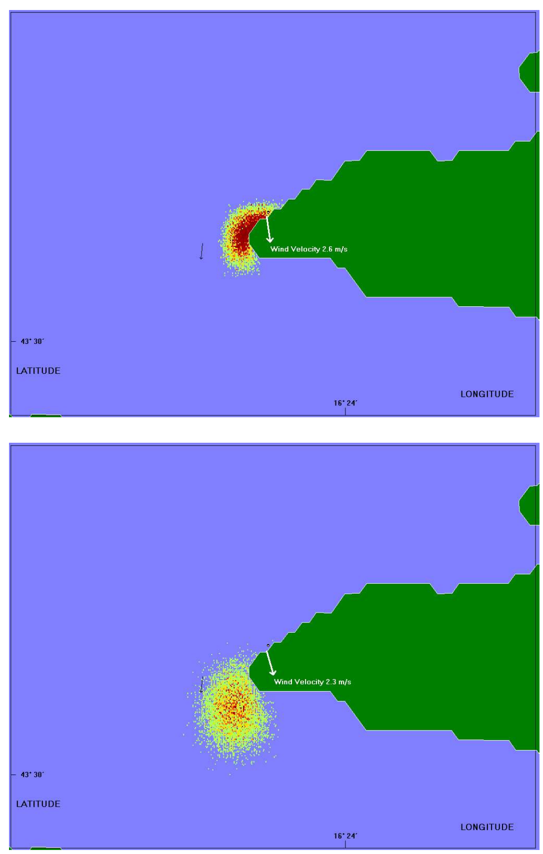

Fig. 5: Model

Oil spill modeling complements AUV operations in two ways for managing spills. Firstly, the initial estimate of spill location, time, depth can be used to very quickly predict the

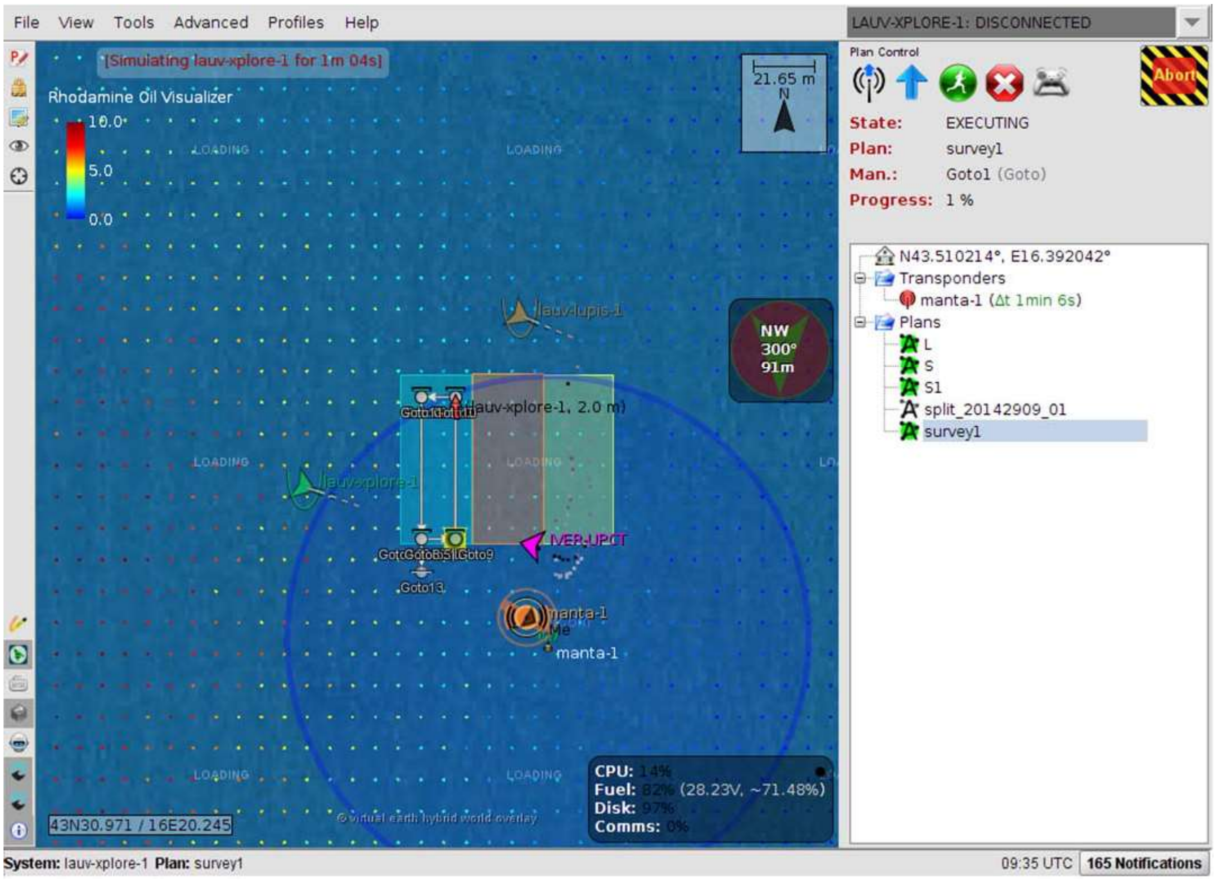

Fig. 4: Neptus - Visualisation and Decision Support System. It shows fleet management information such as position of the base station and active mission agents (colored arrows), designated mission areas (colored squares) and paths. Screen also shows oil -spill information: spatial distribution of the pollution through the 2D overlay of the concentration measurements (equally distributed colored dots), scaled according to the color-bar.

expected trajectory using the best available wind, currents, waves, and water temperature information (typically from a forecasting system). The predicted fate assists in the initial mission planning of AUVs: at least providing an estimate of the affected area to reduce the sampling area. Secondly, the information retrieved by the vehicles (oil concentration, water temperature and currents) feed the oil spill model to predict the fate of the observed plume, including its size and shape. This information is added as a layer in the Neptus as in the decision support system. The simulations are performed by MEDSLIK II (http://gnoo.bo.ingv.it/MEDSLIKII/), an oil spill and trajectory 3D model [7], that predicts the transport, fate and weathering of oil spills and the movement of floating objects (Fig. 5). MEDSLIK II is used by several agencies throughout the Mediterranean (Cyprus, Italy, Israel, Malta, Spain), and plays a central role in the Mediterranean Decision Support System for Marine Safety (www.medess4ms.eu), a service for operational oil spill predictions in the Mediterranean [8].

III. Scenarios

By performing the multi agent mission, a response team would be able of determine the fluorescence of oil-in-water column in near-real time. It provides a unique opportunity to timely monitor and model the oil spill in 3D, not only in 2D (on the surface) as it is the case in using contemporary technologies and tools. The system in general is able to:

- acquire oil-in-water column data in near-real time or with slight delay, depending on mission/fleet configuration
- when fed by concentration measurements, provide numerical prediction of the oil spill fate in a fast and efficient way
- present acquired data and provide decision support via Visualisation and Decision Support System

The simplest scenario involves only one AUV vehicle performing the underwater scanning of the designated area of the water column. Data, recorded on board the vehicle, become available at the end of the mission, once the vehicle is on the surface and within the WiFi range from the support vessel or base station. The UAV commonly performs an initial survey and serves as WiFi range extender as depicted in Fig. 6. In the case that more than one AUV vehicle is used at a time, the size of the scanned area is proportionally increased but it makes the mission more complex and requires more logistic effort.

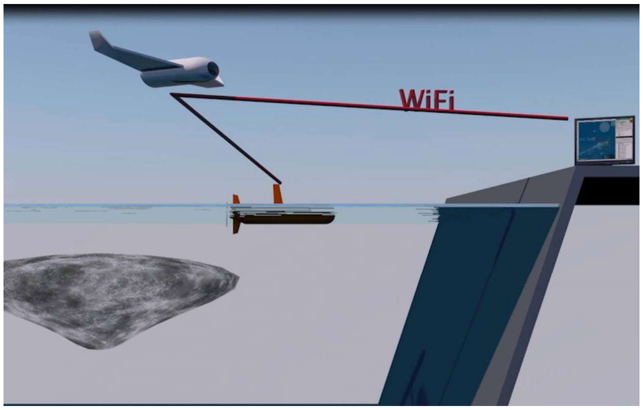

Fig. 6: Scenario 1 - AUV performs the underwater scanning of the designated area of the water column. Once the vehicle is on the surface, log files are transferred via WiFi to the UAV and further to the ground station.

The second scenario involves an AUV and an USV. Such a fleet is capable of transferring near-real-time oil-in-water concentration data to the mission base which must be in WiFi range from the surface vehicle. An AUV continuously feeds the USV with measurement data via acoustic link, which follows the AUV on the surface and forwards geo-referenced concentration data to the base, acting as a data relay (Fig. 7).

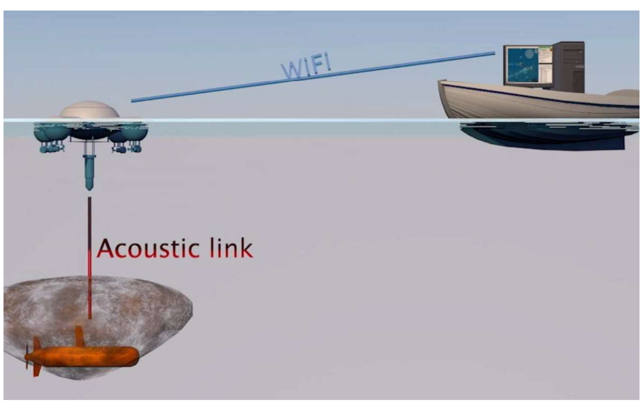

Fig. 7: Scenario 2 - AUV continuously feeds the USV with measurement data via acoustic link. USV transfers near-real-time oil-in-water concentration data to the mission base via WiFi.

The third scenario takes advantage of two-way acoustic and WiFi communication between the AUV and the base station via USV or fixed acoustic modem. This set up allows the operator to visualise real-time concentration data, use modeling and decision support capabilities of the system and in turn change the mission on the fly, according to in-field results. Other scenarios involving multiple vehicles are also possible and useful, but not discussed further here.

IV. Experiments

A first set of experiments was held in Croatia from 22^{nd} of September to 2^{nd} of October 2014. The objective of this experiment was to test: the effectiveness of AUVs with integrated submersible fluorometers for underwater detection of pollution, communication protocols between agents, software developed for multi-vehicle collaborative navigation and visualisation of the system agents and mission results. The system is challenged against the first two scenarios, but with multiple vehicles operating simultaneously. The AUVs are not aware of each other, except through the human pilots, so each single-AUV scenario discussed above is indeed relevant.

The oil spill was simulated with Rhodamine WT, a fluorescent non toxic and biodegradable chemical product commonly used to track flows. We achieved the synchronized deployment of AUVs in this preliminary experiment and tested protocols and software prepared for multivehicle cooperative missions. The first scenario experiment, illustrated in Fig. 6, proved that an AUV with integrated fluorometer can be efficiently used for in-situ spatial detection and quantification of a pollutant of interest as long as adequate flow of water over sensor is ensured and protection from the ambient light. False positive readings were sometimes recorded when the fluorometer was exposed to the sunlight, when the AUV was close to the surface and pitching.

Fig. 8 shows an image of the AUV entering the Rhodamine WT plume. Although detected Rhodamine WT concentrations were in a range of only few ppb's, time series of the underwater Rhodamine WT measurement, given in Fig. 9, shows that areas of Rhodamine WT plume were successfully detected and clearly distinct from the unpolluted sea.

Fig. 8: Image from the AUV onboard forward looking camera, AUV entering the Rhodamine WT plume

The experiment also demonstrated that a UAV is an efficient vehicle for both initial survey and detection of the primary spill location as well as communication link, or range extender, between the AUVs and the ground station. Fig. 10 illustrates the part of the spill area at the moment of AUVs transferring the mission log files to the UAV, which would consequently be transferred to the base station. Fig. 11 presents base-station visualisation of the mission agents at the moment when image from Fig. 10 was taken.

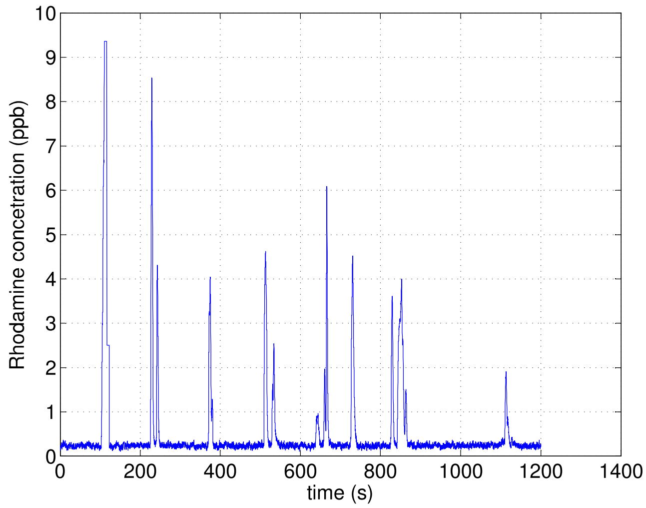

Fig. 9: Time series of Rhodamine concentrations during one mission

Fig. 10: Image from the UAV showing part of the Rhodamine WT patch and 3 AUVs on the surface, resting and transferring mission log data to the UAV

The second scenario experiment, illustrated in Fig. 7, showed that the USV equipped with acoustic localisation and communication systems is able to track the AUV and receive acoustically near-real-time measurements with frequency of roughly 0.6 Hz. Geo-referenced data are instantly passed on to the ground station or support vessel, becoming available for analysis, numerical modelling or generally for decision-making.

Fig. 4 presents the mission details in Neptus, our Visualisation and Decision Support System. The view shows fleet management information such as position of the base station, designated mission areas (squares of different colors), paths and actual positions of all active mission agents as well as oil-

Fig. 11: Real-time visualisation of the heterogeneous system agents from Fig. 10 on Neptus, Decision Support System. Image shows 3 AUVs (orange, green and purple), UAV (white), and base station (brown)

spill information, spatial distribution of the pollution through the 2D overlay of the concentration measurements, scaled accoriding to the color-bar. All this information, available in near-real time, support decision making process shore-side. Having all this information presented in Neptus also indicated successful test of all communication links and protocols, acoustic and WiFi.

V. Conclusion

Preliminary experiments showed that the chosen sensor technology, i.e. flourometers integrated into the mobile vehicle such as AUV, can be effectively used for in-situ measurement of pollutant concentrations in the water column. Performing the coordinated multi-vehicle mission the scanning area was increased proportionally which may be very important for the rapid response in case of oil-spill. Incorporation of heterogenous robotic vehicles in the multi-agent fleet such as aerial and surface vehicle brought extra benefits such as: fast detection of the primary spill location, extended WiFi communication range of the AUVs and near-real-time concentration data availability for decision support and numerical modeling.

The next set of experiments, related to the third scenario, is planned for and will be held in Cartagena (Spain) in 2015. This future work will be focused on the AUV's on-the-fly mission re-planning, initiated either shore-side or by the AUV itself. AUV should generate the best sampling strategy by analysing on-board real-time concentration data. A sampling strategy focused only on identified regions of interest will contribute to faster and more efficient surveys.

Acknowledgment

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