AUV based mobile fluorometers: system for underwater oil-spill detection and quantification

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***Abstract*—The tragic Deepwater Horizon accident in the Gulf of Mexico in 2010 as well as 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 underwater. Along these lines, this paper analyzes application of Autonomous Underwater Vehicles (AUV) with integrated submersible fluorometer for underwater detection of hydrocarbons. Experiments with rhodamine, which was used as a replacement for oil, showed that the proposed system can be efficiently used both as an input into numerical model and consequent visualization of spatial distribution of pollutant.**

I. INTRODUCTION

The oil spill could be defined as unwanted release of a hydrocarbon compound or mixture of hydrocarbon compounds from a closed vessel. The most important information needed to discover and predict oil spill fate are: type of hydrocarbon (crude or refined), volume of release and geographic coordinates and vertical position of release in the body of water. The facts that most spills occur at or near the surface and that oils are usually lighter than water so they find their way to the surface, justify the present focus on the surface work. Moreover, visualisation and tracking of the oil spills is much easier at the surface, allowing relatively simple sampling and study. The tragic Deepwater Horizon accident in the Gulf of Mexico in 2010 as well as increase in deepwater offshore activity have increased public interest in counter-measures available for sub-surface releases of hydrocarbons.

Discharged oil responds to environmental and oceanographic change and response team must be able to track the movements of oil on water in near real-time capabilities. In case of underwater spills, oil plumes form sub-surface patches reaching the surface far away from the spill point. Providing 3D information, regarding sub-surface oil patches, and feeding them into the numerical models significantly improve prediction of the patch movement giving us more time to act and to reduce the consequences of the oil spill. It brings the focus to hydrocarbon sensors that provide data for immediate, rapid response not only at the surface but also in the water column.

There are two main types of hydrocarbon sensors: in-situ sensors that makes direct contact with the oil or polluted media and remote sensors. One of the most effective ways to determine the presence of oil, either remotely or in-situ is fluorescence, electromagnetic absorption and emission. Fluorometers are widely used sensors in tracer experiments to study oceanographic processes, since fluorescent dyes such as rhodamine are detectable at very low concentrations. Development of the solid state light sources in a wide range of wavebands, including the ultra-violet (UV), has led to the introduction of new types of fluorescence sensors including hydrocarbon sensors.

The role of Autonomous Underwater Vehicles (AUVs) with hydrocarbon measuring payload is to provide, presently unknown, sub-surface hydrocarbon concentration data by direct in-situ measurement. Fusion of the measured concentration data with the telemetry data from the vehicle's navigation filter provide spatial distribution of the sub-surface plume. Benefits of using AUV as a sensor platform is possibility to acquire huge amount of data relevant for assessment, in a cost- and time-efficient way. Furthermore, the lightweight AUVs for operation do not require specially certified technical personnel and expensive and complicated logistic.

Our system, AUV based mobile fluorometer have the following advantages:

1. the system is capable of detection and quantification of submerged oil in the water column.
2. the system can operate day and night and in adverse weather conditions, limited only by the deployment/recovery or support vessel.
3. the system provides near-real-time, geo-referenced, time-stamped concentration data via acoustic link between the AUV and the surface.
4. the system can provide other measurements valuable for the numerical modelling of the oil plume such as temperature, sea currents or salinity.

In section II proposed system for the experiment is elaborated. The section III discusses experimental results of using in-situ fluorescent sensor installed on the AUV for underwater detection and monitoring of marine pollution including but not limited to the oil spills. Finally, a set of conclusions are provided.

II. EXPERIMENTAL SYSTEM

System, for this experiment of spatial detection and mapping of a spill, consists of an AUV vehicle, used as a dynamic platform and integrated sensor able to detect concentration of the pollutant in the water, including the water column.

A. Hydrocarbon Sensors

Current hydrocarbon sensors for oil spill prevention and response could be classified into two categories: in-situ and remote sensors.

Remote hydrocarbon sensors are sensors that are not in direct contact with oil or media that the oil is in. They are mainly used to detect the amount of oil that is at the sea surface. These technologies include airborne and spaceborne remote sensors such as: infrared video, photography and thermal imaging, synthetic aperture radar, UV sensors, airborne laser fluorosensors and airborne and spaceborne optical sensors [1]. The various selection criteria are spatial resolution of the sensors, the timeframe for collecting and processing the data, operationality in day, night and in adverse weather conditions, the cost and size of sensors, rate of false detection (e.g. false negative and positive) and ability to perform classification of the oil type. For example, spaceborn sensing is a cost effective system but it suffers from low temporal and spatial resolution. Visible sensors are widely available and they are the best in terms of having a high spatial resolution but they need daylight and good weather condition to operate, they suffer from high false detection rate and do not provide oil classification. Laser fluorosensors are very costly but they can detect oil on various backgrounds with low false detection rate and they have capability to classify the oil. Comprehensive tables of remote sensors description and their comparison is given in [1] and [2]. As a conclusion, there is currently no single sensor available which can give an accurate estimate for all the parameters required for oil spill surveillance and disaster management, accordingly a combination of sensors are recommended.

In-situ sensors are defined as any sensor that makes direct contact with the oil or the media that the oil is in. They are used to measure oil concentration of water samples in laboratory conditions or to determine oil concentration in-situ, either at the surface or in the water column. Some of the in-situ hydrocarbon sensors currently used are: fluorometers, turbidity meters, total organic vapour monitors, mass spectrometers, optical and thermal imaging sensors. Apart from previously mentioned selection criteria, very important are also oil concentration measuring range and the precision. Qualitative assessments of in-situ sensor performance is provided in [2].

Our targeted application, to develop a rapidly deployable system for the in-situ detection and quantification of submerged oil in the water column, defined following set of selection criteria: near real time results; easy calibration for different oils; detection of oil in the water column; capability to work in currents or AUV speeds up to 3 knots; capability to work day and night and in adverse weather conditions, low false detection rate; detection crude oil limit of 0.5 ppb or lower; portability, small size, weight and power consumption; quick and easy deployment. Three adequate technological approaches are proposed in [3]. They are a system using the backscatter from acoustic signals of the Wide Band Multi-Beam Sonar (WBMS), a system uses flow-through fluorometric measurements and a system uses the scattering and refraction of light to determine the mass and volume concentration, droplet size and density of the entrained oil.

The fluorometry, unlike other proposed technologies, is proven in practise and has been utilized in other systems used to detect the presence and concentration of hydrocarbons in the water column [4]. Fluorescence is a process in which a photon is absorbed by an atom or molecule and then emitted at a lower energy (lower frequency) [5], [6]. This change in frequency is called the Stokes shift [7] and process generally occurs on a time scale of nano- or pico-seconds. Ratio between the number of photons emitted to number of photons absorbed defines the fluorescence quantum yield. Since fluorescence yield depends on the chemical environment in which the process occurs, it was shown that it can be used for detection of different compounds such as hydrocarbons.

Based on selection criteria and a state of technological maturity, in-situ submersible Turner Designs Cyclops 7 fluorometer [8] has been chosen for our application. Due to their small size and weight, Cyclops C7 sensors are suitable for integration into any platform that supplies data logging and power. Technical and environmental sensor characteristics are given in table I and optical specifications are given in table II. Sensor support three sensitivity configurations, gain settings; X1, X10 and X100. As the gain increases, the sensitivity increases and the concentration range decreases. Static Gain Control refers to the use of only one gain setting at a time. For most applications the X10 gain will provide the best sensitivity, range, and resolution. Auto gaining refers to the automatic adjustment of the sensitivity according to the voltage output from the sensor. This feature maximizes the performance of sensors allowing users to detect a broad range of concentrations, obtain the best resolution, and read minimum detection limits without having to rewire or manually change the sensors sensitivity.

B. Autonomous underwater vehicle

In order to model spatio-temporal distribution of the pollutant, it is necessary to install the sensor on a dynamic platform. A platform should be able to cover desired area, including the water column, accurately geo-reference measurements [9], [10] and log geo-referenced data. Potential platforms are towed vehicle, remotely operated vehicle (ROV) and AUV. An AUV is untethered vehicle which, as a consequence, does not require support vessel or complicated logistic and have significantly larger area coverage then ROV. AUV can perform preplanned mission, generated according to available information prior to mission or adaptive mission, adapted 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

TABLE I
SENSORS CHARACTERISTICS

Material	Size, Weight	Temperature Range	Depth Range	Signal Output	Supply Voltage	Typical Power Requirements
Stainless Steel	L:10.9cm D:2.22cm W:160g	0-50°C	600m	0-5VDC	3-15VDC	<300mW

TABLE II
OPTICAL SPECIFICATION

Application	Minimum Detection Limit	Dynamic Range	LED (CWL)	Excitation	Emission
Oil - Crude	0.2 ppb	0-2700 ppb	365 nm	325/120 nm	410-600 nm
Oil - Fine	10 ppb	>10,000 ppb	285 nm	$\leq$ 290 nm	350/55 nm
Rhodamine Dye	0.01 ppb	0-1000 ppb	530 nm	535/60 nm	590-715 nm

Fig. 1. LAUV AUV with removed nose section to present physical integration of the C7 sensor

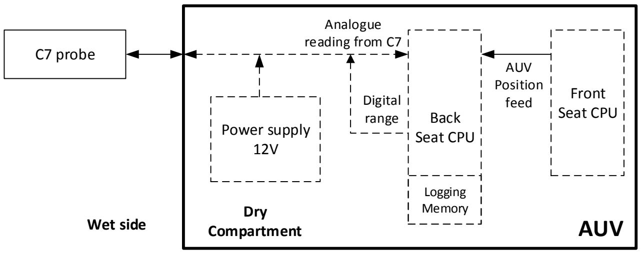

Fig. 2. Block diagram of the hardware integration

such as find the source, monitor the plume (stay in the plume) or find and monitor the plume boundaries. As a data acquisition platform for this experiment, we have used LAUV vehicle (OceanScan) [11], adapted for the integration of the C7 sensors as shown in figure 1. 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 always application specific. Sensor is integrated in the vehicle nose but it can be also positioned underneath the vehicle.

C. Sensor integration

Sensor integration onto the AUV includes: hardware integration and software integration.

Hardware integration includes: cable penetration between dry and wet sections, wiring to provide power supply and to ensure data exchange with the back-seat CPU and physical integration of the sensor. Block diagram of the hardware integration is given in figure 2. Physical integration (figure 1) implies placing the sensor on a appropriate position on the AUV to ensure adequate water flow for reliable measurement, protection from the ambient light which may cause false positive measurements and firm attachment to the vehicle in order to withstand AUV movement. Integration of the sensor into the vehicle nose section is a reasonable option because it complies with all above mentioned requirements.

Software integration consist of sensor management and data management. Tasks of the sensor management system are concentration data acquisition obtained by sampling of the sensor's analogue output, handling of dynamic gain control via sensor's digital inputs and sensor calibration. Data exchange between the front seat CPU, in charge of AUV motion and backseat CPU, designated for this application, fusion of exchanged spatial, temporal and concentration data and data logging are tasks of the data management system.

D. Calibration

Calibration procedure correlates the sensor voltage output to the known concentration values of the primary liquid standards. Following equation, for sensor with fairly linear

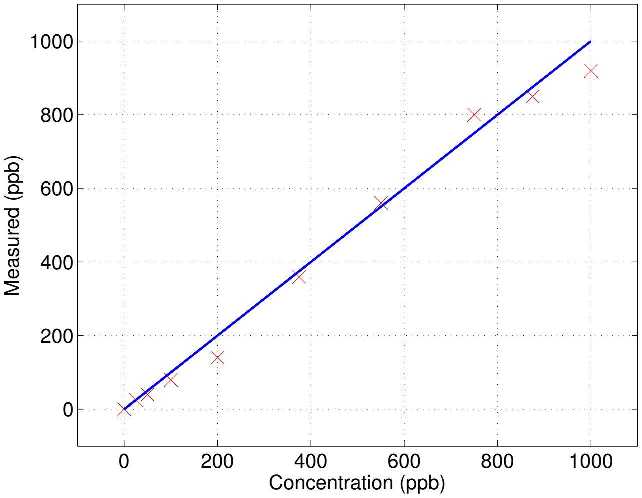

Fig. 3. Sensor calibration and Linearity

response, is used to calculate concentration value of the sample measurements:

$$C_{Sample} = \alpha + \beta U_{Sample} \tag{1}$$

where α is zero offset, β is linear coefficient and U_{Sample} is measured voltage output. α and β are expressed with:

$$\alpha = -U_{Zero} C_{Standard} / (U_{Standard} - U_{Zero}) \tag{2}$$

$$\beta = C_{Standard} / (U_{Standard} - U_{Zero}) \tag{3}$$

where C stands for standards with zero and known concentration and U for corresponding voltage outputs.

PTSA primary liquid standards are generally used for crude oil calibration, while naphthalenedisulfonic acid disodium salt, which has similar fluorescence characteristics to many refined oils, is used for refined oil calibration. For this particular experiment of detection of rhodamine concentrations in the water column, calibration was performed by diluting 2.5% Rhodamine WT concentrate standard. Ten points calibration, performed in the laboratory, with the points distributed along the measuring range, is given in figure 3. It shows success of the calibration procedure and satisfactory sensor linearity. Linearity is observed by checking if reading decreases in direct proportion to the dilution.

Fluorescence is temperature sensitive, as the temperature of the sample increases, the fluorescence decreases. For greatest accuracy it is advisable to log the sample temperature and correct the sensor output for changes in temperature.

III. EXPERIMENTS, RESULTS AND DISCUSSION

A set of experiments were carried out in Kastela bay (43.52 N, 16.36 E) in 2014. summer-fall timeframe. Although the main scope of the project was to detect oil in water, it was not permissible to create oil pollution in reality. For that reason, Rhodamine WT red fluorescent dye has been chosen as harmless, non-toxic oceanographic tracer, in order to simulate the oil spill situation. Diluted tracer was dispersed underwater on different depths as illustrated in figure 4, depending on spill scenario. Two types of scanning missions were employed in order to measure pollutant concentration - constant depth and yo-yo pattern with defined depth limits.

Fig. 4. Rhodamine plume, dispersed diluted tracer

Fig. 5. Two point field calibration with 0 ppb and 100 ppb standards

To ensure reliable measurements, it was of utmost importance to perform field calibration immediately prior to experiment, to check sensor stability and to check for loss in sensitivity. Two point calibration shown in figure 5, employing two different rhodamine concentrations, was considered adequate for that purpose.

First objective of the experiments was to detect the Rhodamine in water column and find the plume. It would confirm that all phases of sensor integration were successfully accomplished and that the system chosen to handle oil spills is fit for and capable of performing required tasks. Experimental results, presenting time series of concentration measurements from single 20 minutes fixed depth mission are illustrated in figure 6. The results proved that the AUV with integrated in-situ Rhodamine sensor was able to efficiently detect pollution when passing through the plume. An attractive image of AUV approaching the plume is given in figure 7. Regardless the fact that Rhodamine WT dissolves quickly in the water, system was able to detect ten areas with rather low concentrations $< 10ppb$ of the tracer. Spatial representation of the very same

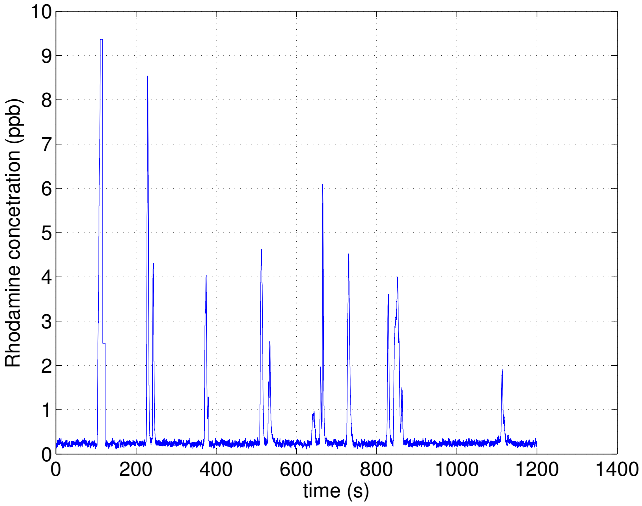

Fig. 6. Time series of Rhodamine concentrations during the one mission

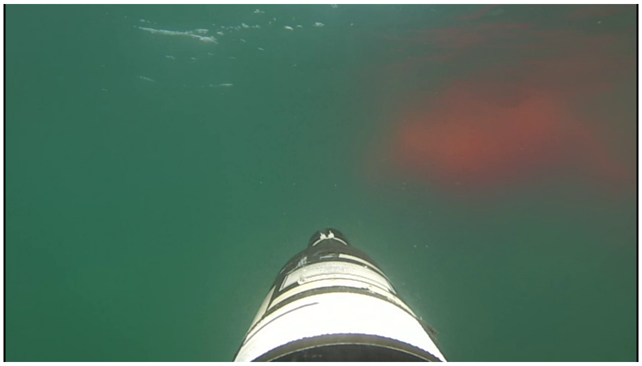

Fig. 7. Image from the AUV onboard forward looking camera, AUV entering the Rhodamine plume

mission is given later in figure 9.

Two practical observations were noted during the experiments. First, the mission starts in auto-gaining mode with the most sensitive setup - gain X1. When reading reaches 90% of the full range the gain is changed automatically to reduce the sensitivity and ensure higher range. If reading drops below 6% of the full range, the gain is switched back to higher sensitivity mode. The experiment showed that it takes approximately 3 seconds for reading to stabilize following the gain change. With AUV cruising speed of 1 meter per second the system yields a blind spot of approximately 3 meters in size. It is not a problem in the case of a large-scale plume. However, for a small-scale pollution, especially when plume is rather non-homogeneous and causes frequent gain changes, this delay can present a serious problem. To handle this types of scenarios, static gain setup of X10 may be preferred as a tradeoff between the range and sensitivity.

Another practical observation from the experimental trials was presence of outliers, false positive detections caused by ambient light. Figure 8 presents time series of depth and concentration measurements logged with sampling period of 0.1 seconds. While AUV was on the surface, i.e. zero depth, some of concentration measurements were higher than 1. They represent false positive readings or outliers. In addition, it is interesting to notice systematic false positive readings every time AUV dives. During this particular trial the Rhodamine probe was installed underneath the AUV facing backwards which explains the influence of an ambient light when vehicle suddenly dives nose down.

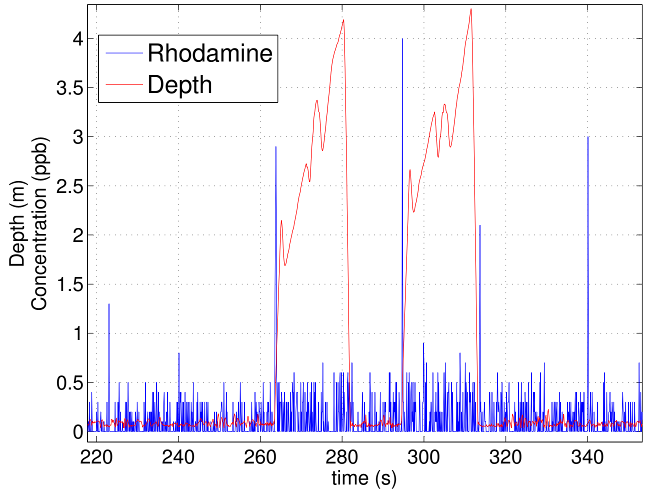

Fig. 8. Outliers - effects of the ambient light

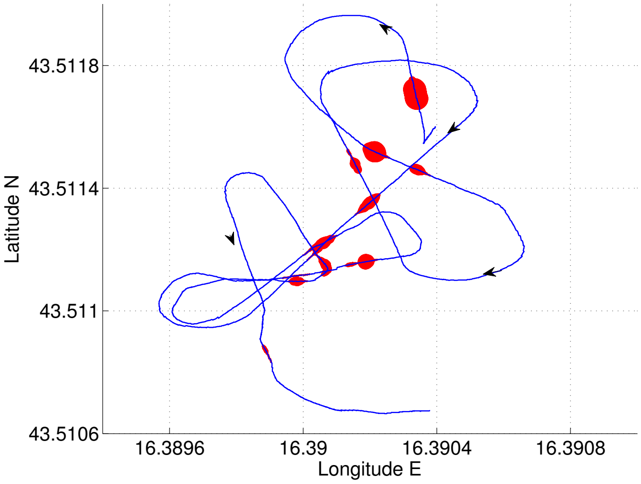

Fig. 9. Spatial map of the Rhodamine plume

The second objective was to geo-reference, log and visualise measured data. Concentration measurements were time stamped and fused with AUV telemetry. Complete set of data was logged every 0.1 seconds. Example of visualisation is given in figure 9 showing the AUV path in blue with red areas representing detected pollutant. Size of red markers corresponds to the measured concentrations.

The third objective was to spatially map the plume. Experiment showed that 3D or even 2D mapping of a plume was not a trivial task. The main limitation of the mobile fluorometers is that they sample the water column at a specific point, one point at the time. As a result, comprehensive spatial mapping of an oil plume would require number of transects at different depths consuming a significant amount of time. It would work for a rather static plume, such as with a continuous subsea leak from a pipeline or a vessel, but not for a transient plume when plums location and configuration may have changed substantially by the time the map image is produced. Therefore, reliable plume map should be produced by the numerical model which takes into account all relevant and available information e.g. oceanographic data and which is fed by geo-referenced, time stamped, near-real-time concentration data. This approach would allow us, not only to generate real 3D model of the plume at any given time but also to forecast and present future progress of a spill.

IV. CONCLUSION

The paper presents application of fluorescence sensors in marine spill detection, visualisation and surveillance. The main targeted application is preparedness for oil spill situations. Experiment showed that fluorometers, when integrated on a dynamic platform such as AUV, can be efficiently used for in-situ spatial detection and quantification of a pollutant of interest.

System, the AUV with integrated fluorometer, generally provided reliable measurements if adequate flow of water and protection from the ambient light are ensured. However, some false positive readings caused by ambient light were recorded close to the surface. Special attention should be paid when using auto-gaining mode due to the time required for stabilization of readings. Still, many applications could benefit from auto-gaining feature, allowing users to detect a wide range of concentrations in best resolution. In applications where continuity of measurement is crucial, static gaining is recommended.

Fusion of concentration measurements with spatial and temporal data provides opportunity to visualize spatial distribution of the pollutant concentrations in a relatively static plume. But if the plume is transient, sole geo-referenced concentration data is not sufficient for reliable mapping of a plume though it represents valuable contribution to the development of the numerical model of the pollution.

So far, our work has been focused on a sensor integration, efficient pollutant detection, quantification and geo-referencing of collected data. Future work will focus on guidance algorithms based on real-time concentration measurement for plume source tracking, plume following and plume boundaries detection/estimation. It will exploit the on-board processing power to analyze real-time fluorometers data and react by making decisions about the best sampling strategy to use. Such directed sampling strategy focused only on identified regions of interest will definitely contribute to faster and more efficient surveys.

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