Sensorized buoy for oil spill early detection

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***Abstract*— The Sea is often a fragile environment to be protected against possible pollutants. This paper contributes to its safeguard by proposing a new buoy equipped with advanced sensors for the detection of oil spills. In particular, the buoy is provided with various sensors for the evaluation of both meteorological and marine parameters (e.g. waves, wind, temperature), and chemical/physical data acquired by an electronic nose specifically designed for the detection of hydrocarbons. Suitable network interfaces and a connector towards a Marine Information system (MIS) allow both for real time data visualization and for long-term assessment of water quality.**

Keywords—Sensorized Buoy; Oil Spill; E-Nose; Hydrocarbon Classification; Marine Information System

I. Introduction

The Mediterranean Sea represents an extremely fragile ecosystem, with the presence of highly polluted areas, heavy commercial and touristic traffic, as well as a very particular position and shape, making its waters slowly renewable. Indeed, being almost completely surrounded by land, it is pretty sensitive to pollutants, especially hydrocarbons, often produced by oil spills and ship transits [1, 2].

Thus, in the Mediterranean as well as in other areas of Europe and worldwide, a number of safeguard methods have been adopted in last years in order to reduce as much as possible the negative impact of pollution on the marine eco system. In particular, in the northern part of the Tyrrhenian Sea, in the area delimited by Corsica, Elba Island, Ligurian coast and Provence, the “Pelagos Sanctuary”, considered among the main feeding and reproductive areas for a number of cetaceans in the Mediterranean, was constituted in order to preserve such animal species from the disruptive impact of pollution [3].

The adoption of innovative strategies for environmental monitoring applied to marine areas has therefore experienced a growing interest in last decades, thus involving more and more sophisticated and reliable methods to accomplish successfully this aim.

Among several strategies adopted throughout the last years, the employment of electrochemical sensors, often included in systems based on the Electronic Nose (E-Nose) technology, could represent a useful add-on to current methods, capable of increasing their sensitivity and accuracy.

Thus, the aim of this work is to present a smart system, based on the technologies of E- Nose, integrated into a moored buoy and capable of monitoring the presence of hydrocarbons on the sea surface in a given area. This system can be complemented by other similar approaches, for example integrated into floating vehicles, as already described in literature [4], for a more complete monitoring both from static and dynamic point of view, of an area of interest. Indeed, the proposed buoy can be used as a node in a monitoring network to control areas of interests; to this end, the buoy is equipped with network interfaces allowing for external communication. A connector with a Marine Information system (MIS), offering storage functionalities as well as suitable interfaces for data fruition and processing (see e.g. [5]), is presented. By the connector, it is possible to access in real time the data acquired by the buoy and transmitted wireless to the MIS and to request particular procedure to be performed. The paper is organized as follows. In Section II the basic facts about the buoy and its sensor payload are introduced; Section III describes the E-Nose from an hardware perspective while in Section IV the onboard data processing functionalities are described. In Section V communication interfaces and connection to the MIS are reported. Finally, Section VI presents and discusses experimental results while section VII ends the paper.

II. Buoy Sensor

The proposed buoy (shown in Fig. 1), which is autonomous thanks to photovoltaic panels, is equipped with a configurable sensor payload. Currently, it is equipped with i) a complete weather station, ii) accelerometers for wave motion evaluation, iii) GPS sensor and iv) the E-Nose which is housed in the immersed part of the buoy and described in detail in the following section.

Fig. 1. The developed moored buoy at sea

The weather station consists in a thermometer for measuring air and water temperature, a hygrometer for measuring humidity, an anemometer and a rain gauge for measuring liquid precipitation. The sensors are connected to a main electronic board (specifically manufactured for the buoy), which performs the actual measurements. A 3-axis accelerometer fixed to the buoy is also connect to the electronic board and allows for wave motion estimation. Finally, a GPS is also available, providing time information as well as the exact location of the moored buoy.

III. THE E-NOSE

The electronic nose system, integrated within the moored buoy, aims to detect, in real time, the presence of pollutants on the sea surface. This smart, reliable tool represents, together with other sensor systems included in this platform, an important add-on, with respect to the current marine monitoring systems.

The E-Nose-based system is made of several components. Such elements include a flow chamber for air sampling, two pumps and an electrovalve for air flow inlet and outlet, control electronics (composed of a smart electronic board) and a sensorized flow chamber.

The flow chamber for air sampling has a cylindrical shape, with an embedded sensor aiming at checking for presence of humidity within the chamber, while pumps and electrovalve are interfaced to the electronic board for their activation, allowing the correct functioning of the air aspiration/purge system. Control electronics, as above stated, rely upon the smart electronic board Arduino Mega 2560, allowing the control of the E-Nose system, including pumps and the electrovalve, as well as sensors. The E-Nose control board is physically connected via RS232 to the main electronic board of the buoy. The choice in favor of an Arduino board has been taken in order to keep its control and programming as simple as possibile, as well as to grant its full adaptability to final users' needs, relying on open access protocols.

The sensorized flow chamber is realized in PEEK, a thermoplastic polymer whose main characteristics are the low density, chemical inertia and good mechanical properties. This component, essential to the correct functioning of the E-Nose system, could be equipped with up to six sensors (for the application described here, only three detectors are employed,. While other slots are left free for further customization) placed radially in the chamber. In particular, within this work, three Photo-Ionization detectors (piD) with different sensitivities are chosen, in order to provide reliable responses even in presence of low concentration of Volatile Organic Compounds (VOCs). Such sensors are classified depending on their label, and named as "Silver", "Bronze" and "Black" piD (from the most to the least sensitive one). Among the sensors commercially available, piDs are chosen for the reliability of the data acquired, their stability to experimental condition changes, their relatively poor drift, as well as their non-responsiveness to major air compounds, such as nitrogen and oxygen.

The piDs are power supplied through Arduino Mega 2560 electronic board by a 5V supply pin, thus allowing for a low power consumption, not otherwise requiring a pre-acquisition warming time, as occurring in the case of many other kinds of sensors.

The principle of operation of the E-Nose system is quite simple: cycles of air suction are defined and performed by activating the inlet duct through pumps and electrovalve movement; the air passed through the air sampling flow chamber where the humidity sensor, also supplied and managed by the electronic board, is placed.

Then, the air enters the PEEK flow chamber equipped by the sensors that perform an analysis of the VOCs contained in the air sample, providing a corresponding output signal correlated with the total VOCs concentration. From the sensorized flow chamber, the air is then purged off the buoy.

Within the purpose here described, the acquisition of data from the piDs is performed at a frequency of 10 Hz, with cycles carried out periodically; each cycle consisted of one minute of air suction, analysis and purge, followed by a variable and adaptive period of resting. This particular procedure is chosen to assure the acquisition of reliable data, possible thanks to the resting time needed by the E-Nose to make the sensors clean after each acquisition.

The E-Nose system is customizable according to the user's requirements and environmental needs and can accommodate other piDs.

IV. E-NOSE ON BOARD DATA PROCESSING

The data collected from the piDs are pre-processed directly on the E-Nose control electronics. Indeed, in order to keep the data transfer rate as small as possible, a compact representation of the collected data has been chosen. In particular, high significant features are extracted from the raw data consisting in temporal sequences of samples from each piD.

#Byte Pos	00-02		04	05	06	07	08	09
Field	"STX"	NavVH	NavVL	NavTy	YearH	YearL	Month	Day

10	11	12	13	14-17	18-21	22-25	26	27
Hour	Minute	SecH	SecL	SatList	Latitud	Longitu	RhInt	RhDec

28	29	30	31-32	33-34	35	36	37-116	117-196
TmInt	TmDec	Rain	WndSp	WndDr	Vbatt	Crc	Acc-X	Acc-Y

197-276	277-308	309-311	312	313
Acc-Z	Nose	"ETX"	<CR>	<LF>

Fig. 2. Buoy packet format

In detail, the following features have been considered:

- Mean value obtained during the acquisition for each of the three piDs (following the order "Bronze", "Silver", "Black" piD) and for the humidity sensor
- Maximum value (peak) obtained during the acquisition for each of the three piDs (following the order "Bronze", "Silver", "Black" piD) and for the humidity sensor
- Peak time obtained during the acquisition for each of the three piDs (following the order "Bronze", "Silver", "Black" piD) and for the humidity sensor, defined as the sample in which each sensor has reached the maximum value

All the processing for feature extraction is carried out on board and the results are then transmitted to the buoy main board.

Notice that this pre-processing is extremely useful to reduce the computational load required for the system management, therefore allowing an increase of the performances of the overall system, with considerable energy saving.

V. Communication (ISTI)

To equip the buoy with networking functionalities, it has been decided to design a specific connector to the MIS (see e.g. [5] for details about the MIS). The communication are bidirectional and are used to send acquired data and to configure buoys functionalities.

From a hardware perspective, the buoy is equipped with a GSM modem. The installed SIM is enabled to send data packets. In brief, the buoy can be configured sending to its internal modem SMS messages, while the acquired data are sent by the buoy to a configurable FTP server in binary format. Then a suitable parser converts the received binary files into CSV that can be easily fetched to the MIS.

A. From Buoy to the MIS

Buoy sends to the MIS two kind of data: i) the actual observations made by the buoy and ii) an auxiliary file containing information and metadata about buoy configuration. The data are placed in a specific FTP folder of the MIS exploiting GPRS connection.

A packet can contain or not a valid E-Nose measurement (depending on the E-Nose trigger rate). Each packet has fixed length equal to 314 byte. Basic organization of the packet is shown in Fig. 2. In details:

- Orange bytes are used for synchronizing packets and check completeness. Pale yellow bytes contain data from the GPS, including GPS time and quality of position estimate.
- Green bytes refer to meteorological measurements, including humidity, temperature, rain, wind speed and direction. Battery status is also included in this block.
- Pale orange packets refer to accelerometer data in three directions.
- White bytes correspond to E-Nose measurement if performed. Otherwise, they are filled with zeroes.

In addition, the buoy provides a text file containing information about its configuration, including its ID, GSM network configuration, FTP settings and other parameters for controlling acquisition and transmission frequencies.

B. From the MIS to Buoy

The MIS communicates with the buoy through text messages (SMS). As mentioned before, the buoy is equipped with a GSM modem used both for incoming and outcoming communication. Meanwhile communication to the MIS exploits FTP connection, the communication to the buoy are sent exploiting formatted SMSs due to the fact that the buoy has dynamic IP address.

The MIS is in charge also of the management of the power management of the buoy. Thanks to its internal logic, it defines the optimal acquisition rate in order to ensure the buoy operations. The optimal acquisition rate depends on battery status and on power supply obtained by the buoy solar cells.

MIS can also change the acquisition rate depending on the data acquired by the E-Nose: in case of a hydrocarbon detection, the acquisition rate will be increased in order to follow the evolution of the possible oil slick.

VI. Test & Results

The E-Nose system has been first tested on laboratory bench by evaluating the response produced by the sensors. Such trials have been necessary to evaluate the performances of the sensors employed, as well as the feasibility of the approach chosen for our specific purpose. In particular, it has been necessary to set up the optimal air flow rate for increasing the reliability of the data acquired, thus maximizing the signal to noise ratio (SNR) produced in output by the piDs used. The optimal SNR has been obtained with an air flow rate of 2 l/min, later chosen to properly dimension the pumps and electrovalves for the system overall. In the same context, the Minimum Detectable Concentration (MDC) of a set of compounds has been computed, including those hydrocarbons normally present on the sea surface after an oil spill or illicit ship transits through a marine protected area. Such substances included diesel fuel, gasoline, kerosene and crude oil, of which the MDC parameter has been considered as the minimum concentration producing a SNR of at least 3:1.

The results obtained in this first assessment are consistent with the technical data provided by the piDs manufacturer, thus spanning from a -3 log v/v for the "Silver" piD (most sensitive) to a -2 log v/v for the other two piDs employed on all the compounds above described.

Another analysis performed in this first test session aimed to define the "T90" parameter, determined as the time needed by a sensor, in presence of odorized air, to reach 90% of the maximum value in terms of output signal amplitude. Even in this case, the results obtained did not differ much from the datasheets, all of them remaining under 20*s* between the stimulus onset and the reaching of the 90% of the maximum output signal. Thus, the detection time are adequate for early warning the authorities and organize a prompt response to the pollution event.

Afterwards, the E-Nose has been integrated with the general electronic of the buoy and the communication mechanisms have been tested. In particular, data transfer to the MIS and setting of acquisition frequency have been validated.

Then, two tests at sea have been performed. The first of them has been held in La Spezia, Italy, within a highly polluted area, due to ship transits towards the nearby harbor, as well as to sewage from factories located in the suburban area of this maritime town. The second test has been otherwise carried on in Capo Enfola, Elba Island, within the protected area of the Tuscan Archipelago, thus representing a completely different environment, without the presence of oil spills and ship transits, and with a well preserved marine environment. The MIS has been able to receive and store all the data, with no appreciable delay. The data acquired during the two sessions have been visualized through the MIS web interface (Fig. 3): they have been found consistent with the two different environmental models typical of the two settings, with pollution detected in the first case and completely absent in the second test.

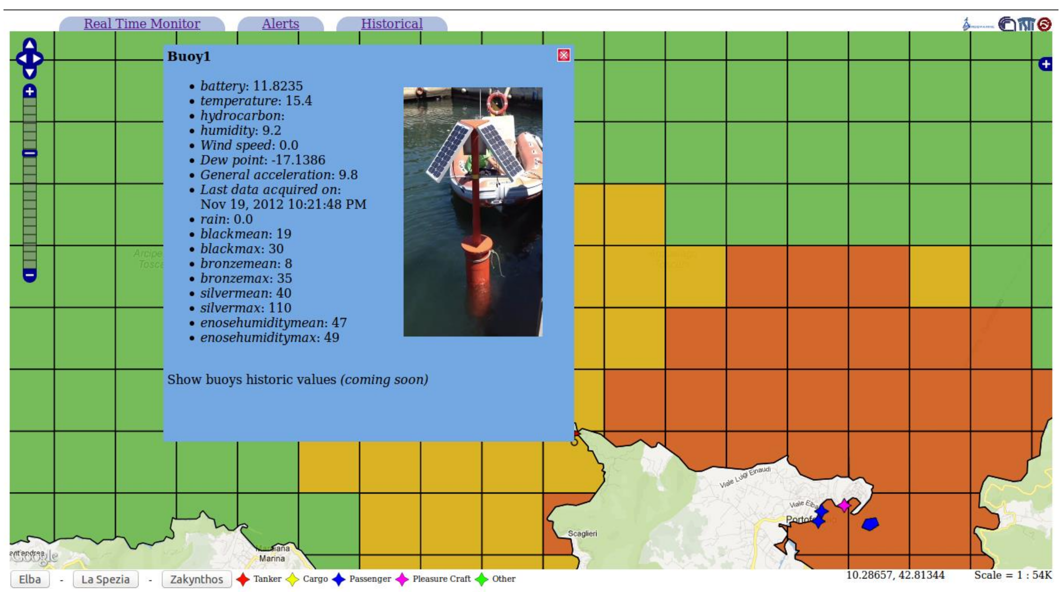

Fig. 3 Buoy data including E-Nose visualized through the MIS web interface

To further process the data obtained by the E-Nose and transmitted to the MIS, two artificial neural networks (ANNs), of the type Kohonen Self-Organizing Map (KSOM) have been trained through Matlab R2011b (The Mathworks, Natick, MA, USA). The ANNs aim respectively i) at evaluating the concentration of the compounds detected and ii) at identifying the correct hydrocarbon within the subset of the known stimuli above cited. To fulfill this task, data obtained from laboratory bench test, La Spezia and Enfola sea sessions, have been employed for training and test. Both the ANNs showed satisfying performances, the first of which demonstrating its reliability in 88.45% of cases, while the second providing correct feedback in 80.83% of cases.

VII. Conclusion

In this paper, we have presented an innovative moored buoy integrating an especially designed E-Nose for pollutant detections. The buoy, whose custom electronics and mechanics has been described in the text, is also integrated in a more general framework for sea monitoring thanks to a connector to the Marine Information System (MIS) presented in [5]. Thanks to this integration, it is possible to analyze in real-time the data acquired by the buoy and to explore historical data in order to understand seasonal trends. In addition, the data acquisition and transmission frequency can be set remotely, in order to adapt the buoy behavior to the level of monitoring required at a particular time. The E-Nose itself is capable to detect hydrocarbons normally present in illicit discharges and oil spills. It has been shown to provide reliable results in terms of repeatability and reproducibility of the signal acquired under similar conditions, and the response in terms of sensitivity (specifically, the minimum detectable quantity) is largely forecasted before the test session, being characterized by the sensitivity of the different sensors employed. Additional processing methods have been included for discriminating several levels of hydrocarbons concentration and for their discrimination into classes. Such methods, based on a machine learning approach, have shown very promising results, also considering that hydrocarbons employed for this analysis are chemically similar, making challenging their identification.

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