CO2Net: A marine monitoring system for CO_2 leakage detection

Aldo Annunziatellis*, Stefano Graziani*, Salvatore Lombardi*, Chiara Petrioli†‡ and Roberto Petroccia†
* Dipartimento di Scienze della Terra
Università di Roma, "La Sapienza"
{aldo.annunziatellis,stefano.graziani,salvatore.lombardi}@uniroma1.it
† Dipartimento di Informatica
Università di Roma "La Sapienza"
{petrioli, petroccia}@di.uniroma1.it
‡ Consorzio Interuniversitario Nazionale per l'Informatica (CINI), Roma, Italy

***Abstract*—Underwater oil and gas extraction and distribution, as well as the investigation of solutions for CO_2 storage underwater, demand for new technologies to perform pervasive real life monitoring and control of underwater critical infrastructures. In this paper we present a system, named CO2Net, we have developed to perform accurate real-life monitoring of underwater CO_2 storage infrastructures. The basic component of our system is the CO2Probe, a new underwater monitoring node which combines sensing, acoustic communications and networking capabilities. CO2Probes are connected via acoustic links in an underwater sensor network which provides robust, real-life communications of the monitored data both in single-hop and multi-hop deployments. The user has a real-time control on the monitoring system, being able to change alarm threshold values and sampling rates. The proposed CO2Net approach overcomes the major limitations of system currently available on the market, and provides a first easy to use, flexible and easy to extend, complete monitoring system for underwater infrastructures, based on the emerging underwater sensor networking paradigm. A first prototype of CO2Net has been tested during summer-fall 2011 at the NATO Undersea Research Centre (NURC) in La Spezia. Results of these experiments confirm system reliability, and its adaptability: all requested data where provided in real-time, the system was remotely accessible and end user could change monitoring parameters.**

***Index Terms*—Underwater acoustic networks, underwater wireless sensor networks, sea trial testing, underwater environmental monitoring, Carbon Capture and Storage, marine monitoring station, dissolved CO_2, CO_2 geological storage.**

I. Introduction

The geological Carbon Capture and Storage (CCS) technique consists of capturing CO_2 from power and industrial activities and storing it in deep geological reservoirs in order to prevent large quantities of CO_2 from being released into the atmosphere. CCS has the potential to contribute over 15% of the needed reductions in CO_2 emissions by 2050, while at the same time providing society with a "bridge" between fossil fuels and renewable energy supplies. Storing CO_2 underground is volumetrically very efficient. As CO_2 is injected into the subsurface it undergoes an increase in density. Consequently, ideal conditions for subsurface storage are at depth of about 1000m where CO_2 is in the super critical conditions, pore-water are saline (non potable) and porosities, in many sedimentary basins, are likely to be high. One of the most promising solutions for CCS is to store CO_2 underwater in deep ocean masses. The best way to prove that the CO_2 is not returning to the biosphere and to quantify leakage if it does occur, is by direct measurements. During injection, the main objective of a monitoring plan is to verify the amounts stored and to ensure that leakage is not occurring. Monitoring then continues when injection has been completed to confirm that the system is behaving as predicted, through further history-matching. Continuous monitoring leads to greater confidence in predictions of the long-term future behavior.

Numerous, relatively-inexpensive, commercial systems exist on the market for on-shore monitoring of CO_2, based primarily on IR sensors. However because of the greater complexity of marine applications only few, expensive systems are available for off-shore environments. The majority of these systems were developed by marine research groups from Germany (e.g. CONTROS Systems & Solutions GmbH) and from the United States (SAMI CO_2 for the measurement of pCO_2, see Figure 1). The high cost of existing solutions limits the number of units that can be deployed, which in turn limits the accuracy with which the monitoring system is able to identify a CO_2 leak from the seafloor.

Roberto Petroccia, Chiara Petrioli, Stefano Graziani and Salvatore Lombardi are also affiliated to WSENSE, "La Sapienza" spinoff devoted to development of cyber physical systems technologies.

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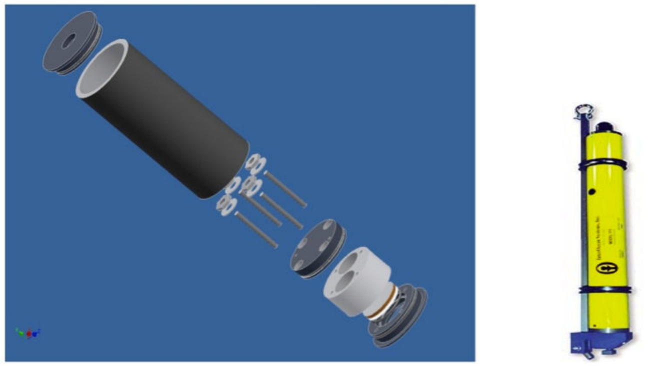


(a) PVC cylinder

(b) Acoustic release

Figure 2. Co2Probe components.

Figure 1. SAMI sensor for pCO_2 measurement.

Moreover, current ocean monitoring systems are typically based on one of two different approaches:

1) Deployment of underwater nodes that record data during the monitoring mission, and then recover the instruments to retrieve the data.
2) Cabling of the underwater nodes to a surface station in order to collect the data on-line and in real-time.

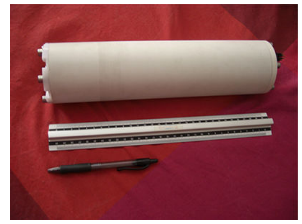
The deployment of the nodes is easy in the former approach. However, this approach suffers from lack of on-line and real-time control on the system. The recorded data cannot be accessed until the instruments are recovered. Moreover, interaction between on-shore control systems and the monitoring instruments is not possible, which prevents any adaptive tuning or reconfiguration of the system. Lack of real-time communications limits system management: in case of either HW/SW problems or nodes disappearing from the deployment area due to strong currents or intense marine activities, this may result in significant degradation of the monitoring quality and accuracy.

The second approach enables complete control on the monitoring system. However, the deployment of underwater cables usually involves sea trips, specialized personnel, and sometimes dangerous operations. Moreover, cabling the underwater nodes bounds the number of sensor nodes and the geographic areas where the system can be deployed (e.g., not to impair ship navigation). This in turn often limits the size of the monitored area, and the potential for identifying a CO_2 leak from the seafloor. Cabling also significantly increases the cost and complexity of deployment.

In this paper we present a new in-house system which overcomes the limitations of the approaches presented above. Our system allows us to decrease the costs of underwater monitoring while at the same time providing higher flexibility than existing systems. It makes use of acoustic communications for remote control of the system and data delivery to a gateway without the need of cables. The control station can then address each of the deployed underwater nodes to retrieve the data, control the system, change system settings, such as sampling rate, frequency with which data are reported, alarm thresholds etc. Each node monitoring the area can locally store the collected information and deliver them to the the central station immediately, on request, at some specific time of the day based on what requested by the central station, or only if an anomaly is detected. A first prototype of our underwater nodes (Figure 7) has been under test during summer-fall 2011 at the NATO Undersea Research Centre (NURC) in La Spezia, Italy. It has been deployed in the harbor area of La Spezia measuring temperature, methane and CO_2 concentrations. The collected data were delivered acoustically to the control station on request and periodically, the system was remotely accessible and end user could change monitoring parameters. The paper is organized as follows. Section II describes CO2Probe and CO2Net. Section III describes the results of the system performance evaluation in the harbor of La Spezia, while

(a) Front

(b) Back



(c) Side

(d) Complete monitoring system

Figure 3. Underwater measurement probe.

section IV concludes the paper.

II. System description

We start describing CO2Probe and discuss its use for underwater monitoring in the past few years. We then present the improvement to the underwater system when combining sensing, communication and networking capabilities. Using acoustic communications the underwater monitoring node can be controlled on-line in real-time without any cabling constraint.

A. *Original measurement probe*

The main components of CO2Probe are:

- 1) IR sensors for CO_2 and CH_4 (methane) and sensors to measure pressure and temperature;
- 2) underwater housing;
- 3) acoustic release;
- 4) battery pack.

The measurement probe consists of a PVC cylinder (Figures 2(a)) connected to an acoustic release (Figure 2(b)). At the base of the probe a Teflon AF membrane (diameter 35 mm) and a supporting porous metallic disk are mounted (Figure 3(a)); the porosity of the metallic disk is much larger than that of the membrane and thus it does not influence the response time of the system. The gas permeable membrane allows for the diffusion of dissolved gases into the probe and their equilibration with the free gases measured by the sensors. Knowing the in situ pressure and temperature it is possible to back-calculate the original concentration of the gases dissolved in the water.

The probe also hosts a lithium battery, a data-logger and the control electronics. This configuration allows the system to record up to 5000 measurements and to have an autonomy of 500 acquisition cycles with a warm-up time of 10 minutes. The IR sensor ranges are $0-100\%$ and $0-5\%$ for CO_2, and $0-5\%$ for CH_4, with the two different CO_2 ranges guaranteeing good measurement accuracy for a wide variety of concentration intervals. The temperature sensor (Figure 3(b)), which has a quoted resolution of $0.0625°C$, is located on the top part of the probe, to avoid heating caused by the IR sensors.

Figure 3 shows the underwater probe (front, back and side) and the complete monitoring system assembled for the dissolved gas deep monitoring, including the probe, the acoustic release, weight and floating for the deployment. Batteries are inside the PVC housing. The back part of the probe has a 8 pins underwater connector, which is used to connect to external hardware, such as external battery pack, PC, control station, etc.

1) Data analysis: Collecting measurements from the sensors is the first step in order to evaluate the status of the monitored area and to detect anomalies. However, once measurements have been collected, another impor-

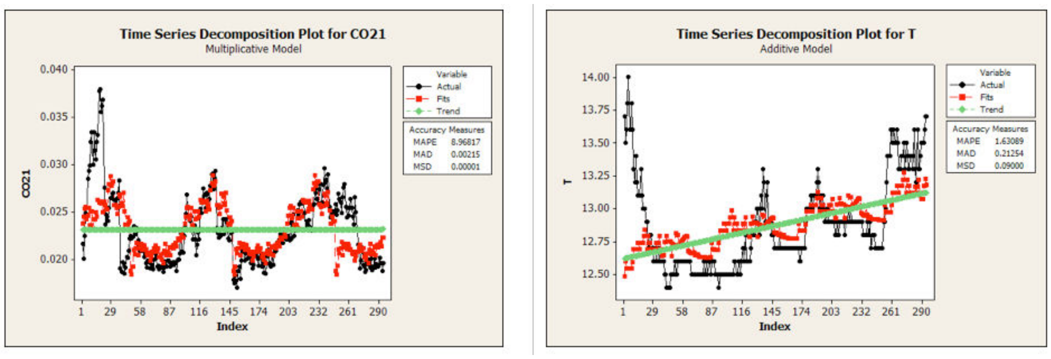


Figure 4. Graphs show an example of the time series decomposition for CO_2 (left) and temperature T (right) applied to a data subset collected in the Northern Adriatic sea. Both for T and CO_2 the two graphs show a seasonal component of 84 measures (14 days). Note that CO_2 graphs do not show any trend while all the temperature graphs highlight an increasing trend in the monitoring period.

tant step is the analysis of time series in order to identify the presence and the types of data patterns.

Such patterns can be distinguished in:

- **horizontal**: fluctuations around a constant value;
- **trends**: general increase or decrease of the value;
- **seasonal**: variations influenced by seasonal factors that recur on a regular basis.

For a more accurate data interpretation all the collected data have to be treated by using the technique of the seasonal adjustment of a time series. This technique consists of the decomposition of the series into its basic components estimating the trend and the seasonal component (Figure 4[1]). In this way it is possible to identify the typical fluctuation of the environmental variables (i.e. baseline) and discriminate the real anomalies detected by the probe.

2) System evaluation: During the last two years, the system was extensively tested at different depths (up to 60m [2]) showing good accuracy and reliability.

In spring-summer 2011, within the EC-funded projects CO_2 ReMoVe and ECO2, a field test was carried out close to the gas emanation occurring at Panarea Is. (Eolie Archipelago).

Figure 5 shows the collected results over two months of monitoring for the two probes deployed at the moderate flux site. Probes are cabled to a shore station. The collected data confirm the good functionality of the system and that the selected NDIR sensors are suitable for the dissolved CO_2 monitoring. In particular the two sensors within each probe show an excellent correlation, as illustrated by the X-Y scatter plots in the figure. This is important because the design choice of built-in redundancy allows for measurements over different concentration ranges ($0-25\%$ and $0-100\%$) and gives the potential for continued data collected even if one sensor would fail. The other important observation is that the two probes, placed approximately 6m from each other in the same general area, show the same trends and individual events (bottom and top graphs), giving confidence in values measured by the individual sensors. Unfortunately CH_4 was not detectable due to the low sensitivity of the sensor relative to the values occurring at the test site.

In order to investigate different configurations and system components, we have also tested the monitoring probe as an independent system (no cables) using internal data-logger and battery configuration. The field test was carried out in the Northern Adriatic sea with several probes deployed in open sea, 15km from the shore, at a depth of about 40m. Figure 6 shows the results, collected over three different monitoring periods, between October 2010 and May 2011. Data collection is not continuous because of the recovering of probes for maintenance (i.e. battery change and fouling remove). The plot shows a variable signal for CO_2 and temperature both at short and large time scale. The former effect is probably due to the random typical variation of all the environmental variables. The latter is linked to seasonal effects. However, as already shown by the cabled configuration, the collected data confirm the good functionality and flexibility of the system.

Although the presented system allows us to decrease costs with respect to existing systems, it still suffers of the same limitations: 1) When no cabling is used measurement probes are easily deployed. However, data can be collected only when the probes are retrieved. There is no possibility of interaction between the user and the system: No tuning and configuration, error detection or data reading is possible when the probes are underwater;

[1] Readers are invited to print the paper using colors to better visualize the presented results.

[2] In February 2012 we have conducted several experiments at the University of Porto on the resistance of the probe housing to the underwater pressure. We have tested our housing in a pressure chamber up to 35 bar without any problems. We were not able to test higher pressures due to the limitations of the pressure chamber.

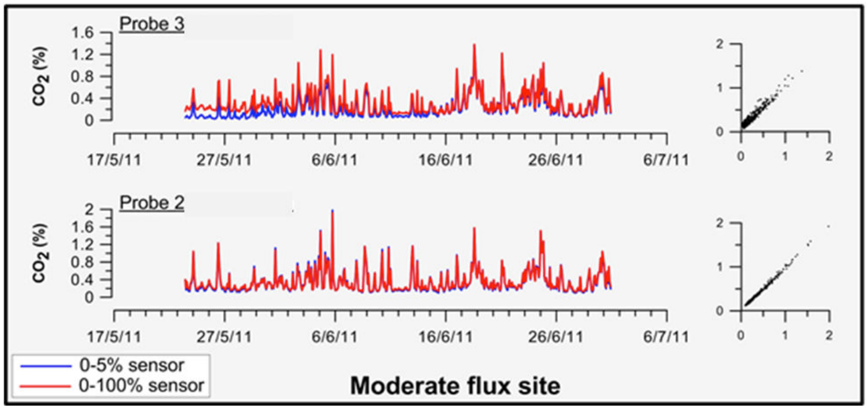


Figure 5. Dissolved CO_2 concentrations (reported as pCO_2) are given for the two probes deployed at the moderate CO_2 flux site (probe 3 above, probe 2 below). Note that in each time series graph data is plotted from the two CO_2 sensors in each probe (red and blue lines), and that the excellent correlation between these two sensors is illustrated in the X-Y scatter plots to the right.

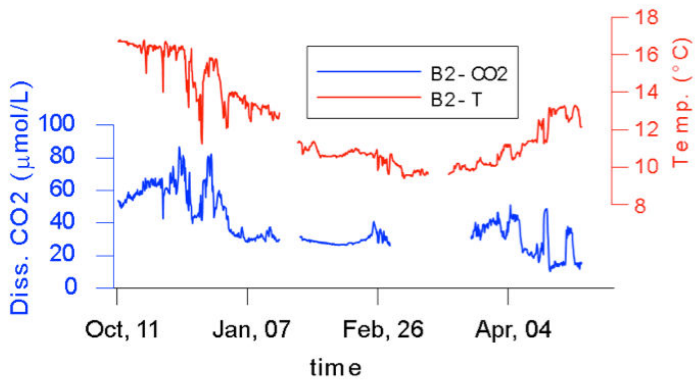


Figure 6. Dissolved CO_2 concentration and temperature in the Northern Adriatic sea.

2) When probes are cabled to a control station it is possible to interact directly with the probes collecting data on-line in real-time. The control station is usually located on shore or at the surface level so that it can be accessed through a radio link. In this configuration the deployment of underwater cables strongly limits the size of the monitored area, the number of units that can be deployed and it usually involves sea trips, specialized personnel, and sometimes dangerous operations, strongly increasing the cost of the monitoring system. Moreover, the deployment of cable is not always possible and can create problems to ship navigation.

In next section we present our solution to overcome all these limitations, which combines sensing and acoustic communication capabilities in order to provide a really powerful tool for real-time underwater monitoring applications.

B. Acoustic communication integration

We have investigated the possibility of combining sensing, networking and acoustic communications capabilities in one single underwater node, in order to provide a really flexible system for underwater monitoring applications. The idea is to integrate together the sensing component (CO_2, CH_4 and temperature); the communication component, which uses acoustic links to communicate when the sensing probes are underwater, thus avoiding the use of cables; the networking component, allowing the node to communicating acoustically to the control station via (possibly multi-hop) paths, reducing energy consumption, the effect of interference, impairments due to acoustic links asymmetry and possibly high BER. In this way the central station (on shore or at the surface level) can communicate with the probes, can control the system on-line in real-time and can instruct the sensors so that they perform specific operations, such as retrieving the collected data periodically, on request or in case of an event detection. Moreover, the use of acoustic modems usually guarantees the possibility to communicate over long distances (several hundreds meter or Kilometers), so that one control station is able to control the underwater probes deployed over a large area. In order to implement the system described above, we have integrated the sensing system described in Section II-A with a framework which implements a complete protocol stack for underwater acoustic sensor networks we have developed, which can be interfaced with different acoustic modems for acoustic communication. Routing, MAC and data fusion and task allocation solutions can be implemented in order to let the underwater probes not only deliver data to the control station but also cooperate to perform the desired tasks, thus improving the number of operations that can be performed by the network. The proposed framework has been strongly evaluated in the past years [1], [2], it can run on small, energy efficiency embedded devices and can share the same housing of the sensors, thus reducing the cost of the integrated node, and making easier the deployment in water.

The resulting CO2Net node therefore comprises the following components, in addition to the CO2Probe:

1. An embedded device running the framework, i.e. the protocol stack used to transmit data in the network. Gusmtix devices [3] have been used in our current solution.
2. An acoustic modem used to transmit and receive data packets underwater. Different commercial acoustic modems have been interfaced with our system (WHOI Micro-Modem [4], Evologics modems [5], Kongsberg modems [6]).
3. Battery pack for power supplying to the modem and the other system components.

The proposed system is really flexible and modular. The different components (control, sensing, transmission, power) are separate and their selection can depend on the specific application requirements. Different acoustic modems optimize different trade-offs in terms of cost, energy consumption, range, throughput, latency, and are therefore a better or worse choice depending on the requirements of the specific scenario. The developed system gives the maximum flexibility of choice to the user which can reconfigure it and change modems of system components at basically no effort. Similarly, different kinds of batteries are desirable depending on the application requirements. This is again easy to change. The flexibility and modularity of our approach allows to minimize the cost of the system given the application requirements. Although the use of acoustic communication overcomes all the limitations presented above, typical of commercial systems, commercial acoustic modem currently available on the market are quite expensive and energy demanding. However our system is flexible enough to support the possibility to also combine the use of both cables and acoustic transmissions. Underwater probes close to each others can be cabled together (shorter cables are needed, thus reducing the problems presented above) forming a cluster where only one node (or few nodes), serving as cluster heads, are interfaced to the modem, transmitting acoustically to the rest of the network the information generated by all nodes in their cluster. Several clusters can be deployed, thus covering a large area. In this way the cost and energy consumption issues can be reduced without reducing the accuracy and leakage detection capability of the system.

III. New measurement probe evaluation

First prototype of our underwater nodes (Figure 7) has been under test during summer-fall 2011 at the NATO Undersea Research Centre (NURC) in La Spezia, Italy under the scope of the collaborative efforts between NURC and the University of Rome. It has been deployed in the harbor area of La Spezia measuring temperature together with the concentration of methane and CO_2 dissolved in water and communicating the collected data to the control station through acoustic links, using Evologics modems.

Figure 7. Underwater monitoring node: acoustic modem and measurement probe with the Gumstix inside the PVC housing.

The tests were conducted during the NURC ACommsNet11 experiment. Four acoustic modems, cabled to the shore, were deployed in the harbor area of La Spezia, close to the NURC facility (covering an area of about 900m ×400m). All of them were running the CO2Net framework and one of them was equipped with the CO2Probe (Figure 7). The node with sensing capabilities was acoustically instructed by the other nodes on interests and tasks to perform. All the communications between the sensing node and the other nodes were done acoustically using the acoustic modem. The cable connection was used only to give the user the control on the nodes without sensing capabilities, so that they could change settings of the CO2Probe and its associated CO2Net node in a real-time and on-line way. Experiments were successful. Each node was able to configure the sampling rate of the CO2Probe and the rate at which the measured data should be transmitted to the other nodes. The node was also able to start and stop the sensing operation on demand and could change the other

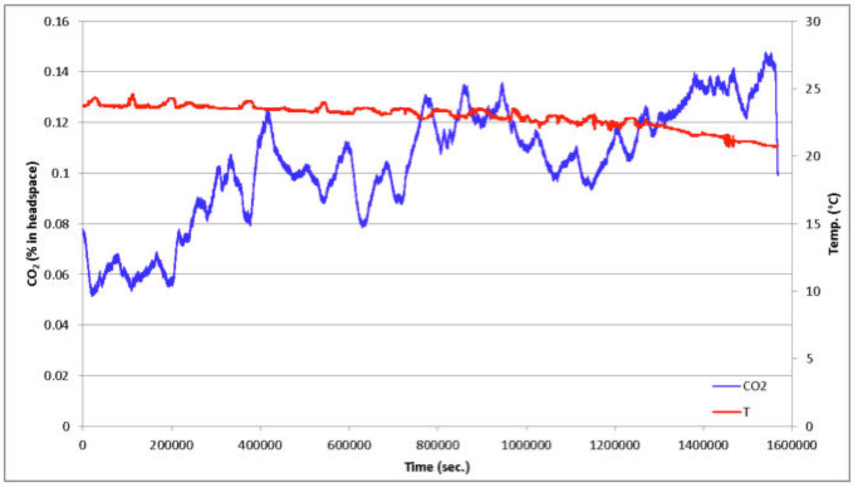


Figure 8. Subset of the monitored data in the harbor of La Spezia, summer-fall 2011.

CO2Net node configuration settings. The node hosting the CO2Probe was able to correctly interact with the other nodes, locally storing the collected environmental data at the selected sampling rate, and forwarding the measurements to the gateway according to the predefined reporting rate. Moreover the user was able to instruct the sensing node on changes of sampling and reporting rates, so that, upon event detection, node operation would change. Alarm threshold could also be configured on-demand.

The field experiment conducted in La Spezia has therefore shown both good data acquisition and good system operation. Figure 8 shows a subset of the collected data (about 20 days), presenting CO_2 concentration and temperature variation occurring over time. It is possible to notice a general increasing trend of the CO_2 value well correlated with the temperature decreasing.

IV. Conclusions

We have investigated the design of a new underwater monitoring node which combines different sensors (temperature and concentration of methane and CO_2 dissolved in water) with communications and networking capabilities. Acoustic communications are used for remote control of the system and real-time data gathering without the need of cables, thus overcoming some of the major limitations of monitoring systems currently available on the market. Underwater nodes can organize themself into a network and interact using acoustic links (in a single-hop or multi-hop way) with the on-shore control station. A complete protocol stack has been implemented allowing the nodes to acquire the underwater channel and to route data and control information to the network sink(s). The proposed system has been tested and evaluated in summer-fall 2011 at NURC presenting good results and performance in terms of accuracy and reliability of both data acquisition and system operations. CO2Net builds on a flexible powerful framework which can be applied to several monitoring scenarios, and can be easily extended with additional sensors or be ported to different platforms. To exploit at best this flexibility current work is addressing integration of additional sensors and porting of our solution on underwater mobile vehicles.

Acknowledgments

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