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On the Design of Atmospheric and Water Pollution Sensors for Deployment over Unmanned Vehicles

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Abstract **-** In this work we present advances on a project oriented to design, test and deploy sensors on unmanned vehicles to measure air and water pollutants. The main objective of the project is to develop a flexible platform composed by mobile nodes that allows dynamic sensing of pollutants in air and water environments. In this way, areas of interest can be discovered during early stages of monitoring, and sampling of pollutants can be adjusted according to priority levels. The design of such sensor devices needs to consider several parameters such as the weight, size, geometry, energy consumption, connectivity, and communication protocols, to provide a smooth integration to the robotic vehicle. In this paper, details are presented about the design of an air particulate matter (PM) sensor and a water nitrite concentration sensor. These devices will be mounted on an aerial and an underwater unmanned vehicle respectively. Also, in this work we sketch a methodology to coordinate the efficient deployment of the dynamic nodes considering a set of robotic agents carrying the sensors. The results of experiments with the sensors taking measurements are shown, revealing their suitability to accomplish the intended task.

Keywords**:** Sensor design; air pollution; water pollution; unmanned vehicles; dynamic sensor nodes.

1. Introduction

Air pollution is a rising problem all around the world. According to the World Health Organization (WHO), heart disease, stroke, chronic obstructive pulmonary disease, cancer, and pneumonia are some ailments that people may suffer due to the high air pollution levels [1]. Each year more than 9 million people die prematurely due to air pollution.

There are six denominated air pollutants (CO, Pb, SO_2, O_3, NO_2, and $PM_{2.5}$ and PM_{10}) determined by the United States Environmental Protection Agency (US EPA) [2]. Usually, the monitoring of those pollutants is being done by fixed certified station distributed in large urban areas. They provide accurate measurements, but they are costly, requires complex maintenance and due to these factors cannot be used massively, so they do not provide good spatial resolution of measurements. On the other hand, satellite-based monitoring can cover wide areas, but they cannot provide accurate information of specific points of interest. Lately, some research is being oriented to use aerial vehicles equipped with sensors, which provide more flexibility to monitor areas of interest.

Water pollution is also a problem of big concern. In many places around the world, water supplying is under stress, due to scarcity and low quality of the fluid. Contaminated water is linked to transmission of diseases such as cholera, diarrhoea, dysentery, hepatitis A, typhoid, and polio. Every year there are more than 3.5 million deaths related to the use of polluted water. Water quality determines water suitability for different applications, such as recreation, drinking, fishing, agriculture, and industry. To ensure water quality, parameters such as temperature, pH, salinity, oxygen balance, and concentrations of nutrient species, such as NO_3 and NO_2, PO_4, HCO_3, NH_4, and SO_4, must be controlled to ensure that they are within the legally established limits. Monitoring pollution in water bodies is usually carried out by taking the samples at fixed locations in situ and performing the analysis later in laboratories. Recently, research is focused on the use of sensors mounted on unmanned vehicles to carry out measurements over distributed sampling locations. Microfluidic sensor devices, deployed in unmanned vehicles, are a promising solution for point-of-care monitoring of water bodies. Moreover, by doing the analysis in situ, risk of degradation or contamination of samples can be avoided.

Unmanned vehicles provide a safer way to deploy air and water sensors to monitor the environment. However, the adaptation of sensors technology to the vehicles is not a straightforward process and requires a thoughtful planning given that a particular application would require a specific design of the device. Also, the impact of such systems in the environment needs to be assessed before their deployment. Other parameters to be considered are energy consumption, payload, data storage, communication, and time between measurements.

In this work we describe advances in a research project aiming to the design, testing and deployment of air and water pollution sensors, considering specific characteristics of the devices, which help to simplify their integration on unmanned vehicles. Also, we present a methodology to allow an efficient deployment on the field of these mobile sensors.

2. State-of-the Art in Environment Sensing

Sensor technology development for atmospheric and water pollution monitoring has been investigated extensively over the last decades, but often from the perspective of static sensor nodes. The ubiquitous availability of compact sensors and internet-of-things (IoT) sensor network frameworks open the door to new approaches for conducting dynamic surveys of the environment and improving environmental policies. This section surveys the recent trends in environment pollution sensing.

2.1. Atmospheric Pollution Sensing

There are two primary methods to measure air quality, the Federal Reference Method (FRM) and the Federal Equivalent Method (FEM) [3,4]. The FRMs were developed by EPA scientists to measure the six primary air pollutants in outdoor air, to ensure accurate air quality data, as well as a uniform manner to obtain it. On the other hand, FEMs are based on different sampling and/or analyzing technologies than FRMs, but they are also an accurate tool for making decisions.

Nevertheless, the mentioned air quality monitors present some drawbacks, such as low spatial resolution, high cost, bulky instrumentation, frequent maintenance, coarse-grained data, limited temporal resolution (i.e., hourly), and only support outdoor pollution monitoring.

Low-cost sensors (LCS) can be an advantageous alternative for monitoring air quality because they are cost-effective compared to the primary methods to measure air quality [5]. Besides, they support high spatial coverage; are easy to maintain and use; can acquire and transmit data in real-time; and, they are also affordable, mobile, small size, and lightweight.

PM measurements are important, because the effects of pollution on humans and climate change could be countered by proper air pollution control measures, policies, and frameworks [6]. In addition, many countries have worked on improving their sustainable development by creating policies for protecting environmental quality and health.

Despite that, LCS have certain shortcomings that must be addressed before being used extensively. Issues are mainly related to the interference with ambient environmental conditions and other factors such as relative humidity (RH), temperature, ambient pollution level, and sensor age that limits the accuracy of measurements.

2.2. Water Pollution Sensing

The exploration of the marine environment, with microfluidic technology integrated on underwater vehicles, is largely focused on marine biology, ecosystems, and sea-related health studies. The vast biodiversity of marine organisms presents a challenge in the development of techniques for the discovery or monitoring of biomolecules. The rapid and accurate detection of toxic microorganism, toxins and indicators of pollution, has been presented as an area of opportunity for microfluidic-based technology [7].

Solutions aiming to automatize the water analysis process have been presented recently. In Lin et al. [8], a system for monitoring phosphate and nitrite in agricultural water environments is introduced. Other solutions integrating microfluidic systems [9] show potential in the deployment with different approaches. A field-deployable platform for automated in situ colorimetric nitrate analysis is presented in [10]. This microfluid device offers different options for analysis based on colorimetry and provides the possibility of integration with small underwater vehicles due to the size of the device. Overall, there are many more types of systems for monitoring pollution in aquatic environments that integrate various strategies, each with their own limitations.

2.3. Deployment Methods for Environment Sensor Nodes

Environmental sensor nodes can be deployed autonomously through a combination of Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs) and/or Underwater Vehicles (UWVs). Sensors can be embedded on these robotic agents which can be assigned the task of collecting environmental data. The main challenges involved with the deployment are factoring in the constraints and capabilities of the robotic agents, as well as task allocation and coordination of them. The physical properties of the robotic agents impose constraints on the sensors; the size, weight, power consumption and computational demands of the sensors must not exceed the capabilities of the robotic agents. Furthermore, there may be a requirement to modify the robotic agents to accommodate a physical mechanism for deploying the sensor, or to integrate the sensor with the robotic agents' own electronics and embedded computers.

Here, a framework is proposed for allocating and coordinating the deployment of sensor nodes extending existing solutions to the multi agent travelling salesman problem [11]. Such a solution seeks to assign multiple waypoints to multiple agents such that the overall travel distance is minimized. Given a set of M robotic agents $R = \{R_i | i = 1,2, \dots M\}, R_i = (x_i, y_i)$ and N waypoints $T = \{T_j | j = 1,2, \dots N\}, T_j = (x_j, y_j)$, the cost function (Eq. 1) must be minimized.

$$C = \sum_{i=1}^{M} \sum_{j=1}^{N} \left(\sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2} \right) \tag{1}$$

We also minimize an imbalance index, V (Eq. 2), where c_i is the cost (distance travelled) for agent R_i to travel to all its assigned waypoints. Without minimizing the performance index, the system may achieve an allocation with a smaller cost. However, this allocation may result in under employment of certain agents. With the performance index V, the workload is more evenly distributed. This more even distribution increases the overall rate of work being done and results in all waypoints reached in a smaller timeframe.

$$V = \sqrt{\sum_{i=1}^{M} \left(c_i - \frac{C}{M} \right)^2} \tag{2}$$

3. Methodology and Experimental Validation

To address some of the limitations of market-ready technologies, new approaches are envisioned, oriented toward the development of sensors to measure air and water pollution, built with specific characteristics, and that make them suitable to be embedded on compact ground, air and water unmanned vehicles. In this section we describe the design and testing of innovative air and water pollution measurement devices that can be integrated on mobile platforms.

3.1. Measuring Atmospheric Pollution

System description

Figure 1 shows a block diagram of the proposed compact Air Quality Monitoring System's (μAQMS) functionalities. The grey dotted line represents the case which contains a 5 V battery, a PM sensor, and the custom designed μAQMS electronic board. The red dotted line symbolizes the μAQMS board, depicted in Figure 2, which embeds a microcontroller; a Bluetooth Low Energy (BLE) module; a LED indicator; an energy regulator; a reset switch; and the connector for the PM sensors. The BLE module is used to send the information via Bluetooth to a cell phone used to record data. The µAQMS collects the information on $PM_{2.5}$ and PM_{10}, Temperature (T), Relative Humidity (RH), and pressure.

Software Description

The µAQMS board sends the sensors data via Bluetooth to the application installed in an Android cell phone; at the same time the cell phone sends the coordinates (latitude and longitude), date, and time to the app from its own operating system. In this way, the sensor system records geographically and temporally referenced data. The application used to test the device was developed with Android Studio. The main functionalities of the app are the data acquisition via Bluetooth, the display of measurements obtained from the sensors, and the storage of text files containing the data. The µAQMS board can work with two different brands of PM sensors: Honeywell (HW) and Plantower (PT).

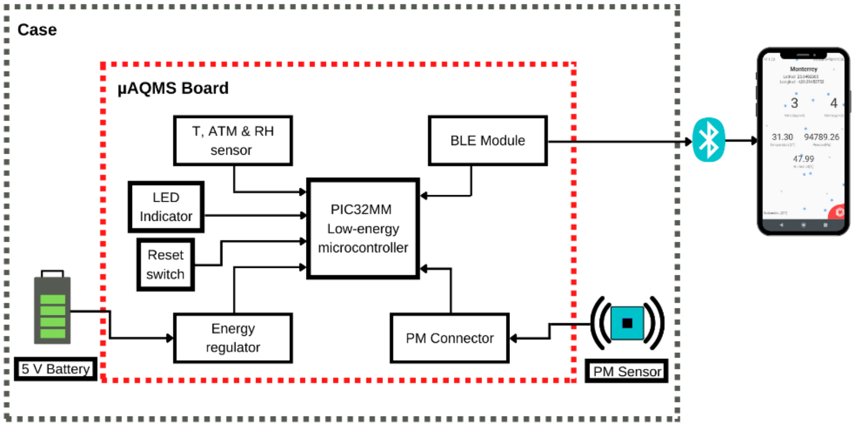

Fig. 1: Block diagram of the µAQMS system.

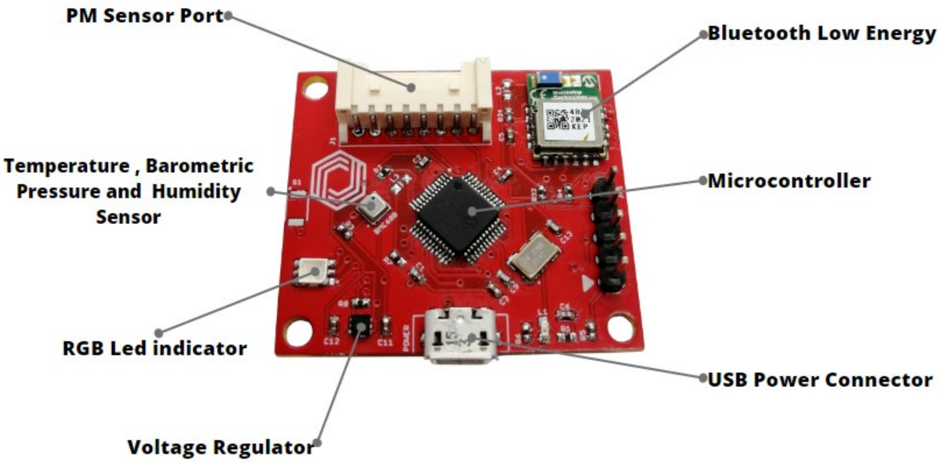

Fig. 2: µAQMS electronic board with the components.

Experiments

The experiment consisted in the collection of data by a pedestrian walking along two trajectories and carrying two PM PM sensor devices from different manufacturers and attached to the µAQMS. It took place in the last week of January 2023, 2023, at different times of the day, and two streets were chosen in Monterrey, Mexico, due to their traffic flow conditions: Garza Sada Ave. for high vehicular traffic flow, and Río Pánuco St. for low traffic flow. Both trajectories were traced parallelly over approximately the same distance of 1600 m.

Results

The graph presented in Figure 3 shows the correlation between the PT vs HW sensor $PM_{2.5}$ measurements in the morning, afternoon, and evening. Both sensors were configured with only the manufacturers' calibration, and it is shown that data present a high correlation. A close inspection revealed that the HW sensor values usually are greater than the PT ones. Finally, it is worth mentioning that the morning graph presents the best behaviour since it has the highest R^2 (0.922) and the lowest RMSE value (3.325); On the other hand, data obtained in the evening looks more scattered. This may be due to the parameters that influence the performance of the sensor, such as RH, T, and the PM concentration values.

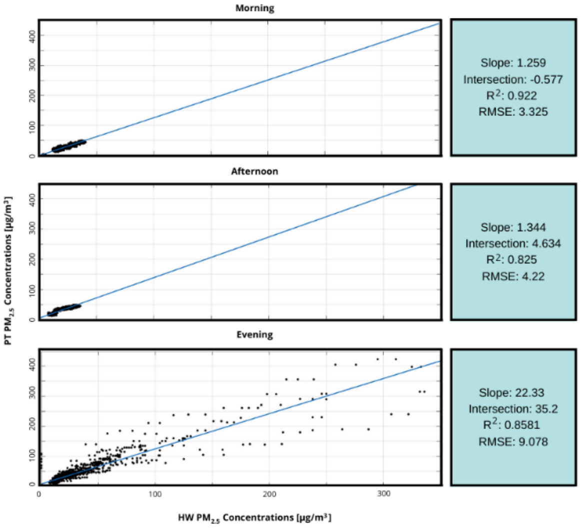

Fig. 3: $PM_{2.5}$ concentrations: PT vs HW.

3.2. Microfluidic Lab-on-Chip Sensor for Water Pollution

System Description

In previous work [12], a study of manufacturing techniques using stereolithography for lab-on-chip (LOC) devices for their integration with autonomous vehicles was carried out. The case study was a microfluidic device for the measurement of nitrate concentration by spectrophotometry. This design was improved and modified for its future integration with a water vehicle. The basic design contains two asymmetric split and recombine (ASAR) micromixers and an optic cell for spectrophotometry. Fluid distribution channels and ports are made for external components such as reservoirs, pumps, and valves. COMSOL Multiphysics software was used to analyse the flow interaction and mixing performance. Figure 4 shows the mold used to manufacture the device and the sensor device itself.

The analysis to be implemented, in the device, is a nitrite concentration assay by spectrophotometry. Using the Beer-lambert law (Eq. 3), we can relate the optical absorption to the concentration of nitrite.

$$A = -\,log_{10}\left(\frac{I}{I_0}\right) = \varepsilon cl \tag{3}$$

where A is the absorbance, I_0 the intensity of the monochromatic light incident upon the substance, I the intensity of the monochromatic light after the substance, ε the molar absorption coefficient, l is the absorption path length and c is the concentration of the sample.

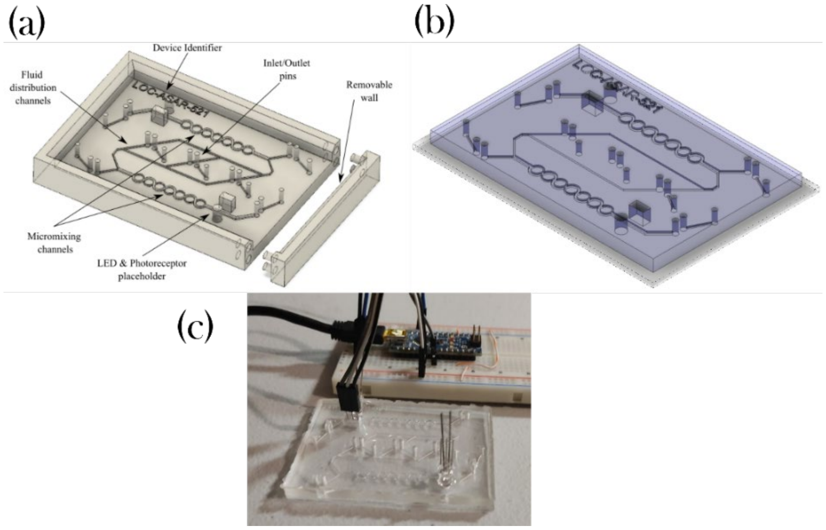

Fig. 4: (a) Mold for nitrite assay sensing module; (b) CAD of final device after casting and sealing with glass; (c) Final sensor device with electronic components.

Experimental results

To assess the device, a calibration curve was obtained (Figure 5) with concentrations between 0 and 10 nmol/well, where each well contains 200 µl of mixture. The measurements of a proof-of-concept circuit were compared with the measurements of a benchtop spectrophotometer. The results obtained show that our device can obtain measurements on site that can be compared in quality to those of a device usually used in a laboratory.

The differences between the two curves can be attributed to errors in the preparation of the wells and in the conditions for the measurements.

3.3. Consideration for size reduction to support efficient deployment with low payload carriers

The initial design of the µAQMS electronic board was conceived to create a fixed commercial air quality monitoring station, embedding low-cost commercial sensors and a high-performance microcontroller which can be used to sense, calibrate, and experiment with different types of calibration algorithms. Some of the sensors included were the PM sensor, O_3, CO_2, CO, temperature, relative humidity, and barometric pressure sensors. Experimental testing revealed some areas of opportunity to improve, such as the size and weight, the power stage that was designed to be connected to a 5V power supply, and the communication protocol using a USB cable. With the knowledge gained in the first design, a second prototype design started to make a more portable lighter version of µAQMS.

To manufacture a smaller board version, some elements were eliminated to reduce the size and power consumption. In the second design the O_3, CO_2, and CO sensors were not included, and only the PM, temperature, barometric pressure, and relative humidity sensors were added. Also, a Bluetooth low energy module was used to communicate with an android device. The overall size was reduced considerably, and now energy is provided by a power bank. This design is oriented to make a portable device, that can easily be carried by a person or a small unmanned vehicle.

It is important to mention the need to use standard communication protocols, to allow an easy integration with the onboard computer in the unmanned vehicles. Other aspects that need to be taken into consideration, are the internal operating temperature, and the protection against moisture and dust, but those will be studied in future work.

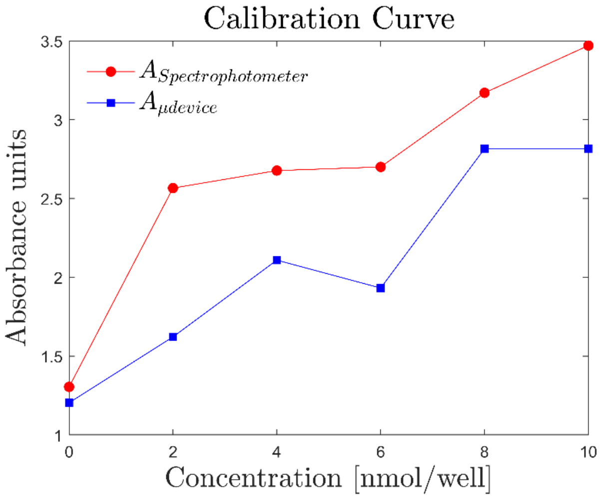

Fig. 5: Measurements of a calibration curve with a benchtop spectrophotometer and the device.

On the other hand, the encouraging results obtained with the water pollution sensor allow to progress towards the integration of the LOC device with an underwater vehicle, thus having the benefits of a mobile monitoring station. The integration implies to deal with some limitations such as energy management, water insulation, payload management and time between each measurement. The first three limitations can be overcome with changes on the geometry or hardware of the vehicle, but if a relatively small vehicle (≈70 cm large) will be used, the focus should be in the reduction of time between each measurement. Given that the reaction time (≈10 mins) cannot be changed, then multiple devices must be used or more iterations performed on the design of the LOC device. Having multiple devices involves an increase in the number of external components, which impacts the payload and space occupied by the devices. The advantage of the proposed microfluidic device and the assay to be performed is that, in the future, a modular design can be approached where more assays can be done with a minimum change in the space required for the lab-on-chip device. Figure 6 shows a first attempt at the integration of this microfluidic device on a compact underwater vehicle (THOR Robotics 110 ROV). Further testing will allow the formulation of more elaborate designs.

4. Conclusion

We have presented advances on the design of air and water pollution sensors manufactured to be mounted on unmanned vehicles. The main objective of the project is to develop a flexible platform composed of mobile sensors which can be deployed to monitor the environment in a dynamic way, adjusting the sampling to focus on more representative areas for pollution dispersion. We also presented the foundations to build a methodology to deploy the mobile sensors, considering the constraints and capabilities of each robotic agent. Early experiments with sensors taking measurements are encouraging, and future work is oriented to mount the sensors over air and underwater vehicles to further test their performance.

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Fig. 6: Mounting the device as an appendage to a remotely operated underwater vehicle.

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