Distributed Chemical Sensor Networks for Environmental Sensing

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Abstract—**Society is increasingly accustomed to instant access to real-time information, due to the ubiquitous use of the internet and web-based access tools. Intelligent search engines enable huge data repositories to be searched, and highly relevant information returned in real time. These repositories increasingly include environmental information related to the environment, such as distributed air and water quality. However, while this information at present is typically historical, for example, through agency reports, there is increasing demand for real-time environmental data. In this paper, the issues involved in obtaining data from autonomous chemical sensors are discussed, and examples of current deployments presented. Strategies for achieving large-scale deployments are discussed.**

Keywords-environmental monitoring, chemical sensors, air, water, sensor networks.

I.   INTRODUCTION

We live in a world wherein people are increasingly accustomed to instant access to a huge and exponentially growing volume of information stored on web-repositories. Through highly efficient search engines, people and organizations expect the internet to provide instant access to repositories spanning entertainment (music, movies, e-books, video clips, TV/radio), news and current affairs, hobbies, Government and Agency reports, financial data, and so on. The recent environmental disaster in Japan again highlights the need for access to real-time sensed information that may provide early warnings of impending events, and rapidly disseminate information to the public to minimize loss of life. This has once again placed the spotlight on how to gather, integrate, analyze and share sensed environmental data. We are particularly interested in how to sense the *chemistry* of our environment, and in particular, how to realize chemical sensors that are reliable, robust, and able to function autonomously for periods of weeks to years. As our ultimate goal is to achieve widely deployed networks of chemical sensors, it follows that the cost of ownership of these devices must be as low as possible.

II.   THE ELEMENTS OF SCALABILITY

The basic building block any sensor network is the sensor/communications platform [1]. Our specific interest is to build autonomous chemical sensor platforms that could provide the basis of a widely dispersed sensor network, providing frequent updates about the concentration of specific target species at many locations [2]. When one considers how to deploy and maintain sensor networks that will comprise many thousands of individual devices scattered across a large geographical area, the issue of scalability becomes paramount. The key to scalability is to produce sensor platforms that are not overly expensive to buy and can function autonomously for as long as possible (ideally months, years), while providing a stream of accurate data. For chemical sensing in water bodies, this is a formidable challenge, as chemical sensors are typically subject to drift and loss of sensitivity over time, and require regular calibration in order to maintain accuracy. Biofouling is a particularly difficult issue for environmental water monitoring that can have drastic impact on electrodes and other sensors directly exposed to the sample within a few days or weeks 3].

In this paper we will demonstrate how a microfluidics approach can provide very reproducible sample and reagent handling, enabling reliable data to be generated by autonomous chemical analysers deployed in hostile environments. The small reagent and sample volumes required to perform microfluidic assays means that multiple assays can be performed using relatively small reservoirs, and a small lead-acid cell can provide enough power to sustain the analyzer for a period of up to several months. For example, the typical reagent volume consumed is in the region of 50-100 µL per assay, which translates to 1000 - 2000 assays per 100 mL of reagent. Continuous monitoring at a frequency of 1 measurement per hour means that the platform can operate for 50-100 days per 100 mL of reagent, and provided the reagents are stable, this obviously scales as the volume per assay is reduced, or the reagent volume is increased. In parallel, we have fabricated similar platforms employing IR gas sensors targeting important environmental targets. These can function unattended for many months and yet remain within calibration, as they do not depend on a sensitive sensor surface to generate the analytical signal, or a supply of analytical reagents to function. The gas/air and water analysis platforms follow the same basic analytical approach in that they sense the analyte in the sample, process the analytical signal, store the data locally, and transmit the data to a remote server, for example, using GSM, Wifi or zigbee wireless communications. Both platforms have an integrated power source that can support all operational functions for periods of several months without intervention.

III. NUTRIENT (PHOSPHATE) MONITORING

A. Autonomous Nutrient Analyzer

The autonomous nutrient analyzer is a compact and portable device capable of performing reagent based chemistry in remote locations. The first-generation (GEN1) system originally developed at Dublin City University [4] has been extensively field trialed both at waste water treatment plants [5] and in natural waters [6]. In excess of 10,000 assays have been performed using the platform across 12 separate field trials. Current work is focused on the development of an improved version of the analyzer platform that provides equivalent or better analytical performance for a component cost of less than €200 per unit. Initial field trialing of the second generation (GEN2) system has recently commenced and the results from a three day field trial are reported below along with a description of the analyzer design and operation.

Figure 1: GEN2 Nutrient analyzer design; (1) Sample inlet; (2) Control board and detection system; (3) Dual channel peristaltic pumps; (4) Reagent bags; (5) IP68 enclosure

B. Analyzer Design and Operation

The GEN2 analyzer is a fully integrated system incorporating fluid handling, microfluidic technology, colorimetric chemical detection, and real time wireless communications in a compact and rugged portable device. The major system components are shown in Figure 1.

The sensing system is employs the molybdenum yellow method, a simple colorimetric technique based on the formation of a yellow-colored compound when a reagent is mixed with a phosphate-containing sample. The color of the reacted sample is detected at ca. 380nm using an ultra violet light emitting diode (LED) light source and a photodiode detector. This reagent chemistry is preferred

due to its long-term stability even though it is less sensitive than other more commonly employed reagent chemistries.

The sensor implements a two-point calibration protocol using a blank solution (0 mg/L orthophosphate) and a standard orthophosphate solution. The concentration of the standard solution can be varied depending on the range of orthophosphate levels in a particular sample/site. The two-point calibration is carried out for each sample measured. The importance of this procedure lies in its ability to correct for:

• Changes in LED output/photodiode response due to temperature fluctuations;
• Possible drift in response of detection system over time;
• Possible change in sensitivity of detection system over time.

The system communicates using short range ZigBee radio to a remote network gateway, which passes the sensor data via GSM or Wifi to a web-database for remote access by the user. This setup allows the user to not only monitor sensor data in real time but also to remotely change the sensor setup parameters, such as sampling rate.

C. Field Trial

Following an initial laboratory based calibration, the system was placed *in situ* at Broadmeadow Water Estuary, Co. Dublin, Ireland on 04/09/2010. This estuarine water body is know to have elevated nutrient levels due to a combination of inputs from industry, agriculture and a nearby waste water treatment plant. The trial location is shown in Figure 2. The analyzer was initialised to take samples at 30 minute intervals for the duration of the deployment.

Figure 2: Broadmeadow Water site

The sensor output over the 62-hour deployment period is shown in Figure 3. The sensor performed 124 autonomous measurements during the trial, and four manual samples were collected for lab analysis and validation. These

samples were analyzed in the laboratory using a Hach-Lange DR890 Portable Colorimeter. Figure 4 shows the excellent correlation (r = 0.9706) between the sensor output and the manual sample phosphate concentrations. The manual sample collected at 13:35 on 06/09/2010 shows the largest deviation from the sensor value. However, on that day, the river water levels did not allow this sample to be taken close to the sensor sample inlet. All other manual samples were taken at the sensor sample inlet. The daily fluctuations in the phosphate level can be attributed to the tidal nature of the estuary which lead to significant dilution of the outflow of the nearby waste water treatment plant.
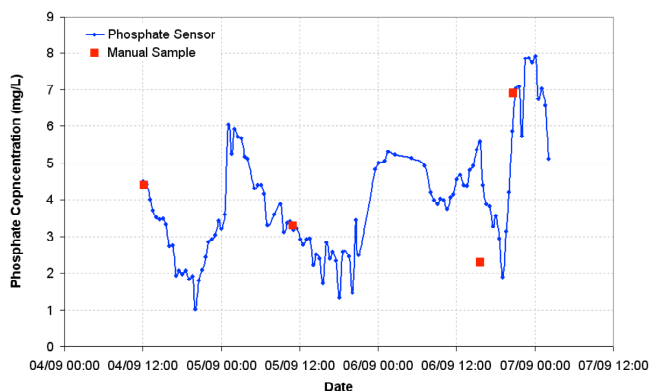

Figure 4: Phosphate concentrations measured during the trial by the phosphate analyzer and by parallel manual samples (red)

IV. AUTONOMOUS GREENHOUSE GAS MONITORING

European directives [7] have driven a growing need for autonomous platforms that can provide real-time monitoring of gases in the environment. Such platforms, along with the accompanying data recording and interface software, provide an attractive alternative to the current norm, which still depends largely on labour intensive manual monitoring [8].

A. Design concept

For the autonomous gas-monitoring platform, components are housed within the same robust casing used for the nutrient analyzer, which we knew to be suitable for long-term outdoor deployment (Figure 5). Our primary goal was to meet a need for a remote autonomous platform for monitoring greenhouse gas levels (CH_4 and CO_2) in landfill site boreholes. This system is designed to fit to borehole wells, which are typically located at the landfill site perimeter, to facilitate monitoring of gas migration [9].

The monitoring operation is controlled via a custom programmed MSP430 microcontroller (1), managing the gas extraction (4), gas sampling (5) and data communication (2). The power supply (3), a 12V 5Ah lead acid battery, currently allows a deployment of 8 weeks at a sampling frequency of four sample cycles per day (approximately 220 separate sample cycles in total). The principal components of landfill gas, carbon dioxide (CO_2) and methane (CH_4) [3], are measured by infrared gas sensors (Dynament Ltd. IRCEL-

CO2 and IRCEL-CH4). A SKC Grabair pump (SKC Inc., 222-2301) extracts a sample at 0.6 L/min from a depth of 1 metre in the borehole well. The data are statistically represented and sent in SMS format to a central base-station via GSM communication (Siemens MC35iT). As a backup, all harvested data are stored locally on an onboard flash memory chip. At the central base-station, the communicated data are parsed and placed onto a database, whereupon email alerts are sent to stakeholders. In addition, all present and historical sampled data are accessible to the relevant authorities and site personnel via a web-based visualisation application. This communications and web-portal design is the same as that used with the nutrient analyzer.
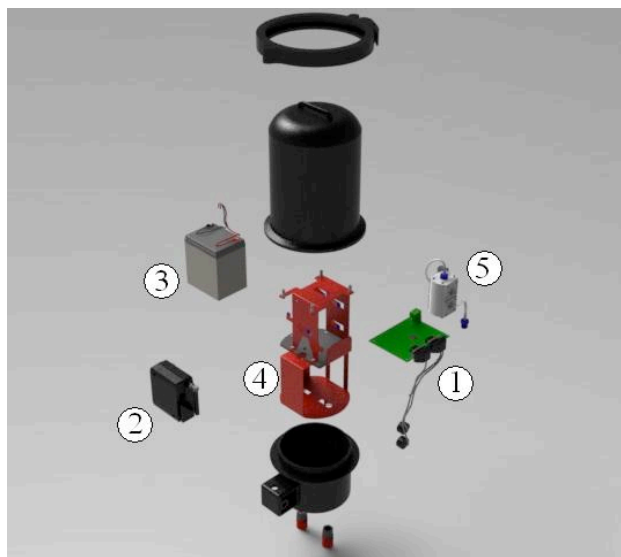

Figure 5: Exploded view of the autonomous landfill gas monitoring platform. (1) Control board, (2) GSM Module, (3) Battery, (4) Extraction pump, (5) Sample chamber and sensors

B. Deployment results

To date, extensive field deployment trials have resulted in gas monitoring platforms achieving continuous deployments in excess of 12 months. For the purpose of this results section and to highlight the benefits of this system, a subset of the data corresponding to June 2009 is displayed in Figure 6 [10]. The CO_2 levels can be seen to fluctuate significantly over this period, and greatly exceeding the threshold limit (1.5 % v/v) for significant periods.

Consultation with the landfill site operators revealed that an increment in soil cover restricted the dissipation of generated gas, resulting in a build-up of CO_2 concentration (events 1 and 2 as annotated in Figure 2). These actions were rectified by increasing in the extraction flow rate by site personnel. However, this remedial work was hindered by a partial blockage in the underground gas extraction pipe (event 3), which was subsequently identified and removed. The diagnosis of events and subsequent monitoring of the effectiveness of remedial measures illustrates the usefulness of this system in landfill site management.
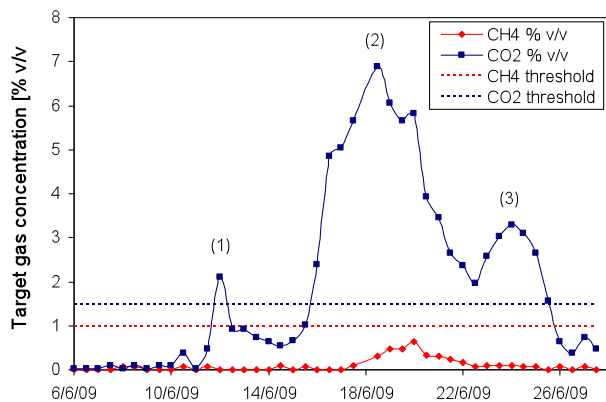
Figure 6: Recorded gas concentration data for June '09 with threshold limits of 1.5% v/v for CO_2 and 1.0 % v/v for CH_4 also indicated [10].

C. Further system development

As mentioned in the introduction, a key goal for scalability of deployments has to be the duration of autonomous operation. Currently continuous deployments of the platform in excess of 12 months have been achieved at two locations on an active and dormant landfill site. During this time, the system successfully monitored gas migration, with the batteries being remotely monitored and manually replaced when depleted. The systems uptimes were calculated upon retrieval, and were found to be approximately 83% over the duration of both deployments. The discrepancy from complete autonomy was attributed to the 12V/5Ah battery depleting below its operating threshold (ca. 11.5V) after approximately one month in the field (see original code battery decay in Figure 7). Below this threshold, the GSM unit cannot draw sufficient current to transmit and the data cannot be accessed remotely via the website. While battery replenishment can be achieved reasonably quickly, it is obvious that a reduction in power usage would increase the duration of autonomous operation. This has been achieved through optimization of the microcontroller C-code to refine the device functionality, and in particular introduce sleep modes. Using this optimised code resulted in a three-fold increase in battery lifetime (i.e. ca. 3 months). The battery decay of a unit programmed with both the old (blue series) and new power saving code (red series) can be seen in Figure 7.

In order to further extend deployment lifetime, and potentially realise a fully autonomous field-deployable sensing platform, a solar cell has been assessed as a local energy generation source for the platform. A study was conducted by coupling the system with a charge controller (4Ah, Radionics 706-7934) and photovoltaic module (17.5V, 0.27A, Radionics 194-149). The solar cell was chosen to provide sufficient power to charge the battery even in low lighting conditions. The charge controller serves to regulate the power being delivered to the battery, and to provide

protection against battery overload, reverse polarity and feed. For the purpose of this study, one of the systems was retrieved after the 12-month deployment and retro fitted with the charge controller and solar cell (wiring configuration shown in Figure 8). Once the solar cell was fitted, the unit was setup on a test borehole well, sampling as per the normal field setup (with the old inefficient code). The monitored battery level can be seen in Figure 9. The graph also includes the decay of the battery before it was fitted with the solar panel. This shows the graph initially decaying from its full charge until the operating threshold is crossed.
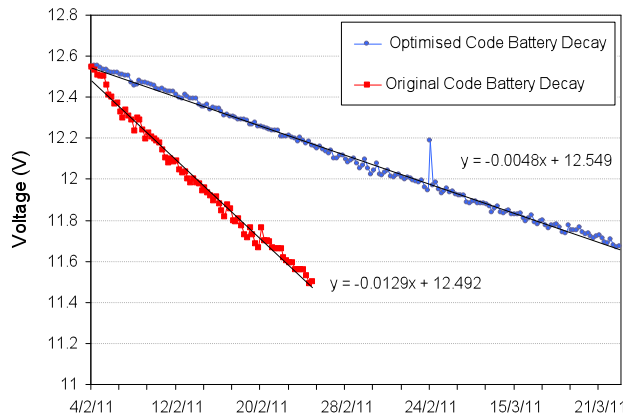

Figure 7: Battery decay curves passing operating threshold with both the original code (red), and the new updated code (blue) which includes sleep routines.
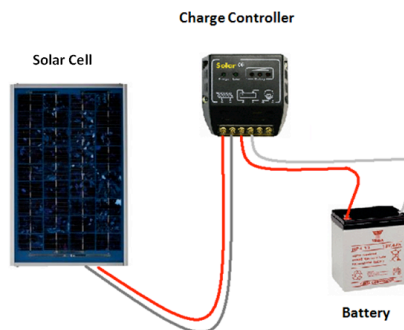

Figure 8: Annotated schematic of the solar charging configuration, demonstrating the wiring configuration

When integrated, the integrated solar cell immediately begins to produce a net positive increase in battery level. Voltage fluctuations, as seen from the repeating pattern reading at a period of 6 hours, are attributed to the changing sunlight conditions. Despite these fluctuations, it is clear that the battery charge is accumulating. Although these are only initial studies (6 days), we are confident that a fully autonomous gas sensing platform will be realised with the

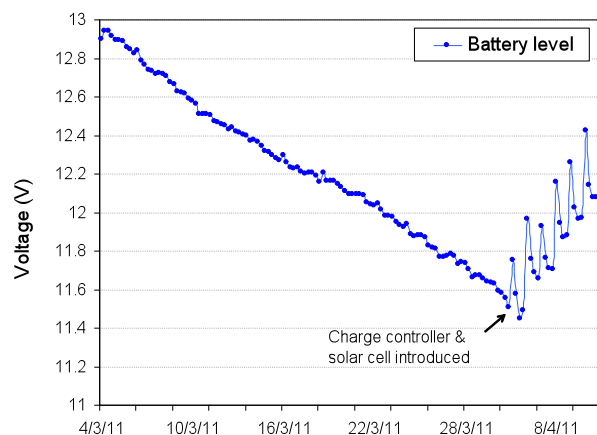implementation of the these power saving/generation measures.

Figure 8: Battery level monitoring showing the initial decay from fully charged to failure threshold (ca. 11.5V) at which point the solar panel is integrated, and the voltage begins to accumulate while the system continues to operate as normal.

V. CONCLUSIONS

The cost of ownership, reliability and duration of autonomous operation of chemical sensing platforms for air and water monitoring will improve dramatically in the coming years, enabling widely distributed networks of these devices to be realized. This in turn will generate new information about our environment, which can be made available to environmental scientists, technical specialists, regulatory agencies, communities and commercial entities. In this way, knowledge of the status of our water and air chemistry will become integrated with other information sources (e.g. satellite based weather and remote sensing data) to provide a much richer picture of the dynamics and inter-relationships that together determine the quality of our environment.

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