

Chemical Species Concentration Measurement via Wireless Sensors

Jer Hayes, Stephen Beirne, Breda M. Kiernan, Conor Slater, King-Tong Lau, and Dermot Diamond

Abstract—This paper describes studies carried out to investigate the viability of using wireless cameras as a tool in monitoring changes in air quality. A camera is used to monitor the change in colour of a chemically responsive polymer within view of the camera as it is exposed to varying chemical species concentration levels. The camera captures this image and the colour change is analyzed by averaging the RGB values present. This novel chemical sensing approach is compared with an established chemical sensing method using the same chemically responsive polymer coated onto LEDs. In this way, the concentration levels of acetic acid in the air can be tracked using both approaches. These approaches to chemical plume tracking have many applications for air quality monitoring.

Keywords—Environmental sensing, chemical sensors, wireless sensor networks.

I. INTRODUCTION

POLLUTION of the environment affects human health and reduces the quality of our land and water. Therefore, there is much interest in monitoring water quality and air quality and ensuring that all areas are compliant with legislation. It is difficult to constantly monitor all potential areas of pollution at all times and sometimes environmental monitoring sampling is not frequent enough or distributed enough to capture possible pollution events. Another area of much concern is nuisance pollution, namely odour pollution. Most of the complaints registered by the Environmental Protection Agency (Ireland) each year about landfill sites and waste transfer stations are complaints about odour [1]. As fresh waste degrades, it produces odours which are unpleasant for those working near or living near these areas. But these odours are difficult to track and by the time the complaint has been made, the odorant plume has dissipated and the source of the odour cannot be tracked. This is one area where the type of plume tracking described in this paper would be

advantageous. These facilities already have numerous cameras on-site and it would be quite easy to have chemically responsive polymers situated near them and any colour changes tracked. These colour changes could be used to trigger other instrumentation on-site to verify the exact concentration or decipher the different acidic species present. Our research group has already developed a number of autonomous environmental monitoring systems for both air quality [2] and water quality monitoring [3]. These systems are expensive and are power hungry to run all the time when compared with the sensing systems described in this paper. But these systems can be triggered to operate only when a species is present.

One development towards this ideal of continuous, real-time monitoring over the last 10 years is the application of wireless sensor networks (WSN) to environmental sensing. The concept behind WSN is that it envisages a world in which the status of the real world is monitored by large numbers of distributed sensors, forming a sensor 'mesh', that continuously feeds data into integration hubs, where it is aggregated, correlations identified, information extracted, and feedback loops used to take appropriate action [4].

Wireless sensor networks are composed of sensor nodes which are the smallest component of a sensor network that has integrated sensing and communication capabilities (and sometimes referred to as motes). The sensor node has basic networking capabilities through wireless communications with other nodes, as well as some data storage capacity and a microcontroller that performs basic processing operations. Typically a sensor node comes with several on-board transducers, for temperature, light level, motion and so on. They will often have a sensor board that usually slots onto the controller board and which allows for the interface of other sensors provided the signal is presented in the appropriate form for the controller.

We have stated that sensor nodes often come with several on-board transducers, for temperature, light level, motion and so on and that there is usually a sensor expansion board for the connection of other sensors. Ideally, chemical sensors can be connected to these expansion boards. There is, however, a "disconnect" between the development of wireless sensors and the development of chemical sensors as research into both are still essentially discrete fields despite the growing interest in merging these two disciplines.

The current focus of WSN research tends to be on hardware, communication protocols and power management

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The authors wish to thank the following for their support: Science Foundation Ireland (SFI 03/IN.3/1361 and SFI 07/RFP/MASF81Z), the Marine Institute (AT/04/01/06) and the Environmental Protection Agency, Ireland (2005-AIC-MS-43-M4).

and also on simulation/modelling of these networks. Clearly research has to be carried out on these areas as they are fundamental. However, we also note that sensor nodes are platforms for hosting sensors and, as such, consideration must also be given to the sensors as they provide the initial information on the environment.

The vision behind WSN is one that conceives a networked world. However, this networked world will ultimately be made up of a myriad of different sensors, sensor systems and architectures. The integration of all these data will be a significant problem. It may also be the case that in a location one sensor system may be more precise than its neighbours and that where this sensor system uses more resources (e.g., has a higher power consumption) we may want to only switch on this sensor system when an event has occurred. In this paper we compare the operation of a novel sensor based on a wireless camera and a network of sensors based on the mica2 dot mote.

II. CHEMICAL SENSORS

The field of chemical sensing is a vast one so we confine this section to an outline of the chemical sensors that will be used in the experiment in Section III. There is much interest in the field of environmental sensing and especially in large-scale deployments of chemical sensors in sensor networks. These types of large-scale deployments can only happen when the sensor nodes are essentially self-sustaining in terms of all consumables, e.g., energy and reagents, for many years. One example of a chemical sensor is the autonomous phosphate system developed by the Adaptive Sensors Group [3]. This system measures the quantity of phosphate present in water samples. When a phosphate-containing sample is mixed with an acidic reagent containing ammonium molybdate and ammonium metavanadate, the intensity of the resulting yellow colour indicates the amount of phosphate in the original sample.

Monitoring a colour change can be completed using a variety of simple technologies including, photodiodes, LEDs and CMOS. The Adaptive Sensors Group has used LED optical sensors to monitor a range of colorimetric analytical methods, e.g., iron(II), cadmium(II) and lead(II), solution pH, and gas phase ammonia [5,6] in the past. Essentially, the LEDs are used to measure a change in colour when the target is detected in a pH based sensing polymer, using bromophenol blue (BPB) as an indicator.

A. Wireless Sensor Nodes

The wireless chemical sensor node utilized in the study reported in section III is a development upon the device described in [7]. A comprehensive analysis of the operation and response characteristics of the developed wireless chemical sensor node will be reported elsewhere. Each node is based on an MPR500 Mica2Dot mote from Crossbow with a transceiver radio operating at 868 MHz (www.xbow.com). An MPR400 MICA2 mote mated to a MIB510CA serial interface board was used as the network base-station. The

LED based optical chemical sensor was interfaced to the mote platform using an MTS510A sensor prototyping board. Hardware components of the complete node (Fig. 1) were encased within a protective enclosure. A threaded fitting incorporated into the enclosure design facilitated connection of the node to available ports on the custom chemical sensor testing chamber.

The opposing LEDs optical chemical sensor component was as described in [7] and consisted of a pair of 1206 format super bright orange surface mount LEDs (Kingbright KP-3216SEC 3.2 mm × 1.6 mm) on a 2.0 mm header in an emitter and detector arrangement. The opposing LEDs sensor was controlled using two digital I/O pins. The forward biased emitter LED was driven in series with a 1 kΩ current limiting resistor to ensure that the detector LED was not saturated and to minimise power consumption. The polymer layer acts as a filter which modulates the portion of emitted light that passes through the chemically sensitive layer onto the detector LED. A colour change in the polymer layer, proportional to the concentration of contaminant present in the device's immediate environment, was measured as a reduction in the discharge rate of the detector LED.

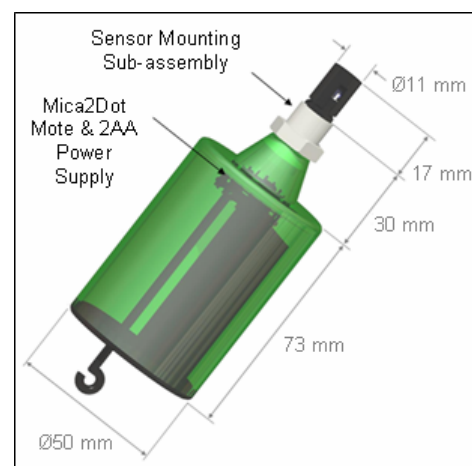


Fig. 1 The wireless sensor node

Sensor nodes performed samples and reported sensor data at a frequency of 0.5 Hz. Data packets containing real-time sensor data received by the base-station at 2 s intervals were forwarded to a PC over a standard RS232 connection. Bespoke software was used to handle the on-screen visualization, real-time data processing and data logging for analysis and comparison to data extracted from camera images.

B. Wireless Camera Sensor

A 2.4 GHz CMOS wireless camera (SWANN) was used to monitor the colour change of the chemically responsive polymer attached to a platform/holder. In the future we envisage coating the lens with the colorimetric polymer but at this stage a holder for the chemically responsive polymer was used. The holder contains a plastic transparency sheet with

polymer applied to the surface. The camera continuously monitors the holder (with the attached sensor). Images are captured and then processed to monitor any colour change in the sensor. The sensor holder is displayed in Fig. 2. The colour change may not appear obvious in a black & white image but it involves a change from blue to green (and then to yellow when fully saturated).

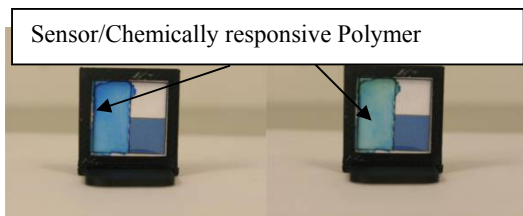


Fig. 2 The holder with the sensor. The sensor changes colour when exposed to a target gas. Beside the sensor are two “squares” which are used as a reference as they do not change colour, being inert to the target gas. The colour change is from blue to green

The images from the wireless camera are processed to retrieve average RGB values for regions of interest, i.e., the area of the image which contains the sensor.

III. EXPERIMENTAL

An experiment to simultaneously monitor the reaction time of the wireless sensor nodes and the wireless camera sensor was carried out. The low volume chemical sensor testing chamber (13 L) has been developed for testing of small scale (1–6 nodes) WCSNs to known contaminant concentrations (see Fig. 3). The target contaminant is added via an injection port at the top of the chamber. An internal 12 V fan distributes the contaminant vapour evenly throughout the test chamber.

Materials

The colorimetric sensing polymer was prepared by dissolving the pH indicator bromophenol blue (BPB) into a solution of ethyl cellulose in ethanol. In order to prepare an acidic responsive sensing polymer, it was necessary to stabilise the BPB in the blue base form. This was achieved by adding the salt tetrahexylammonium bromide (THABr), which acts as a solid state pH buffer, to the polymer formulation.

This colorimetric sensing polymer was applied in two different ways: (1) the polymer was placed onto the surface a plastic transparency sheet (to be used with the camera-based sensor). This was left to cure in dry air for 24 hours; and (2) a small volume of the polymer formulation was applied directly to the lens of the LEDs by pipette on a number of the crossbow-motes. These were allowed to dry in air for 24 h, which ensured that the resulting polymer sensing layer adhered well to the LED lenses and was free of any residual solvent.

Equipment

An environmental sensing chamber (ESC) has been developed for testing of small scale (1–6 nodes) WCSNs (see

Fig. 3). The chamber enables testing of physical sensors, and a range of chemical sensors developed in our labs under semi-realistic conditions. It has been specifically designed to hold up six sensor nodes described in Section II A via special holders. However, additional sensor nodes can be placed with the chamber.

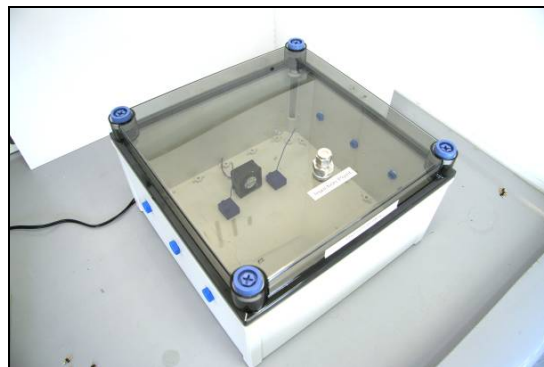


Fig. 3 The low volume environmental testing chamber

The ESC is completely air tight and a liquid is added via an injection point at the top of the chamber with the vapours being allowed to disperse throughout the chamber. Internally the chamber also has a fan to distribute the target gas throughout the chamber.

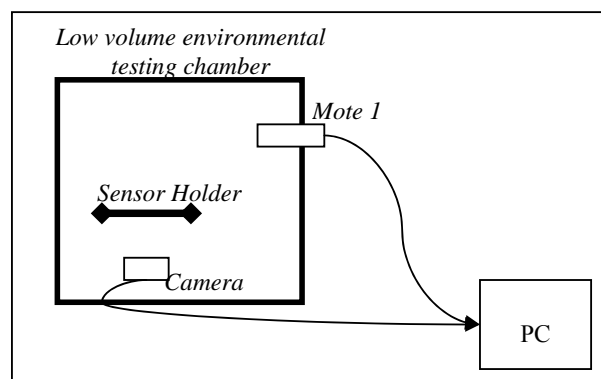


Fig. 4 Layout of equipment during the experiment

The experimental set up is shown in Fig. 4 (with the wireless camera placed inside the ESC chamber facing the sensor holder). Controlled volumes (13 μ L) corresponding to 1 mg of acetic acid per litre of air, where acetic acid was the target contaminant were incrementally injected into the chamber at 3 minute intervals. The responses of a wireless chemical sensor node were captured by a nearby base-station, while an image was taken via the wireless camera every 10 seconds. All data were logged on a PC workstation.

IV. RESULTS

The response of the wireless camera sensor and the responses of the wireless sensor nodes are given in Fig. 6. A simple image analysis technique was used to process the

images from the wireless camera whereby the average RGB values for regions of interest were used. This was completed via a bespoke Java application. The red values for the reference region of interest were subtracted from the sensor region of interest. From the sensor platform described in Fig. 2, two regions of interest were determined: one which covered the centre of the sensor strip and the other which covered the blue polymer (the colour of which should remain constant during the trial). The red channel for both regions of interest is given in Fig. 5. It can be seen that the sensor showed a major change in colour on three occasions which match the periods when acetic acid was added to the chamber. It is also clear that the wireless camera sensor is susceptible to changes in local lighting conditions, i.e., when an injection occurred there was typically a drop in the light reading.

In Fig. 6, the reaction from the wireless chemical sensor node is outlined. Again, the change in the amount of gas in the environmental chamber is reflected in a shift in the readings from the sensors. From Fig. 6, it can be seen that there are three points where acetic acid is injected into the environmental sensing chamber and at each point the LED-based sensors respond accordingly.

The results from both sensors appear to detect the same pollution events. However, the wireless sensor nodes took more measurements (approximately one reading every 3 seconds) and offer a finer grain of sampling into the millisecond range. The results demonstrate that the wireless camera could detect the same changes as the WSN. Therefore, it should be possible to use the camera-based sensors to trigger more sophisticated sensors/instruments, such as systems which autonomously monitor landfill gas migration [2].

V. CONCLUSION

This paper describes the use of wireless chemical sensors in a low volume environmental testing chamber. One sensor which was based on a wireless camera platform was tested in conjunction with a more established wireless chemical sensor network based on LEDs coated with a colorimetric polymer.

The wireless camera platform was demonstrated to work successfully when responding to the increase of acetic acid in the chamber making this a novel chemical sensor. The LED sensors also responded to the increase of acetic acid in the chamber. The release of acetic acid mimics a chemical pollution event (albeit in a controlled environment).

The wireless camera detects the same pollution events as the more sophisticated wireless chemical sensor network and so in future work it is planned to use readings from the wireless camera sensor to trigger the operation of a more sophisticated instrument, e.g., the system designed to measure landfill gas migration [2].

REFERENCES

- [1] EPA, Ireland, "Focus on Environmental Enforcement 2004-2005", 2005, pp 23-30.
- [2] B. M. Kiernan, W. Guo, C. Slater, J. Hayes, and D. Diamond, "Autonomous monitoring of landfill gas migration at borehole wells on landfill sites using wireless technology". Proceedings of the 10th International Conference on Environmental Science and Technology, Kos Island, Greece, Vol. A, 2007, pp. 679-685.
- [3] C. M. McGraw, S. E. Stitzel, J. Cleary, C. Slater and Dermot Diamond, "Autonomous microfluidic system for phosphate detection", *Talanta*, Volume 71, Issue 3, 2007, pp. 1180-1185.
- [4] D. Diamond, S. Coyle, S. Scarmagnani, and J. Hayes, "Wireless Sensor Networks and Chemo-/Biosensing", *Chem. Rev.*, 108, 2, 2008, pp. 652-679.
- [5] M. O' Toole, K.T. Lau and D. Diamond, "Integrated PEDD flow analysis device as optical sensor for colorimetric detection", *Talanta* 66, 2005, pp. 1340-1344.
- [6] K.T. Lau, R. Shepherd and D. Diamond, "Solid state pH sensor based on Light Emitting Diodes (LED) as detector platform", *Sensors* 6, 2006, pp. 848-859.
- [7] R. Shepherd, S. Beirne, K.T. Lau, B. Corcoran, D. Diamond, "Monitoring chemical plumes in an environmental sensing chamber with a wireless chemical sensor network", *Sensors and Actuators B: Chemical*, Volume 121, Issue 1, Special Issue: 25th Anniversary of Sensors and Actuators B: Chemical, 2007, pp. 142-149.

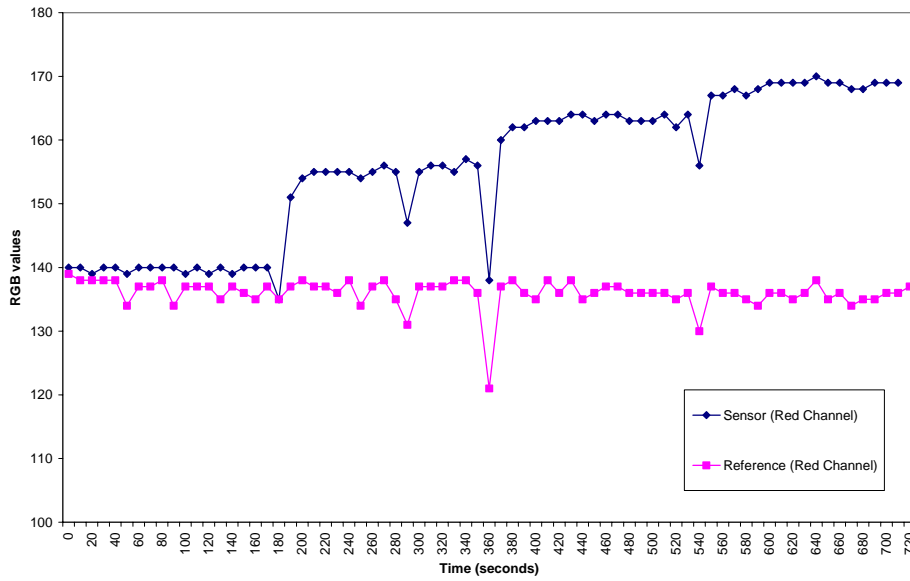


Fig. 5 Readings from the wireless camera. The red channels for the “sensor region” and a reference are shown. The red channel increases with the addition of acetic acid

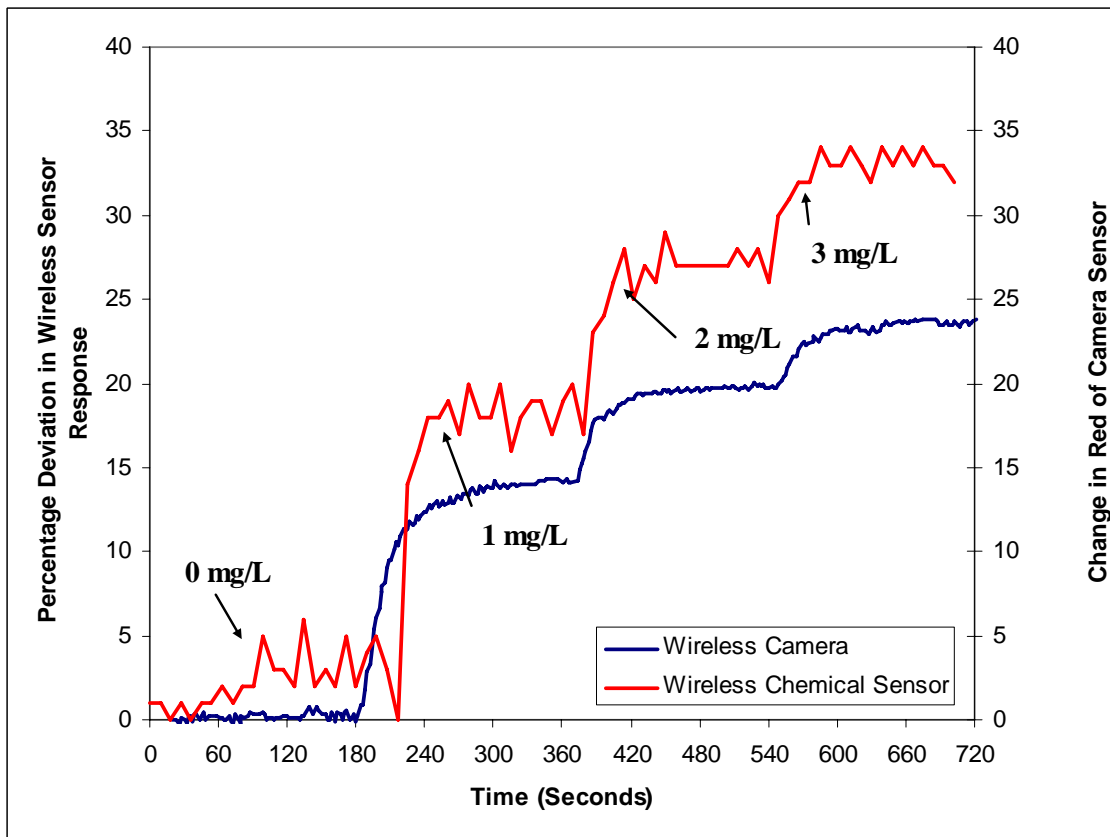


Fig. 6 A comparison of the response of a wireless sensor node and wireless camera sensor to the introduction of acetic acid. Sensor nodes are placed at the side of the environmental sensing chamber. During the experiment as more of the gas is added the response of the sensors increases. A simple image analysis technique was used to process the images from the wireless camera whereby the average RGB values for regions of interest were used. The red values for the reference region of interest were subtracted from the sensor region of interest