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Biomimetics and materials with multiple personalities - The foundation of next generation molecular sensing devices

Dermot Diamond  
*Dublin City University, dermot.diamond@dcu.ie*

Robert P. Byrne  
*Dublin City University, rbyrne@uow.edu.au*

Fernando Benito-Lopez  
*Dublin City University*

John Cleary  
*Dublin City University*

Damien Maher  
*Dublin City University*

*See next page for additional authors*

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Abstract
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Authors
Dermot Diamond, Robert P. Byrne, Fernando Benito-Lopez, John Cleary, Damien Maher, John Healy, Cormac Fay, Jung Ho Kim, and King Tong Lau

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Biomimetics and Materials with Multiple Personalities - The Foundation of Next Generation Molecular Sensing Devices

Dermot Diamond*, Robert Byrne, Fernando Benito Lopez, John Cleary, Damien Maher, John Healy, Cormac Fay, Jungho Kim, King-Tong Lau
CLARITY Centre for Sensor Network Technologies
National Centre for Sensor Research
Dublin City University, Dublin 9, Ireland
*dermot.diamond@dcu.ie

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Introduction
It is self-evident that the availability of low-cost devices capable of remote autonomous monitoring of chemical species for extended periods of time will have very significant impact in applications

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Figure 1: Dual strategy for developing chemical sensor networks. The goal is to drive down cost, whilst maintaining functionality and reliability in order to achieve scalability. Significant advances (1) can be made using smart engineering and imaginative integration of technologies such as LED-based optical sensing of reagent-based analytical methods, and low-power wireless communications. We have demonstrated that platforms produced using this approach can have significant functional advantages over existing devices, at a fraction of the cost. Achieving massive scale-up (2) requires further advances that will emerge from fundamental materials science research. One area that requires particular attention is new approaches to controlling liquid movement through microfluidic manifolds.

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related to environmental monitoring, personal health monitoring, and security/threat detection [1]. However, devices capable of generating accurate analytical data for periods of weeks to months, without human intervention, tend to be very expensive, and therefore are not scalable to large numbers integrated into a sensor network [2].

Despite the very large body of literature describing chemical sensors based on a multitude of forms, configurations and operational principles, systems capable of remote operation typically cost >$20K per unit, and require regular maintenance. The high cost arises from the need to calibrate, which in turn requires the integration of a liquid handling system based on (expensive and power hungry) pumps and valves, and storage capacity for standards and reagents. In this paper, we will describe advances in the engineering of chemical sensor platforms based on colorimetry, using LEDs tuned to the absorbance of a target-selective reactive dye as the light source for the detector [3]. We will also suggest routes to generate truly disruptive technologies based on breakthroughs in materials science that could provide the basis of future widely distributed chemical sensor networks.

### Strategy to Realise Massive Scale-up

Figure 1 shows the overall strategy we have adopted to simultaneously produce better-than-existing sensor platforms that can be immediately deployed (‘evolutionary improvements’ 1), while simultaneously working on disruptive technologies (‘revolutionary improvements’ 2) based on breakthroughs in fundamental materials chemistry that will produce a true paradigm shift in the performance of future chemical sensor networks. This dual strategy brings many benefits to research teams working in this area. Specifically, it:

- Enables immediate demonstrations of sensing platforms that offer significantly improved price-performance over existing commercial systems. This quickly establishes credibility with companies and agencies and offers attractive routes to low-risk exploitation of these platforms by companies or through spin-outs.
- Provides new analytical time series data about the environment through these deployments, This enables links to be rapidly formed between the instrument development team, end users, and specialists in data mining, pattern recognition, event detection etc.
- Facilitates stress-testing of the various technologies required to produce the fully integrated autonomous platform and enables the key technology challenges to be identified.
- Informs the prioritisation of fundamental research programs and enables effective bidirectional transfer of knowledge between fundament materials science and applied instrumentation researchers.

For example, figure 2 shows an analysis of the component costs for a 1st Generation (Gen1) platform that we have developed autonomous monitoring of nutrient (ortho-phosphate) levels in water [4]. The platform integrates wireless communications (GSM, Zigbee) with fluidic control including a microfluidic chip custom-designed to perform the well-known reagent based yellow-method, reagent/waste storage, LED-based colorimetry, and sampling within a tough pelicase enclosure [5]. Figure 3 shows results from a recent deployment in a river estuary near Dublin, which is
close to the output of a waste water treatment plant. Throughout the 18-day trial, the platform functioned without problems, and the resulting data provided time-series data on the local o-phosphate levels throughout this time. The average level was ca. 4.0 mg/l, at times rising to above 6 mg/l (sharp spike at 22/10, and around 25/10). A major event is evident around 30/10, when levels reached almost 10 mg/l. The data correlated closely with a reference method using manual sampling (data shown as discrete red points), which provides a degree of validation for the platform’s analytical performance. Previously, the platform had also been successfully deployed at a waste-water treatment plant over a period of seven weeks.

Driving Down the Cost of Chemical Sensor Platforms

Existing autonomous chemical sensing platforms typically cost from €20,000 upwards, plus additional maintenance costs. Consequently, the vision of widely deployed networks of chemical sensors is practically unrealizable. Analysis of the component costs of the Gen1 platform (figure 2) shows that of the total (€2,130), almost 85% arises from fluid handling components, such as pumps, valves, and liquid storage units. Electronics accounts for 11% of the costs, and the enclosure the remaining 4%. Through re-engineering of the platform, and judicious sourcing of components, we have been able to drive the total component cost down to €190, with the fluidic handling still being the major contributor (63%), compared to electronics (11%) and the enclosure (26%). Deployments of the Gen2 platform are currently in progress, and we expect that the analytical performance will be at least as good as the Gen1 platform. This highlights the importance of good engineering in driving rapid improvements in the price-performance of these autonomous sensor platforms. Allowing the typical 5-10-fold multiplier on production costs compared to commercial price (and accepting that labour costs have not been factored in), the potential commercial price of these devices has dropped from €10K -20K for the Gen1 platform, to €1K - €2K, meaning that end-users can deploy 10 Gen2 devices for every single Gen1 device, without any additional cost.
Clearly, it is possible to make significant advances in the price-performance index of autonomous chemical sensor platforms and dramatically increase the number of devices deployed. However, to achieve massive scale-up, new technologies are required that will provide further order-of-magnitude improvements in the price-performance index. These improvements will be achieved through breakthroughs in fundamental materials science related fluid handling for example (as this is the most expensive part of the platform) or through creative ideas that could lead to radically new approaches to the concept of remote sensing [6]. Figure 4 shows a prototype ‘matchbox’ analyzer we have developed that incorporates a polymer actuator pump based on polypyrrole membranes that flex when the redox state is switched from oxidized to reduced [7]. The flexing motion is used in a dual-reciprocating arrangement to drive fluid through the device, mixing reagent with the sample, and passing through an integrated LED-based flow cell wherein colorimetric measurements can be made. The platform, costing ca. €20 in components, has been applied to the analysis of Fe$^{2+}$ in water using the phenanthroline method, and the performance is surprisingly good. Advances in printed electronics, and printed optical components such as o-LEDs, together with polymer microfluidics and polymer actuator pumps and valves together are likely to make such low cost analytical platforms increasingly reliable and practical. However, in order to realize this potential, research teams must integrate engineers and material scientists together to a much greater degree than is currently the case.

References