

Guest Editorial

Special Issue on Machine Olfaction

IN TODAY'S society there is an urgent and growing need to detect, identify and quantify both simple and complex odorous compounds. Applications lie increasingly in the areas of security (e.g., chemical warfare agents), disaster response (e.g., toxic industrial chemicals), environmental monitoring (e.g., pollutants), food safety (e.g., taints, bacterial spoilage) and personal health (e.g., bacterial infection). An approach towards solving these challenging sensing problems has evolved over the past thirty years that seeks inspiration from the sense of smell. The approach is called *machine olfaction* and is based upon the premise that odorant chemical compounds can be identified by combining an array of cross-selective solid-state gas sensors with suitable pattern recognition algorithms. The field of *machine olfaction* is inherently cross-disciplinary, and poses interesting problems in basic science and engineering, from materials science to artificial intelligence and neurobiology. Challenges abound and include sensing materials that are more sensitive, selective, and stable; sampling systems that can efficiently deliver analytes to the sensors; and algorithms that can extract information from noisy non-stationary sensor signals. In the pursuit of *machine olfaction*, much can also be gleaned by studying the architecture and processes within biological olfactory systems – both mammalian and insect.

Advances in chemical micro-systems will soon make it possible to develop portable instruments with analytical capabilities that a decade ago only existed in large bench top analytical instruments. When integrated with wireless network or cellular infrastructures, these next-generation sensors may be used to monitor chemical emissions over wide geographical areas. However, in order for such systems to operate largely unattended for long periods in complex environments, solutions are needed such as adapting sensing parameters in response to changes in the local environment, coordinating sensing operations across multiple nodes, and managing the limited energy budget at each sensing node.

This year is the 10th anniversary of the first special issue on *machine olfaction* of the IEEE SENSORS JOURNAL. During this past decade, the field has grown in a number of exciting directions, including spectroscopic and olfactory receptor-based sensing, computational models of olfactory processing, and mobile and distributed sensing. This second special issue provides a timely update on advances during the past decade (as well as a vantage point from which to evaluate the last 30 years) in the field and, more importantly, the challenges that still lie ahead. It includes invited papers based upon presentations given at the International Symposium on Olfaction and Chemical Sensing (ISOCS) that was held in New York

City in 2011 (see www.olfactionsociety.org). To provide a balanced view of the various advances in the field, the special issue is organized into six distinct topic areas: biological sensors, chemical sensors, sensor systems, data processing, and electronic nose applications.

The topic area of biological sensors recognises the fact that considerable effort is being directed towards improving the capability of artificial olfactory sensors by exploring more closely the biological system and seeking to mimic it more closely. To this end Persaud has reviewed this approach and demonstrates the advantages of biological receptors and adopting such a strategy when trying to solve complex olfactory problems. The related sense of taste is also important because, together with smell, it defines the flavor of a substance. Again the biological receptor and its coupled ion channel are being studied with Wu *et al.* reporting on the measurement of PDK channels for extracellular recording of signals. Sweetness and saltiness are key descriptors of substances in field of gustation or taste; and here Szöllösi, reports upon the measurement of sweeteners in soda while Mielle reports on in-mouth detection of the release of salt when chewing foods. Electrochemical cells are widely used today as gas sensors, and are normally operated in an amperometric mode to detect harmful toxic gases, such as ppm levels of carbon monoxide in air. In a paper by Haruyama *et al.*, conventional electrochemical cells have been functionalised through the addition of biological cells that can couple themselves to an electrode within a complex ionic matrix. This approach not only enhances the specificity of the electrochemical cell to NO but also permits faster screening of samples. Alternative approaches are still being sought to measure odours and there is increasing interest in the use of optical methods. Optical spectroscopy has, of course, been used for decades to identify compounds through the molecular adsorption bands, but it requires large and expensive analytical instruments (i.e. UV-IR spectrometers) best suited to quality assurance laboratories. However recent research has led to the development of low cost narrow-band infra-red sensors based upon semiconductor materials. Here Huang describes how such a sensor can be tuned to adjust the output wavelength to that required to target a specific molecular compound.

The field of machine olfaction has been somewhat handicapped by the limited numbers and types of sensor materials currently available. Recent advances in nanotechnology are now fueling sensor developments and there is promise of a new generation of sensor materials. Zinc oxide nanostructures and nanorods present unique sensing properties that are described by Shaolin Zhang *et al.* in two papers. These materials are capable of sub ppm detection of analytes. Apart from electrically conductive sensor materials, there have been developments in materials that change optical properties in

response to an analyte, and a paper by Cesar Elosua and co-workers documents an array of fiber-optic sensors used to evaluate the odour of beverages. The evolution of different types of sensor materials based on a range of transduction principles augers well the translation into a wider variety of practical applications of machine olfaction.

The topic area of sensor systems includes three interesting contributions. Ishida *et al.* contribute a review article on the integration of chemical sensors and robotics platforms. This survey article covers aspects of chemotactic behaviours in nature, chemical trail following, chemical source localization, as well as current trends and future directions for robotic chemical sensing. Persaud *et al.* describe a very large chemosensor array containing over 16,000 individual sensors with 24 different sensing materials, developed as part of the European project NeuroChem. Finally, Karabacak *et al.* present an array of doubly-clamped resonators that exploits changes in mass and stress to achieve up to $\times 100$ higher sensitivity than cantilever devices of similar dimensions.

In the topic area of data processing, the special issue includes three articles as well. Marco and Gutierrez-Galvez present a survey of advances in signal and data processing for machine olfaction over the last ten years. The article includes an update on traditional problems such as feature extraction/selection, classification, regression, and system optimization, as well as a focused review of techniques to improve the robustness of multivariate models to drift, environmental factors, background odours, and sensor replacement. De Vito *et al.* present an application of semi-supervised learning (i.e., techniques that combine labelled and unlabelled data) to two relevant problems in machine olfaction: sparse datasets and sensor drift. Finally, Nakamoto *et al.* describe an approach for approximating odour mixtures from individual odorants through non-negative matrix factorization of the respective mass spectra.

In the electronic nose applications theme, the question often asked is whether these are trustworthy tools to evaluate food quality and safety. Concina *et al.* addresses this issue providing paradigms for the reliability of sensors in food analysis. Another issue addressed by Raman *et al.* is the use of solid state microarray devices to detect harmful contaminants such as toxic industrial chemicals. Both approaches rely on solid state chemoresistive gas sensors.

We expect that the Special Issue will also attract the interest of researchers outside of machine olfaction, including those in the process industries (petrochemical, paper, pharmaceutical), food and drinks industry, environmental monitoring and safety, homeland security (detection of explosives, narcotics and illicit substances), as well as those in the area of multivariate process control (fault detection, identification and diagnosis).

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Julian W. Gardner is currently a Professor of electronic engineering with Warwick University, Coventry, U.K. His research was commercialized by AlphaMOS, and he has collaborated with over 20 companies in the past 20 years in the development of commercial e-nose instruments. He is a Founder and the CTO of Cambridge CMOS Sensors Ltd. He was the President of the International Society for Olfaction and Chemical Sensing when the ISOEN conference was held in May 2011, New York. He is the author or co-author of over 450 technical papers of journals and conferences as well as six technical books in microsensors and machine olfaction. He holds several patents. His current research interests include smart chemical sensors, biomimetic sensing, and biomedical engineering.

Krishna C. Persaud is currently a Professor of chemoreception with the University of Manchester, Manchester, U.K. In 1982, he and G. Dodd co-authored a seminal paper in *Nature* that started the field of machine olfaction. Since then, he has been involved in the development of gas sensor arrays for sensing odors based on conducting polymers, which was commercialized by Aromascan plc (now Osmetech plc). His current research interests include biological studies on animal models, development of sensing technologies, and application of chemical sensing to diverse problems in healthcare and environment.

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Prof. Gutierrez-Osuna was a recipient of the NSF Career Award for his research on biologically inspired models for machine olfaction. He is an Associate Editor of the IEEE SENSORS JOURNAL and was the Program Chair of the ISOEN 2011.