CHEMICAL ENGINEERING TRANSACTIONS

VOL. 47, 2016

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Angelo Chianese, Luca Di Palma, Elisabetta Petrucci, Marco Stoller

ISBN 978-88-95608-38-9; **ISSN** 2283-9216

DOI: 10.3303/CET1647001

Nano and Micro-Sensors: Real Time Monitoring for the Smart and Sustainable City

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With sensors becoming smaller, more accurate and networked, the knowledge about our environment in urban studies can be enriched; thanks to the availability of diffused fine-grained and real-time information layers, the smart city concept can be enhanced as the sustainable city. For example, the use of electrochemical sensors for monitoring urban air quality allows the deployment of multi-scale high-density air quality sensor networks at fine spatial and temporal scales, and in both static and mobile configurations, pushing the boundary of traditional environmental and urban studies.
In addition, deploying diffuse biosensors to measure qualitatively and quantitatively specific behavior from communities (i.e. biomarkers) might foster a completely new approach to the study of cities and their urban environment, people, and technology.
The paper will therefore present a systematic review of previous studies on micro and nano-sensors applied to the smart city concept and projects, stressing challenges and positive outcomes. Monitoring for surveillance, urban management, knowledge support for assessment, and decision making processes are the main features potentially enhanced by the use of sensors for the smart and sustainable city, and starting from the different experiences analyzed, the paper will discuss how sensors are currently changing the way cities are studied and managed.

1. City sensing for environmental sustainability

The urban environment has a profound effect on people's health and well-being. Governments are rethinking their developmental paths adapted to ensure a sustainable lifestyle. Environmental sustainability of urban society is a key issue in the era of smart cities and information services for quality of life.
Scholars has not been detailed enough the relationship between smart city projects (or smart city) and its sustainability, although there are working groups that stress the importance of the theme (United Nation Agency International Telecommunication (ITU) - Focus Group on Smart Sustainable Cities 2015). Specifically, the main stakeholders (managers, politicians, planners and citizens) seem to act independently facing the technologies without focusing on the fact that a joint action could lead to positive results. The city managers choose to carry on smart projects motivated by opportunities to drain funding or by IT companies boost and, of course, to solve management issues. Politicians out themselves such projects even if the best results are beyond the short term corresponding to their mandate. Citizens grasp opportunities given by technology to optimize their time and their quality of life; planners look with a certain distrust new technologies almost might fear of not knowing how to govern. This leads to a low level of knowledge on the technologies implemented.
A city consists of countless physical structures, layered by multiple infrastructures, and the information that a city can generate at any moment is massive. Within these increasingly complex urban systems, ICTs can act as a platform to help overcome these challenges and take advantage of emerging opportunities, as cities advance in the process towards becoming smart and sustainable. Examples of what ICT can attain include, data prediction, analytics, big data, open data, Internet of things (IoT) (Jara et al. 2014), data accessibility and management, data security, mobile broadband, ubiquitous sensor networks (Mounier et al. 2014), all become essential in "Sustainable Smart City" but not sufficient.
Therefore, proponents of the vision of "smart cities", by the use of interconnected micro and nano-sensors, elevate ICTs as an important new force shaping their form and organization, whether in grand plans for new

Please cite this article as: Poletti A., Treville A., 2016, Nano and microsensors: real time monitoring for the smart and sustainable city, Chemical Engineering Transactions, 47, 1-6 DOI: 10.3303/CET1647001

cities or the transformation of existing ones, asserting that it will enhance some advantages or mitigate some problems traditionally ascribed to cities. Urban technological innovation, via ICTs, are found in literature with a positive connotation: the “city of bits”, the “virtual cities” (Dodge et al. 1998), the “computable city” (Batty 1997), the “ubiquitous city” (Lee et al. 2008; Jang & Suh 2010). The “real-time city” (Calabrese & Ratti 2006), and “city sensing” (Borga 2014) are all ICT-driven concepts and approach. However, while today’s “smart city” concept, adopted in many cities for self-promotional purposes, assumes positive impact of ICT on the urban form, it hides a paucity of definition and precision, rhetorical aspects and a lack of principles which would make them more progressive and inclusive (Hollands 2008). Additionally, the real effectiveness of the smart city as a matter of environmental sustainability is often unclear and evasive. This paper analyzes a selection of projects from this perspective, aiming at focusing on their results and validity for environmental sustainability.

2. Methodology

This paper uses selected publications involving sensors project in order to identify the potential of the use of nano and micro-sensors in real time monitoring for the smart and sustainable city.
Traditional search strategy was applied, such as defining “search queries” with Boolean operators for composite searches in correlated concepts, using “controlled keywords” and alternative keywords, and, such as: “City sensing”, “nanotechnology”, “smart city”. The first selection process involved the consideration of publications on sensors at the international level. The first selection was made according to the following main criteria: time (recent publications), authoring (publications by academic researchers belonging to University departments; publications by major international organizations), objective (publications that explicitly referred to research work or to the use of research methodologies), and works in English language, overlooking works in other languages. The second selection process was made after analyzing the papers content through the following criteria: subject matter, main aim, technology of the used sensors, declared detection limit, and where possible, costs. The selected papers, therefore, aim at representing the most noteworthy ongoing projects for the smart and sustainable city involving nano and micro-sensors, in particular in their potential use real time environmental monitoring in smart city networks.
After the selection process, the analysis of the resulting papers through the criteria identified led to an interpretation of the state of art, strengths and weakness, and potential for future implementation. The paper therefore stresses challenges and positive outcomes of the use of nano and micro-sensors based on successful experiences and current technology constrains. Because the selected research projects include also worldwide investigators in physics/chemistry and engineering materials, comprising nano-sciences and nanotechnologies for sensing applications, the frontier of its future implementation for the “smart sustainable city” can be discussed. Among the main focuses of evaluation, cost-effectiveness and reliability of nano and micro sensors are contemplated.
In particular, after section 2 dedicated to the methodology, section 3 makes a detailed analysis of results and inferences on the scoping bases, emphasizing strengthens and drawbacks. Section 4 provides some open issues and/or promising applications that the papers refer. This paper finally argues conclusions (section 5) pointing out the significance of the presented work.

3. Review

The first selection led us to a set of 50 papers (some of which are referred to within this paper). Among those 50 contributions, some major types can be identified, according to the covered subject: sensing data collection and open sensor data utilization, environmental indices, street and lightning control and sustainable mobility, smart city and smart home. It is however evident that the authors try to go beyond quantitative outcomes, since people are primarily interested in qualitative human-oriented solutions (Samaras et al.2013).
According to the methodology described in the previous section, we made a second and final selection considering papers about smart city reporting the significance of nano and micro-sensors for real time environmental awareness. The following ones appeared to be the most noteworthy for their application to the smart city concept and projects. Table 1 summarizes the main characteristics of the papers content, comparing their subject matter, methodology and results, with the aim of contributing to the nano and micro-sensors technology debate among the application for the smart and sustainable city.
The first outcome concerns the fact that real time environmental monitoring via nanotechnology, especially air sensing, is one of the most prosperous use of nano and micro-sensors in smart city projects. Considering the complexity of the smart projects proposed each one designing a sensor network platform using commercially available or experimental components the number of options is tremendous. The goal of the study is therefore the architecture of the system and not the sensor. Conversely, the use of electrochemical sensors and aerosol sensors for monitoring urban air quality is one of the main applications found in the ongoing research, thanks

Table 1: Paper overview about nano and micro-sensors used or potentially useable for the smart city

Reference (year)	Subject matter (scale)	Main aim	Sensor technology	Detection limit	Cost (only sensor)
(Jara et al. 2015)	Smart Santander Smart City (Spain) (City scale)	Temperature, city- traffic delays and congestion	Temperature: electrochemical cells Traffic: magneto-resistive sensors	Temperature: -40 ~ +85 ºC operational range. 0 ~ +65 ºC Full accuracy range with accuracy: ±1 ºC Traffic: frequency of 2.4 GHz and a data rate of 250Kbps	Temperature: (2.5 €) Traffic: Low
(Parra et al. 2015)	Sustainability of groundwater resources (coastal city aquifer)	Groundwater salinization process	Salinity Sensors based on solenoid coils of enamel copper wire (conductivity sensor)	0.58 mS/cm to 73 mS/cm	Less than one euro (but the number of devices could be very high)
(Penza, 2014)	Technical overview in new sensing technologies for environmental sustainability in the context of the smart cities (city scale)	Air pollution (NO_2; O_3; CO; SO_2; NH_3; H_2S; PM10); greenhouse gases (CO_2; CH_4; N_2O); and volatile organic Compounds. Indoor/outdoor energy efficiency, odour monitoring,	A wide variety of chemical sensors (systems related to community-based sensing using wireless sensor network) e.g. the O_3 sensor: a metal oxide semiconductor gas sensor	O_3 20 to 200 ppb (special range on request) 0 100% RH (humidity sensor) -40 to 123.8 °C (-40 to 254.9 °F) (temperature sensor)	Low
(Murty et al. 2008)	Citysense project (pilot prototype for monitoring outdoor air quality and indoor air pollution in school)	Air quality (including CO; NO; NO_2 & O_3) and weather. For school temperature; relative humidity; CO_2; VOC (volatile organic compounds); NO_2; noise and radon	Different sensors: O_3 sensor based on a nanotechnology-enhanced, gas-sensitive semiconductor; NO_2 a semiconducting, nano-crystalline metal oxide; optical absorption (CO_2)	O_3: 0 – 150 or 0 – 500 ppb, lower detection limit: 1 ppb; NO_2: 10 – 2000 ppb, lower detection limit: 10 ppb; VOC's: Alcohols, aldehydes, ketones, organic acids, amines, aliphatic and aromatic hydrocarbons	NA
(Clougherty et al. 2013)	New York City Community Air Survey (sensor network) (150 sensors installed on light poles) (City scale)	PM2.5, BC, NO_2, O_3, SO_2	The sampling unit includes a microprocessor-controlled, volumetric flow rate air sampling instrument with 37mm Teflon filters for collecting PM2.5 and passive chemical samplers for gaseous pollutants	NA	Passive sampler (100 €)
(Mead et al. 2013)	CamMobSens, (sensor network) (City scale)	Air quality CO; NO; NO_2; temperature and relative humidity	Electrochemical (with meteorological filter to remove local influences on the measurements)	Instrumental detection limit (IDL) of 4 ppb for CO	Low

to the high interest in deploying of multi-scale high-density air quality sensor networks at fine spatial and temporal scales, in order to pushing the boundary of traditional environmental and urban studies. In fact, advances in air quality monitoring via nanotechnology have been proven since a decade ago (Baraton & Merhari 2004) and more recent projects of city sensing, listed in the table, including unit sensors for chemicals and particles (such as ultra-fine particles) have shown the potential for a large-scale implementation with benefits in terms of cost effectiveness and quality of data. The sensors based on nanomaterials can be very versatile in terms of their detection and monitoring (Malik et al.2013). Gold nanoparticles (GNPs) with controlled geometrical, optical, and surface chemical properties have great potential applications in environmental detection (Long et al. 2013).

Within real time environmental monitoring via nanotechnology, bio sensing is less prosperous but extremely promising in smart city projects potentially leading to the sustainable city. In fact, the possibility of deploying sensors to measure quantitatively wastewater from communities might allow a new approach to the study of cities and their urban environment, people and technology. Developing biomarkers as sensors for both psychoactive substances and health and lifestyle factors is a recent and emerging research topic aimed at pushing the boundaries of genomics and epidemiology. Specific biomarkers have been proposed for a real-time estimation of small-area population (Daughton 2012a), while more recent techniques, such as using isoprostanes, have been proposed as potential biomarkers to measure the collective and systematic oxidative stress response of an entire community as a wider measure of community health (Daughton 2012b). Ongoing research, such as the European COST 054/13, also aims to increase the space-time resolution of the sewage analysis approach, while recognizing the importance of integration between epidemiology and social sciences (European Cooperation in the field of Scientific and Technical Research 2013). In both nano and micro sensors, for real time environmental sensing for the smart and sustainable city, such as air-sensing and bio-sensing, is possible to underline similar strengthens and drawbacks on the basis of the paper reviewed.

Accuracy of data coming from the nano and micro-sensors mentioned in the papers is the most challenging outcome of such projects. As electrochemical sensors work by facilitating a chemical reaction, either reduction or oxidation, which results in a voltage based on the concentration of the pollutant, the registered voltage data is reported as different voltage values, and undergoes a specific conversion, according to a calibration curve. Also in the case of biosensing such as virus and bacteria detection, the stability and accuracy of biochemical measurement technologies is improving.

Cost is the second element of analysis of micro and nano-sensors application for smart networks. Because smart cities are connected to the idea of “pervasive sensing” and “ubiquitous computing” considering the reality of the idea of an “electronic skin” on our cities (Gross 1999), a large number or cost-effective sensors is required in the “Everyware” vision (Greenfield 2006). While the cost of the projects mentioned in the table are relatively “low” (affordable also for participatory sensing scenarios, unit cost €1000), their potential implementation at a pervasive scale is still challenging.

Connected to both previous critical aspects, technology is showing great potential while the trade-off between affordability and reliability, cost and applications is still under debate in both nano and micro-sensors for real time environmental sensing for the smart and sustainable city, such as air-sensing and bio-sensing.

However, improvements in nanotechnology is rapid, and in some cases, micro and nano-sensors are being developed with acceptable performance for a given application. In the case of air quality sensing, some monitoring objectives can or likely will be achievable in the near future (Snyder et al. 2013, p.11370).

4. Issues and future applications

While these findings emphasize the challenges of this recent technology, rapid developments are occurring, and it is likely that sensors will improve in data quality and be ready to be implemented at a large scale for urban mapping. In fact, the development of the sensing industry is rapid, and the last decade saw a fast growing and improving low-cost sensor technology. New electrochemical sensors for industrial applications based on nanoparticoles for the determination of gas (such as H2O2) (Ampelli et al. 2015) are emerging and are of great importance in environmental studies. Improving data quality and cost-effectiveness is also a remarkable strength for the diffusion of sensing, especially in a limited resource context of a developing country. Many countries have limited governmental monitoring stations for air quality or water, which is sometimes highly polluted in urban rivers (Chin and Ng 2015), and the potential diffusion of nano and micro-sensors opens doors to vast implementation for improving everyday activities and quality of life. It is therefore likely to assist in the short-term future, pushing a paradigm shift towards more and more monitoring attention, measurements, mapping and awareness, and once sensors improve in data quality and they will be ready to be implemented at a large scale for smart and sustainable cities. Carbon-based materials are critical for sensing applications because of their physical and electronic properties and resonance-frequency capacities whose reach limits for gases such as ammonia down to 10^{-24} (Manzetti et al. 2015). While the research community is exploring the potential of sensing networks, such as for air quality studies as the examples show, governmental authorities are starting to discover its opportunities. For instance the US EPA, in the last two years, is strongly supporting the “Next Generation Air Measuring” (United States Environmental Protection Agency 2014), profiting from the rapid developments in micro and nano-technology that is leading to the production of small, low-cost air pollution sensors. They encourage discussions about advancing innovative air sensor technologies, by bringing together government, scientists, policy makers, technology developers, data analysts and community groups.

Future applications of nano and micro-sensors are therefore likely to be implemented in smart city projects, and for that perspective, they share some common issues. Firstly, concerns can arise from the pervasive sensing for real time monitoring, as a form of city management, such as “the corporatization of city governance and a technological lock-in” or the creation of a “panoptic city” (Kitchin 2014). Secondly, the issue of communication, transparency and misinterpretation of data coming from sensors is still a main argument of debate, especially in the case of air sensing or bio sensing, where the subject affects citizens information and awareness on personal health. In future applications, accuracy can be improved using pervasive sensing and participatory sensing platforms, collecting a high amount of data by sacrificing data accuracy for data quantity; with the help of big data analysis tools and machine learning process, it is possible to extract meaningful information via less accurate sensor technology. However, privacy remains a relevant challenge for smart city project using nano and micro-sensors for real time monitoring. In fact, data privacy and the ethics behind every sensing project that required collecting data from humans are big unsolved concerns; pervasively collecting data, ultimately resulting in a vast database containing detailed information about citizens’ behavior, is particularly controversial and ongoing international debate, and future implementation need to face this issue.

5. Conclusions

Researchers have developed solid-state sensors based on functional materials for several decades and recent improvements in nanotechnology and multifunctional materials have opened up the possibility to foster a new generation of sensitive, selective, and stable sensors, with largely improved capacity to give relevant information both on a personal and systematic level. The recent progress in real-time optical sensor and biosensor technology has revolutionized our ability to characterize and quantify environmental pollutants. The future integration of wireless communications systems will generate huge interest, as this will inevitably lead to the emergence of extensively networked multiple autonomous analytical stations for correctly managing contemporary cities.

Overall, the potential of micro-and nano sensing emerged from this work seems to be very high for its application to the smart and sustainable city, but more for future elaboration than immediate implementation, given the recent technology and the current challenges experienced. Many worldwide investigators are involved in research in physics/chemistry and engineering materials, including nano-sciences and nanotechnologies for sensing applications, although various challenges remain in creating more improved, cost-effective, and reliable nano and micro sensors. Accuracy, cost, and the trade-off with available technology are the main challenges that are being overcoming. Put together as attributes of the city adjectives smart and sustainable emphasize the need to create a bridge between interdisciplinary and shaded knowledge fields (Poletti 2015). Thanks to the availability of diffused fine-grained and real-time information layers, the smart city concept can be enhanced as the sustainable city.

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