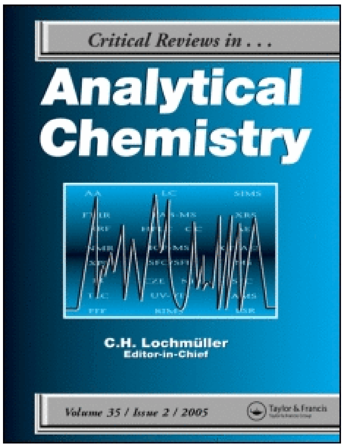

Critical Reviews in Analytical Chemistry

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713400837

Wireless Electrochemical Sensors: A Tool for Process Control Past, Present and the Future

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To cite this Article van Staden, Jacobus F. , Stefan-van Staden, Raluca I. and Balasoiu, Simona C.(2010) 'Wireless Electrochemical Sensors: A Tool for Process Control Past, Present and the Future', Critical Reviews in Analytical Chemistry, 40: 4, 226 — 233

To link to this Article: DOI: 10.1080/10408347.2010.515450

URL: http://dx.doi.org/10.1080/10408347.2010.515450

Critical Reviews in Analytical Chemistry, 40:226–233, 2010

ISSN: 1040-8347 print / 1547-6510 online
DOI: 10.1080/10408347.2010.515450

Wireless Electrochemical Sensors: A Tool for Process Control Past, Present and the Future

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Wireless sensors are widely used in analytical chemistry. Their utilization in control will make the feed-back of the quality of processes in real time possible followed by immediate remediation of the problems regarding quantity and quality of by-products and final products. The mini review will outline the current situation in interactive-intelligent-real-time process technology with remote on-site wireless sensors as well as giving aspects of the historical background of process and process control from wired to wireless.

Keywords electrochemical sensors, wireless, process control

INTRODUCTION

Effective cost control plays a very important role in the efficient management of modern industrial processes, in mining and refining of raw materials and minerals, in agriculture, in food and animal feed stuff manufacturing, and in health care and pharmaceutical manufacturing. It forms the cornerstone to prevent the current instability in the world with climate changes, pollution threats, and financial crisis with the provision of high-quality, value-added products in a highly competitive world where a clean sustainable green chemistry environment should be inaugurated and maintained. In order to achieve this goal, real-time monitoring and control of processes on an analytical base is essential. This is needed so that interactive action is taken immediately on a continuous basis once the results are known.

EARLY HISTORY

To have a complete scenario of the complexity of wireless sensors together with process analytical instrumentation (process analyzers) in interactive process control, it is necessary to look at a historical background of the development of chemical analysis in analytical chemistry to the modern outlook of process analytics in order to put the current situation into the correct perspective. Initially with the traditional and historical approach to quality control, process monitoring, and process control, samples from a sampling site in a process environment were removed manually and transported to a centralized analytical routine laboratory where the analysis was performed by analytically qualified technical staff who acquired and processed data and reported the results obtained to people directly involved with the process environment (for example, a plant in industrial processes). A decision was then taken by the process environment (operation system) management, sometimes (mostly rarely) in collaboration with laboratory personnel, and corrective changes, if needed, was then done by people in the process environment. Examples of these process environments (process operating systems) are a plant in industrial processes, effluent streams from industrial plants, water resources (rivers, dams, etc.), health environments, etc. This type of traditional approach was known as off-site or off-line analysis. A block diagram of the traditional approach [1–3] is given in Fig. 1.

Originally, in the period of the early 1930s the involvement of sensors was barely known and analysis was mainly done by using wet chemistry or physical properties. This was a period of no wireless and not even direct wired communication of analysis. According to the literature [4–6], the first process analyzers appeared in the late 1930s in the Ludwigshafen research laboratory of I.G. Farbenindustrie in Germany with the development of a non-dispersive infrared (NDIR) analyzer for process gas streams by Dr. Karl Luft followed a few years later by the development of a paramagnetic oxygen analyzer by Dr. Erwin Lehrer. These types of process analytical instrumentation were installed in a research laboratory as analytical instrumentation for doing chemical analysis. It must, however, also be

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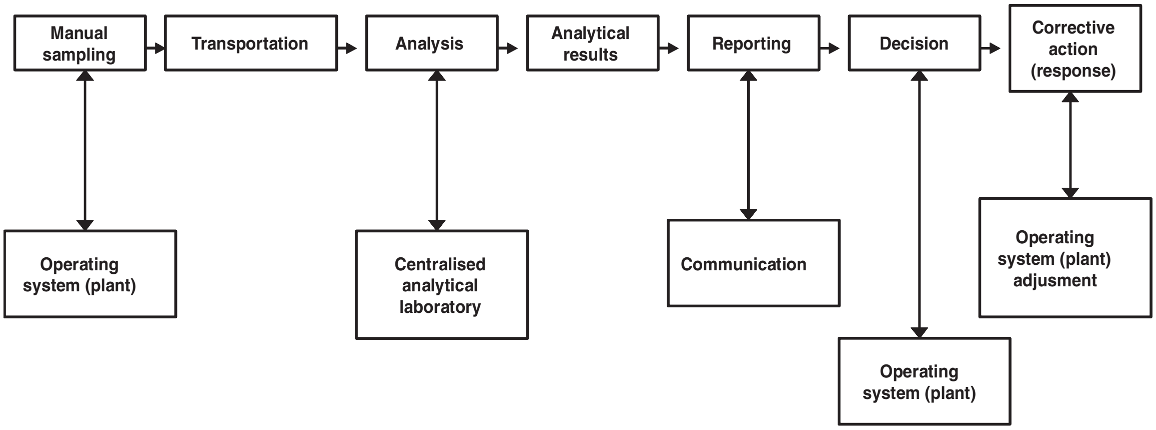

FIG. 1. Traditional approach to process control.

mentioned, that a large part of the success of the chemical industry in Germany during the 1930s even up to the 1950s was due to the fact that chemical engineers had a thorough education and knowledge of chemistry on a post graduate level before becoming chemical engineers.

The whole process of analysis (Fig. 1) was actually tedious and time-consuming with many disadvantages between sampling and the final corrective action taken by adjustment in the operating system. This did not include proper treatment of the sample (for example, preservation of water, clinical, etc. samples or temperature adjustment in petroleum refinery samples) and correct transport with proper sample conditions. There was a long time delay from sampling to sample analysis, to data processing, and to reporting until a final decision was reached; several hours and even days with the result that the data, although analytically correctly performed, were doubtful and sometimes of no value to the actual process environment. Most of the time there was not a direct two-way communication, consultation, and decision making between the analytical laboratory personnel (analytical chemistry management) and engineers (chemical plant engineers) in the traditional approach to process control and, as such, this time-delayed monitoring, a typical operation taking several hours or days between sampling to corrective action, sometimes cost industries dearly.

THE PERIOD 1940 TO 1970

Traditionally, most chemical manufacturing processes and especially petroleum refineries have been primarily controlled by monitoring operational variables such as temperature, pressure, flow rate, and liquid level [7–9]. These variables could be measured reliably and the equipment needed was relatively easy to install, calibrate, operate, and maintain. Furthermore temperature-measuring devices (like thermocouples) and pressure gauges could be installed as non-destructive invasive intrusive probes inside the process stream. The failure rate and down-time of these devices was furthermore very low. As there was actually no sampling and sample transport involved, real-time measurement was obtained, but process control was done manually by plant operators. The whole operation was performed on-site and, therefore, no wired communication was necessary. In the petroleum industry, the traditional American Society for Testing (ASTM) laboratory test methods for measurements of physical properties such as flash point, pour point, cloud point, vapor pressure, boiling point (ASTM distillation), and octane number form the backbone of quality control of products and monitoring of process streams. The first physical property analyzers, such as viscometers, boiling point, flash point, and density analyzers were installed in the late 1950s, but the first analyzers were not very reliable. Therefore, operator confidence in the data generated was low and their use for process control was not considered [8].

THE SASOL EXPERIENCE

After the publication of James and Martin in 1952, there was a tremendous growth in gas chromatography (GC) in the petroleum industry, offering the advantages of separation and quantitation of components in a sample, all performed in a single instrument operation. The Orsat apparatus was an essential instrument in the start up of the Fischer-Tropsch synthol process for synthetic fuel from coal at SASOL [10] in the late 1950s and early 1960s. This was also the period when SASOL used the first on-line wired communication from different sections of the process plants to a central control room. The purpose of the centralized control room was mainly to monitor operational parameters such as temperature, pressure, flow rate, and liquid level from where process control and decision making was done before conveyed to plant supervisors and operators for corrective action [10].

The majority of further continuous monitoring of plant operations at SASOL during the 1960s and 1970s was done via the first manual information management (MIMS) system where samples were collected, manually transported to a centralized depot at the main laboratory, and recorded before sending the samples to the routine analytical wet chemistry and physical property laboratory and to the GC laboratory for analysis. In the early 1970s, the GC analytical laboratory at SASOL [10], with the collaboration of Siemens, was one of the first laboratories in the world to semi-automate 38 gas chromatographs by computerizing the data acquisition and data processing of the different individual gas chromatographs in such a way that results were continuously assembled on a centralized laboratory computer system for immediate reporting manually to the different plants. The movement from the previous manual measurement of peaks on chromatograms and manual calculations to computerized data acquisition and data processing save an enormous amount of time. For the NAFTA cracker at the NATREF [10] refinery this was an enormous step forward in a far better process control of their plant. It must be emphasized that this was a step forward from the very long time-delayed monitoring to a closer-time monitoring of process streams. At the same time, SASOL enhanced reliability of their analytical laboratory results by bringing in control samples with better wired communication between analytical laboratory management and plant chemical engineers.

INTEGRATED CIRCUITS AND MICROPROCESSORS

The emergence of integrated circuits and micro-processors boosted the development and commercialization of more complex and sophisticated analytical instrumentation from the mid-1960s to the early 1980s [4, 7, 8, 10] and even beyond. In 1962, aerospace systems were the first to apply integrated circuits (ICs) in computers. Dual in-line packages (DIPs), invented at Fairchild in 1965, were the mainstream of the microelectronics industry in the 1970s and 1980s. In 1971, Intel engineers, led by Federico Faggin, created the first commercial microprocessor family with the central processing unit (CPU) integrated onto a single chip. In a review in 1976, Bishop [11] reported that the application of micro-processors has only recently started in earnest.

THE PRE-INTERNET WIRED COMMUNICATION NETWORK PERIOD

In the pre-internet era between 1960 and 1980, most wired communication network activities were limited by nature to allow only communications between stations on a local network using a central mainframe computer model [12]. Wired network communication was used in some chemical industries and petroleum refineries like SASOL, and in central laboratories like the hydrological research institute (HNI) and central clinical and diagnostic medical laboratories in South Africa [10] mainly for centralizing analytical data and process monitoring. Process applications of process gas chromatography, UV/Vis spectrophotometry, mass spectrometry, infrared (IR), near infrared (NIR), and Fourier transform infrared started to be employed for on-stream assays during the 1970 to 1990, mainly as on-site (at-site) at-line analyzers where the sample is either manually sampled or sampled via a by-passed on-line sampled feed-channeled transport system to a dedicated analyzer located at the sampling site [1–4, 7–10] mainly for process monitoring. There was no proportional-integrative-derivative (PID) controller involved with all of these analytical instrumentations and, therefore, the instrumentation was not able to perform real-time interactive process control. Sample preparation was, however, simplified and the measurement technique modified to permit the use of robust, reliable instrumentation to cope with the production environment in a process known as close-time monitoring or near real-time monitoring. At this point in time, there was a closer collaboration between highly skilled analytical chemistry researchers, analytical routine analysts, analytical laboratory management, and process chemical plant engineers with decisions and corrective actions in process plant adjustments as analytical results were fed by wired communication to both groups involved for further attention. Except for sample feed to a sample inlet and with the exception of GC instrumentation, most of these analyzers were based on a non-flow analyzer principle. Furthermore, except for the thermal conductivity and FID detectors in GC, most detectors (sensors) in this instrumentation were based on optical properties. The first electrochemical sensor (ion-selective electrode) was reported by Prof. Erno Pungor and Hollo-Rokosinyi in 1961 [13].

FLOW-BASED SYSTEMS

The increasing demand of samples in the clinical laboratories led to the continuous flow approach in 1957 with the innovative paper by Skeggs [14] on automated analysis where the main instrumental development was dedicated to liquid transport in dynamic flow conditions. His design of an automatic analyzer presented several novel features on the automatic analysis of blood for urea nitrogen, glucose, calcium, chloride, alkaline phosphatase, and acidity. These principles have been exploited and extended in the Technicon "AutoAnalyzer" which dominated the continuous flow field during the 1960s and the first part of the 1970s. Originally, the most popular detection system was an optical sensor (colorimetry) and the detection signal was fed to a recorder. In some Autoanalyzer instrumentation in the 1970s with more sophisticated detection technologies, the analytical data were fed to a centralized data system in the analytical laboratory by wired communication.

The evaluation of the performance of the first electrochemical flow-through sensors in unsegmented continuous flow systems dates back as far as 1970, when Nagy et al. group were the first to report on the use of graphite electrodes for the voltammetric detection of samples injected into continuously flowing streams [15]. It was not until 1975, however, when Růžička and Hansen [16] coined the term flow injection analysis (FIA), that analytical chemists became aware of the scope and potential of this technique. The introduction of FIA marked an important breakthrough in unsegmented automatic continuous flow systems.

The basic characteristics of FIA are the absence of air bubbles and the rapid injection of an aqueous sample into a continuously moving unsegmented carrier stream of water or reagent solution. A reagent solution(s) is continuously added to the carrier downstream through a T-connection. The injected sample forms a slug or zone that is mixed with the carrier and reagent solutions, is dispersed at the same time, and reacts with the reagents to form a product that is transported into a flow-through detector (optical and electrochemical sensors) for measurement and then to waste. The dispersion or dilution of the sample zone can be controlled and adapted to the required analysis by suitable choice of the injected sample volume, the flow rate of carrier and reagent streams, the reaction coil length, and the inner diameter of the tubing. As the sampling period is very short, usually less than 2 s, a very high sampling rate can be achieved. This, in turn, allows the use of a rapidly moving carrier stream, which in contrast to the AutoAnalyzer concept, does not need to be segmented by air. There are no air bubbles involved and consequently there is no need to control the air bubble size and air bubble pattern, whilst pulsation is reduced because of the absence of air bubbles. Again, the most popular detection system was an optical sensor and the detection signal was fed to a recorder. With the introduction of more sophisticated analytical detection instrumentation and the introduction of computer technologies, the analytical data were fed to a centralized data system in the analytical laboratory by wired communication for process monitoring.

The introduction of the sequential injection analysis (SIA) technique in 1990 [17–20] broadened the scope of flow analysis. SIA is a technique that has great potential for on-line measurements due to the simplicity and convenience with which sample manipulations can be automated. The versatility of the SIA technique is centered around a selection valve where each port of the valve allows a different operation to be performed [1–3, 17–22]. An important advantage of the SIA technique is the versatility that the multi-position valve provides. Each port of the valve is dedicated to a specific purpose and the combinations of samples, standards, reagents, and detectors around the valve are easily modified to suit a particular analysis. The basic components of the system are a peristaltic pump (piston or milliGAT pump) with only one carrier stream, a single selection valve, a single channel, and a detector. The concept is based on the sequential aspiration of a wash solution, sample zone, and reaction zone(s) into a channel. In this way, a stack of well-defined zones adjacent to each other is obtained in a holding coil. After the valve has been selected to the detector position, the flow in the carrier stream is reversed and the zones mutually disperse and penetrate each other as they passed through a reaction coil to the detector. The flow reversal as a result of the injection step therefore creates a composite zone in which sample and reagent zone penetrate each other due to combined axial and radial dispersion.

Controlled dispersion and reproducible sample handling is an integral and indispensible pre-requisite for the success of SIA. Computer control of the SIA system is, therefore, an essential pre-requisite since an analytical procedure often requires a complex and high reproducible flow pattern. Although computer control was essential for SIA, the analytical data assembled on a computer was initially used for reporting results; later on, with higher technological processing and technologies, results were fed to a centralized data system in the analytical laboratory by wired communication for process monitoring.

These concepts of flow-based systems were enhanced by the introduction of Zone fluidics in 2003 [23] for SIA and the lab-on-a-valve concept in 2000 [24] for FIA.

EVOLUTION OF PROCESS ANALYTICAL CHEMISTRY (PAC) AND PROCESS ANALYTICAL TECHNOLOGY (PAT)

It became clear in the early 1980s that more detailed real-time chemical measurements and data information had become the key to lowering quality costs in petroleum refineries and chemical plants; were essential to ensure that environmental regulations on aspects such as impurities, solvents, and waste waters were met; and were necessary to ensure that these plants were safely operated for communities near chemical plants and for a sustainable environment. These increasing demands for real-time quantitative chemical information on a growing list of manufacturing processes presented new challenges to analytical chemists, instrument engineers, and plant supervisors [9, 25]. In response to these needs, the Center for Process Analytical Chemistry (CPAC) was established in 1984 at the University of Washington with Bruce Kowalski as the first director to work with industry to identify, prioritize, and address generic needs in the newly emerging area of process analytical chemistry. It was, therefore, already clear in the first publication by CPAC [25] that the key element for success should be improved process monitoring and control. Furthermore, the advances in electronic hardware at that stage with microcomputers and improved algorithms for feedback control had led to the rapid implementation of distributed "intelligent control systems." However, the process control intelligent systems were starving for information and the continuing lack of sensors, especially chemical sensors, had became a major bottleneck.

In the first comprehensive application review on process analytical chemistry in 1993 [26] by authors from industrial analytical laboratories, it was clear that advances in the technology for process instrumentation still lagged several years behind laboratory instrumentation regarding reliability and safety. It is clear from the comprehensive application reviews on process analytical chemistry of 1995 [27] and of 1999 [28] that process analytical instrumentation became far more sophisticated using the full complement of advanced computer technology with modern micro-processor and integrated electronic circuit units as well as interface facilities to move to a higher level of technological process monitoring. Furthermore, the 1999 review [28] emphasized that to be most meaningful, process measurement science should tie into the needs in the engineering disciplines related to process control. There was a strong need for cross discipline appreciation, understanding, and co-operation in order to effectively incorporate the new developments in analytical measurement science with the advances in process modelling, monitoring, and control. The new developments were facilitated by continued improvements in the computer-related fields (semi-conductor, automation, interfaces, software, etc.) and chemometrics with mathematical algorithms and dynamic multi-variate calibration. It was further very important to incorporate these new developments into analytical instrumentation and to explore it for ideas in micro-instrumentation. These key aspects for process analytical chemistry included chemometrics and process control algorithms; optical; chemical, and electrochemical sensors; optical spectroscopy; chromatography, and mass spectrometry in non-flow semi-flow and flow based systems. Expansion of process analytical chemistry into the mainstream education of chemists and engineers promised to break down many of the limitations to broader utility.

Process analytical technology (PAT) originated in the late 1990s and the early stages of the new millennium as the brainchild of the U.S. Food and Drug Administration (FDA) with a regulatory framework to guide and encourage the voluntary development and implementation of innovative pharmaceutical development, manufacturing, and quality assurance. The guidance [29] was prepared by the Office of Pharmaceutical Science in the Center for Drug Evaluation and Research (CDER). The FDA's viewpoint on PAT is that it is a system for designing, analyzing, and controlling manufacturing through timely measurements (i.e., during processing) of critical quality and performance attributes of raw and in-process materials and processes with the goal of ensuring the final product quality. It is further very important to note that the term analytical in PAT is viewed broadly to include chemical, physical, microbiological, mathematical, and risk analysis conducted in an integrated manner. The document includes various PAT tools (multi-variate tools for design, data acquisition and analysis, process analyzers, process control tools, and continuous improvement and management tools), a risk-based and integrated systems approach, and a real time release. This coincided, confirmed, and extended earlier viewpoints from process analytical chemistry (PAC) [1–3, 8, 9, 25] that PAT is actually the application of analytical science in its broadest sense to monitor and control any activity also called operating systems (or processes) as a global entity (in totality) in real-time with the integration of various strategies in different topics (using various disciplines such as chemistry; physics; statistics; mathematics; chemometrics; engineering; biosciences; biotechnology; computer and information sciences with data acquisition, processing, and transfer; and automatic feedback process control strategies with intelligence interactive management and control) into a global workable system that can be practically implemented and applied in the different real practical world of any activity or operating system (or of multiple activities or multiple operating systems with multi-point real-time measurements). As these ideas, concepts, and principles were implemented on a wider context in various approaches of global documentation, various pitfalls in the totality of successful employment of the concept in the complete scenario become evident. These pitfalls and obvious errors with chemometrics and PAT in the pharmaceutical and biotech industries [30, 31], as well as the other industries, should be avoided in a broader perspective for the implementation to be successful.

There are currently a number of research groups, but only three consortiums [32] involving universities, government laboratories and institutes, and industrial partners involved for the purpose of advancing research in process analysis and control technologies: CPAC (established in 1984), located at the University of Washington, Seattle, Washington; the Control Theory and Application Centre (CTAC, established in 1992), which is based within the School of Mathematical and Information Sciences at Coventry University, Coventry, UK; and the Centre for Process Analytics and Control Technology (CPACT), a multi-disciplinary center formed in 1997 through the Foresight Challenge initiative, including the universities of Newcastle, Strathclyde, and Hull in the UK.

THE NEW SAMPLING/SENSOR INITIATIVE (NESSI)

The rationale for small, smart, and integrated sensors and sampling systems originated from a tutorial at a November meeting in 1999 at CPAC where industries requested ways to improve and hopefully standardize process sampling systems [32–34]. Early work with a new sampling and sensor initiative (NESSI) began in July 2000 by Peter van Vuuren (ExxconMobil Chemical) and Rob Dubois (Dow Chemical). One of the main driving forces behind PAC and PAT was to remove the bottleneck, and time lag, associated with sampling, sampling conditioning, sample transport to a laboratory, and waiting for the analysis results. By moving the analysis to the process, results could be obtained closer to real-time, which effectively improves the ability for the control action to correct for process changes (i.e., feedback and feed forward control). The complexity of modern petroleum refineries and petrochemical and chemical processing plants with numerous unit operations, involving the production of one or more products from various raw materials, required more sophisticated and advanced technologies. In order to control different processes and process stages, various measurements are performed at the different stages of processing to improve both product quality and operational safety. These measurements, either from simple sensor devices (such as temperature, pressure, flow, sensors etc.) or from sophisticated chemical analyzers (providing composition of one or more components in the chemical stream), are typically used as inputs to various chemometric process control algorithms to give a “snapshot” of the process operation and to control the process to ensure it is operating efficiently and safely. NESSI was successfully developed and employed in platforms as Generation I (sample systems) and Generation II (connectivity using a NESSI-bus, a digital communication bus that is specifically tailored for process analytics and a, small computing device called the sensor actuator manager, (SAM). It is however, clear that NESSI was mainly tailored for implementation as process analytical measurements in the petrochemical, chemical, and oil refining industries. These process analytical measurements were mainly aimed for quality monitoring of raw material feeds or final products, environmental compliance, safety, energy reduction, or process control purposes. Vapor applications included hydrocarbon feed stocks and intermediates (ethylene, ethane, propylene, etc.), natural gas streams, liquefied petroleum gas (LPG) streams, hydrogen, and air gas streams. NESSI has further improved itself as a template for deploying new micro-analytical devices in Generation III [32–34].

WIRELESS SENSORS AND COMMUNICATIONS

There has been a dramatic increase in research and development in the field of sensors since the 1960s with an exponential acceleration in the last two decades [35–38]. According to the literature, various attempts have been made to discriminate between a chemical sensor and a physical transducer. A physical transducer is popularly regarded as a device that provides an electronic signal through which changes in a particular property in its environment can be monitored. Examples of transducers in common use include devices for temperature measurement or monitoring (thermocouples, thermistors, or platinum wires), physical property measurement or monitoring (piezoelectric pressure transducers, flowmeters, humidity sensors), light density sensors (photodiodes, charge-coupled devices, photomultipliers, photoresistors), and linear-rotational movement transdusers. These devices often come close to meeting the general requirements of an ideal sensor in that they are sensitive, selective for the parameter of interest, cheap to purchase, physically robust, and easy to calibrate and use. A chemical sensor is a device that provides the user with the chemical nature of its environment and its overall character is usually determined by some type of chemically selective membrane, film, or layer at the surface of the sensing tip or probe. The composition and form of the surface layer is of crucial importance in determining the effectiveness of the sensor, as it controls the selectivity, sensitivity, lifetime, and response of the chemical sensor. The physical transducer is part of the chemical sensor's body that converts the chemical property detected into a signal for further processing. Whereas the surface of just a solid glassy carbon, solid graphite, graphite paste, or carbon surface in a screen-printed device in an electrochemical sensor served as the sole sensing part for the recognition process, a biosensor is a sensing device that incorporates a biological entity (enzyme, antibody, bacteria tissue, etc.) as part of the sensing process and this obviously stresses the signal generation sensing process. The prediction of the development of intelligent analytical instrumentation with chemical sensors in 1989 [39] paved the way for the introduction of "smart sensors" as devices that incorporate certain electronic logic, control, or signaling processing functions, and therefore offered enhanced measurement capabilities, information quality, and functional performance that was a great step forward in their functionality as more reliable monitoring devices.

The chemical literature for wireless sensors and networks was flooded in the new millennium with numerous publications and proceedings on conference material from various disciplines and special issues like Multisensor Data and Information Processing (Vol. 1, August 2005), MEMS and NEMS: Devices and Systems (Vol. 2, October 2007), Modern Sensing Technologies (Vol. 90), and Microsystems: Technologies and Applications from Sensors and Transducers [40], only a few were selected for this review [41–50]. According to recent literature on developments in wireless sensing technology, a number of issues regarding modelling, two-tier architecture, joint power control and rate adaption, modeling, temporal constraints, performance index, interface design implementation methods, application practices, supervisory control, and miniaturization of circuits and systems were addressed. This includes modeling aspects of distributed control systems (DCC) that showed that the DCS modeling domain can be configured into layered architecture: one formally expresses the system's requirements and the other articulate the operational domain, claiming that such an architecture can improve the understanding of a complex system. The UML platform and the PetriNet tool have been used to verify the thoughts. An algorithm that encompasses a cascaded feedback scheduling module for sampling period adjustment and a direct feedback scheduling module for priority modification were used on closed-loop scheduling of network resources in order to improve the quality-of-control (Qoc) of networked control systems (NCSs). Further research reports also results in a media access control of a fieldbus protocol, performance factors involved with the Ethernet power link network, interfaces and platforms that are compatible using the latest chemometrics, and existing professional mathematical software tools such as LabView, Matlab, Mathematica, and Maple.

There are already numerous successes in real-time monitoring with digital communications networks. Examples of these are Nessi$^{\text{TM}}$ [33,34] for implementation as process analytical measurements in the petrochemical, chemical, and oil refining industries; Robotscan [51], a robotic scanning system for monitoring the contents of vehicles at border posts; Air Robot [52], a video miniaturized computer system for monitoring various scenarios, like field fires, from the air; and PhillCam [53], a small ingestible capsule device equipped with a miniature video camera to visualize the small intestine (PillCam SB) and esophagus (PillCam ESO) for detection of damage or disease in patients. Analytical scientists, in particular those working on chemical sensors, biosensors, and compact, autonomous instruments, have obtained various successes and are in a powerful position to provide the gateway between the ideal sensing system and the real process environment as users via an internet-scale control [36, 41].

CONCLUSIONS

It is clear that the modern process analytical instrumentation (non-flow based or flow-based) became very sophisticated using the full complement of advanced computer technology with modern micro-processors and integrated electronic circuit units, and interface facilities to perform process monitoring with the emphasis on process monitoring. However, in the complete chain between advanced instrumentation, the internet/ethernet, and a complex process environment (complex chemical industry with various complex parameters), these whole complete internet-enabled analytics technology are still unable to do complete continuous process diagnostics on multiple variable parameters with a continuous independent interactive intelligent process control remotely for a long period of time without any human interference. This means that this whole complete internet-enabled analytics technological system should run, for example, a complete chemical industrial plant alone for a long period of time. I still believe this can and will be done soon.

Analytical scientists, in particular those working on chemical sensors, electrochemical sensors, and biosensors, should make sure that their sensors should be stable over a very long-term deployment and that the sensing membrane, film, or layer of each sensor in a multiple sensing device, when exposed to a sample, generates a sensitive, selective signal from each analyte that links an individual molecular binding event to the value of a digital number. The current internet options 802.11 standards; Bluetooth and Zigbee as well as Radio Frequency ID still have a number of shortcomings to be suitable for long-term autonomous continuous operations in very remote locations and still need intensive research to function without any breakdowns in connectivity, even for very short flashpoint type of breaks. Much work still has to be done on chemometrics and mathematical software tools to implement the analytical signals received for transmission over wireless networks in such a way that continuous independent interactive intelligent process control could function remotely for a long period of time without any human interference to be possible. The ideal systems should be possible for self-operating, self-contained analytical wireless sensing systems when such a system includes a self-contained energy or power source; reliable multi-functional chemical and/or biological sensors; reliable electronic sensor interfaces; reliable computation/data storage devices with intelligent, interactive, "thinkable" chemometrics hardware/software as well as fast, continuous, reliable peer-to-peer links between analytics and the process environment (Fig. 2).

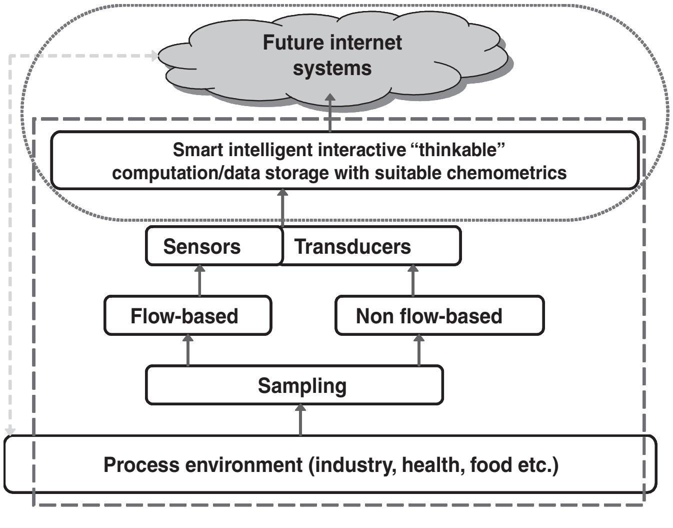

FIG. 2. The way an ideal complete self-operating, self-contained, analytics wireless internet enabled-process environmental technological system should work.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support received from the project financed by contract 746/19.01.2009 from PN II, Ideas.

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