Engineering complex systems for health, security and the environment

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Abstract— Several important societal and economic world problems can be addressed by the smart use of technology. The last forty years have witnessed the realization of computational systems and networks, rooted in our ability of crafting complex integrated circuits out of billions of transistors. Nowadays, the ability of mastering materials at the molecular level and their interaction with living matter opens up unforeseeable horizons. Networking biological sensors through body-area, ad hoc and standard communication networks boosts the intrinsic power of local measurements, and allows us to reach new standards in health and environment management, with positive fallout on security of individuals and communities. This article reviews the Nano-Tera.ch research program, addressing the enabling and disruptive technologies that stem from the combination of nanotechnology with large (tera) -scale information and communication systems.

I. Introduction

The new frontiers of research and development of electronic and information systems are delimited by the availability of technologies and by the opportunities of the markets. In microelectronic, the continued downscaling of the features of integrated circuits (Moore's law) has enabled the production of increasingly more complex systems with a simultaneous reduction of the cost of computation and storage per bit. While this trend is still ongoing, it is appropriate to investigate the new disruptive nanotechnologies, their interaction with existing semiconductor processes, and the markets that they open up or expand. Indeed this decade is witnessing an unprecedented application of new technologies and materials, from carbon electronics to phase-change memories, as well as the first integrated biosystems for diagnostics and computer-assisted medical care.

The technology push is multifaceted. CMOS scaling has enabled the fabrication of transistors in the [15-32] nm range as well as the integration of billion of devices in chips with good yield. *Silicon Nano Wires* (SiNW), *Carbon Nano Tubes* (CNT), *Graphene* and similar planar molecular structures [4] offer tremendous possibilities as computing elements, interconnect, storage and sensing devices. Moreover, the integration of new materials with CMOS process offer new functionalities and competitive advantages in various sectors, and specifically in the realization of integrated sensing and processing systems.

In recent years, the market pull has been driven by consumer electronics and by the need of providing high-quality, low-power computing and communicating systems with effective human interfaces. Smart phones and tablets represent a considerable and increasing market, which can be extended by the addition of capabilities enabled by new nano devices for sensing and displaying information. In general, ubiquitous connectivity boosts the effectiveness of sensing, and we are seeing now large-scale wireless sensor networks deployed for various applications, as, for example, for earthquake monitoring [7].

It is important to stress that major societal and economic issues can be addressed by the deployment of smart sensor networks. Examples include, but are not limited to: i) smart grids for electric power distributions with multiple distributed and multi-scale sources; ii) water management with quality and quantity control; iii) remote monitoring of elderly and disabled individuals as well as outpatient remote care; iv) advanced diagnostics to be used at point of care; v) risk mitigation systems based on early warnings of earthquakes, tsunamis, glacier/rock movement, floods etc... Thus, it is important that national governments and transnational organizations foster the breeding of electronic technologies and systems, because they are the current and future avenues for dealing with most urgent environmental and social issues, as well as because they can lead to a rationalization and reduction of costs (e.g., medical care costs). It is also important to remark that the management of personal and societal information requires advances in security, safety and privacy technologies, as a result of related R&D investments.

A few initiatives [9, 7, 8] and research centers [11, 10] are tackling some of these important issues. The Swiss *Nano-Tera.ch* program addresses the applications of nanotechnologies to large (tera) -scale systems with a broad vision, and it is has been instrumental in fostering research and innovation in this domain.

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II. The nano-tera.ch program

Nano-tera.ch addresses system engineering research that leverages micro, nano, information and communication technologies. The broad objectives of the program are both to improve quality of life and security of people across different levels of education, wealth and age and eventually to create innovative products, technologies and manufacturing methods, thus resulting in job and revenue creation. The application areas are health, environment and security. The strong interest on energy issues has lead to an extension of environmental research to smart energy production and distribution. The intrinsic value of the underlying research is to bridge traditional disciplines, including electrical engineering, micro/nano-mechanical systems engineering, bio-medical sciences and computer/communication sciences, with the objectives of i) deepening the understanding of enabling technologies, ii) reducing scientific concepts to practice, and iii) mastering the novel challenges of designing large-scale complex systems.

The Nano-Tera.ch program has been launched by the Swiss government in 2008 and is articulated in three phases, with the second 5-year phase just starting in 2012. The funding rate is 15MCHF/year (Approximatively 16.5MUSD/year at the exchange rate of 10/ 2011). This funding is matched by an equal amount provided by the partner institutions. Nano-tera.ch has been established as a *simple partnership*, which enables Universities and Research Centers to provide a neutral platform for collaboration and development.

Nano-Tera.ch distributes money for funding projects on a competitive basis, and the Swiss National Science Foundation provides Nano-Tera.ch with proposal reviews for quality control. At present Nano-Tera.ch funds 19 large projects, 15 small-scale projects and 19 education and dissemination events. More than 80% of the funds are dedicated to the large projects, dubbed *Research, Technology and Development* (RTD) projects, which, by construction, involve multi-discipline, multi-institutional teams of researchers addressing cutting edge topics within the program scope. Typically, these projects require a strong investment which is not readily available from other funding sources. A total of about 600 researchers participate in the RTD projects and about 120 doctoral theses are supported by the program. It is not the purpose of this article to provide a detailed description and statistics of these projects, which is otherwise available online [6]. Conversely, I will present a few case studies of projects in the health and environment spectrum to give a flavor of the program.

III. Health

Future health management systems will require an increasingly large presence of automation, information extraction and elaboration, as well as control of the medical procedures. In essence, we can envision three major areas that require innovation: i) real-time sensing and data acquisition of bio-chemical compounds; ii) information networking through a specialized physical layer; iii) data elaboration, retrieval and classification.

Sensing is a discipline that traditionally has been developed by communities related to fundamental sciences (e.g., physics, chemistry and biology). Despite the large number of sensors available, their effective use is limited by size, power consumption and lack of effective integration with electronic and information systems. In other words, sensing is still based on discrete components, much as a transistor radio was assembled fifty years ago. The integration of sensing with electronics, and thus the merging of sensing and electronic design, is key to achieving miniaturized, low-power, low-noise data acquisition chains with detection limits in regions of interest for clinical study. To date, only glucose monitoring has reached some form of maturity and FDA-approved devices are available for diabetic patient monitoring.

The challenges of biomedical electronic systems are related to both data acquisition and communication. Indeed, sensors in the body need to communicate to external devices. Brain implants are very critical and key examples of the challenges of communication technology [1]. Power delivery means can obviate the need of implanted batteries, which always present some risk factor. Sensors on the body communicate through *Body-Area Networks* (BAN), a new technology with several challenges, including energy-efficiency, bandwidth and security. Biocompatibilty and the selection of materials and related technologies is also an important matter.

Information systems for biomedical applications have been developed, but they are typically used off line. The need of fast responses and their secure interaction with electronics on the body and/or in the body is still an area of research. Nevertheless, the combination of networked databases with on-line data acquisition chains opens the door to better therapy as well as to promoting the autonomy of the patient and convalescent.

A. Bio-sensing

About one half of the Nano-Tera.ch RTD projects deal with sensing technology. Here I describe in detail a project for sensing, applied to the development of an implanted device (in the body), where sensing, electronic and communication technologies are fused together.

The broad objective of the *I-IronIC* project is the improvement of health care with special focus on personalized therapy and chronic patients who require daily monitoring of different metabolic compounds. Some systems for on-line monitoring are available in the market. They use wearable devices (accelerometers, heartbeat monitoring system, etc) but they do not measure metabolites.

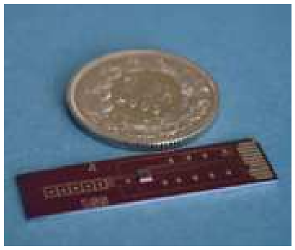

Fig. 1. Integrated sensor plate and data acquisition electronics

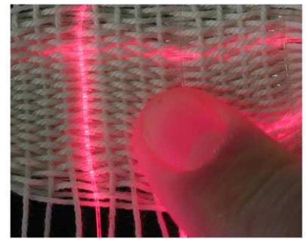

Fig. 2. Electro-optical textile fabric. Courtesy of G. Troester

The only available real-time, implantable/wearable systems for metabolic control are limited to glucose monitoring and used by diabetic patients. However, many different molecules present crucial relevance in human metabolism. They are monitored daily in general hospital practice by automatic blood sampling. The amount of metabolic molecules is estimated by using off-line, large and expensive laboratory equipments. So far, there are no available implantable/wearable systems for multi-metabolites, real-time, on-line monitoring of the human metabolism.

The I-ironic project addresses an innovative, highly integrated, fully implantable and real-time monitoring system for human metabolism. The monitored metabolic molecules are lactate, cholesterol, ATP, glutamate, glucose and others. The system to be realized consists of: i) a fully integrated sensor array and data acquisition electronic unit; ii) a wearable station for remote powering and signal processing; iii) a remote station for data collection and storage. The main scientific challenge is related to fabricating the implant to be housed in a bio-compatible cylinder of about 2mm of diameter and 15mm in length, to be placed in the interstitial tissue [5]. The current prototype includes: a sensor array, a CMOS mixed signal chip and a tridimensional integrated coil for receiving inductive power and transmitting data via backscattering. The sensor array is realized with an innovative technology, where CNT-nanostructured electrodes enable us to measure metabolites with increased sensitivity and lower detection limits as compared to the state of the art. The integrated electronic and sensor array require 0.5 mw to operate; electronic power is harvested by the coil. An electronic patch on the body produces the inductive field to power the implant, receives the backscatterd data, and transmits it to a base station using the blue-tooth standard.

B. Electronic textiles

Body-area network technology is crucial to extract information from various sensors and convey them to a local hub. Several aspects of body-area networks have been investigated [3] and standards have been proposed. In particular, *electronic textiles* provide us with a very interesting functional material for realizing BANs. Moreover, electronic textiles can merge both sensing and communication in the same medium.

The *TecInTex* project aims at the development of textile-based advanced (electrical/optical) fibers incorporating sensors, signal transmission andr other active nano-components. The research objectives are devising both: i) a family of new sensorized and functional fibers, enabling *in situ* measurements of body functions like continuous *electrocardiograph* (ECG) monitoring and biological species in body proximity, and ii) approved fabrication processes and working prototypes dedicated for health-care, rehabilitation and prevention. A demonstrator of this technology is embodied by an electronic underwear for paraplegics, who typically suffer from pressure ulcers in average twice a year. With intelligent textiles, ulcers can be prevented with an important reduction of pain and associated health care costs.

The research includes development of biosensing optical fibers and the design of a prototype for testing the fibers. Biosensing fibers are obtained by modifying standard optical fibers with a sensitive, porous layer specific to relevant biomarkers. Detection is based on optical changes, placing a light source and a detector at both extremities of the fiber. pH sensing fibers were developed by replacing the cladding of the fiber over a length of [2-6] cm with a porous solgel layer encapsulating pH sensitive dyes. pH changes results in color changes of the layer, which are detected by measuring absorbance changes at the wavelength of maximum absorbance. A photodetector and a transimpedance amplifier are needed to convert light into photocurrent and eventually into a voltage for further signal processing. This transimpedance amplifier is integrated into the textile, as close as possible to the photodetector to reduce the noise influence. Therefore, a transimpedance amplifier was fabricated in the form of an enhancement load gain stage with a feedback resistor on a flexible substrate. The transistors and resistors needed for the amplifier are made of semiconducting amorphous indium-gallium-zinc-oxide.

C. Advanced diagnosis tools

Advanced diagnosis relates both to the design of new methods for probing the human body as well as making diagnosis tools portable and available at points of care.

The *lab on chip* technology [2] and the use of *microarrays* has reduced the size and cost of some tests while enabling specific tests (e.g., genotyping) which were not available before. The miniaturization of diagnosis equipment requires often the use of new technologies, and opens the way to radically new procedures.

The *Nexray* project targets the development of novel small X-ray sources and X-ray direct detectors whose outputs will be combined to new image processing systems. The miniaturized X-ray sources are based on *Multi-Walled Carbon Nano Tube* (MWCNT) cold-electron emitters. Differently from classical thermionic emission, field electron emission of the CNT is voltage controlled, and thus enables high modulation frequencies up to GHz level. The X-ray direct detectors are based on crystalline Germanium absorption layers grown directly on a CMOS sensor chip, yielding high resolution and high sensitivity X-ray detectors. Single photon detection enables a significant improvement of contrast for applications in security, health care and non destructive testing. Moreover, the direct integration of germanium absorption layers into CMOS sensors results in on-pixel signal pre-processing capabilities, which can be exploited for various application.

The outcome of this project relates to two radical new approaches to X-ray imaging. First, *X-ray time-of-flight* (xTOF) measurements can be used to probe the depth inside objects. This calls for an intensity-modulated X-ray signal in the MHz range which is not possible with conventional X-ray sources but can be achieved with CNT-based cold emitters. Second, we can achieve tomographic imaging by exploiting the fact that both the X-ray source and the X-ray detector are pixelated. Indeed the X-ray source is built as a matrix of micro X-ray sources that also can be addressed and controlled individually. The combination of pixelated X-ray sources and detectors opens up completely new imaging capabilities.

Fig. 3. Test X-ray source. Courtesy of A. Domman

IV. ENVIRONMENT

Objectives of environmental monitoring include evaluating the quality of the air and water, by measuring pollution in terms of biological and/or inorganic compounds as well as instrumenting the environment to detect movements that can lead to catastrophes, such as rockslides, avalanches, floods and the instability of constructions such as buildings and bridges.

The environmental domain has several similarities to the health domain. Environmental systems rely on sensing, data-acquisition chains, data transmission and processing. There are two important differences: i) sensors are less constrained as compared to those used for medical applications in/on the body; ii) data transmission occurs over greater distances, possibly in a harsh environment. As in the health domain, energy consumption for sensing, elaboration and transmission is critical and should be as low as possible.

A. Cell-based sensing

The *LiveSense* project addresses environmental sensing by using living cells. Living cells are the most natural biosensors, since they integrate the biological effects of the compound mixtures and respond by metabolic or phenotypic changes that are relevant to potential effects in the human body. In living cell-based sensors, the cellular responses are measured in real time by secondary probes or sensors that can be optical, chemical or electrical microsensors. Whereas it is now firmly established that living cells are excellent for biosensing of toxic compounds, the main scientific and technological challenge is to control growth conditions and embed living cells within an autonomous microsystem for a long period of time. Furthermore, research must address the response detection by secondary sensing methods, and the integration into a microsystem. Thus the project is centered around the realization of a complete autonomous microsystem that would include: i) a cell culture microbioreactor, ii) a number of secondary sensors to measure cell response and monitor the microbioreactor process, iii) a signal processing control unit and iv) a wireless communication unit to link the microsystem to a sensor network.

Two cell types are used. First, bacteria because there is already a wide experience on bacterial bioreporters and they are relatively easy to culture. The scientific challenges is in constructing a microbioreactor supporting continuous cell growth and a supply of active cells. Second, eukaryotic cells because of their metabolic response to the toxicological reaction pathways in human and possibly more relevant to health-effect interpretations. Further technological and engineering challenges are to achieve the hybrid integration of living components into an autonomous microsystem and to interpret the secondary sensors signals into environmentally relevant information that can be sent through a sensor network.

The sensing platform will be embodied as a hand-held or networked analytical instrument (e.g. for food analysis, personalized health, gas monitoring). In the longer term, this technology can directly benefit by the progress of genetic engineering and microtechnology, because it will be possible to detect viruses and bacteria by engineering cell expressing suitable recognition complexes and appropriate transduction mechanisms. Possible applications include sensors networks for real-time monitoring expansion of pathogenic vectors such as, for example, the spread of airborne viruses (e.g. H5N1 avian influenza) or bacterial pathogens in water (e.g. Legionella pneumophila).

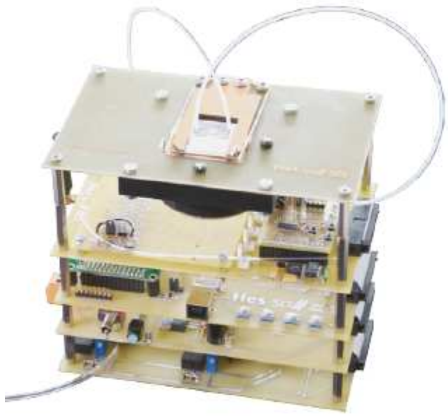

Fig. 4. Prototype with stackable boards. The microfluidic module is shown on top with the fluorescence detection module just below. Courtesy: P. Renaud

B. Air monitoring

Wireless sensor networks and publishing of sensor data on the Internet bear the potential to substantially increase public awareness and involvement in environmental sustainability. These technologies enable capturing sensor data by involving public authorities and the general public and making real-time information on environmental conditions available to a wide public. Air pollution monitoring in urban areas is a prime example of such an application as common air pollutants have direct effect on the human health. However, bringing the vision of public involvement in environmental monitoring to a reality poses today substantial technical challenges for the communication and information systems infrastructure, to scale up from isolated well controlled systems to an open and scalable infrastructure where many nano-scale sensors generate terabytes of data. A wide variety of sensors (meteorological data, air pollutants such as O_3, NO_2, NO, SO_2 and fine particles) is used and measurements have to account for atmospheric transport phenomena, sensors are frequently mobile (public and private vehicles, personal devices, airborne vehicles) and air pollution is today mostly a matter of public interest.

Project *OpenSense* addresses key research challenges related to air pollution sensing using wireless sensor network technology, namely: i) reducing noise and data volume of heterogeneous sensor data by exploiting redundancies derived from complex environmental processes; ii) performing real-time data gathering with heterogeneous and mobile sensors and intermittent connectivity, in particular in urban environments; iii) compiling numerical models of complex spatial processes into qualitative approximations that can be used for efficient signal processing and sensor interpretation; iv) sharing measurement and model data through an open community platform in a trusted and fair environment, providing security against manipulation and faulty data.

The project will result in open technology that allows us to integrate diverse sensors, including mobile sensors, into a single environmental model. The information processing techniques we develop will provide important insights to enable other Nano-Tera application domains dealing with monitoring complex events.

Fig. 5. Prototype of a sensor placed on top of a bus. Courtesy of M. Rajman

C. Rock and glacier movements

Global climate change dramatically influenced the visual appearance of mountain areas like the European Alps. Global warming may trigger and/or intensify destructive geological processes, which influence the stability of slopes and may induce landslides, posing a threat to local communities. Unfortunately, the interaction between these complex processes is poorly understood.

The project *X-Sense* has the following goals. i) Develop wireless sensing technology as a new scientific instrument for environmental sensing under extreme conditions in terms of temperature variations, humidity, mechanical forces, snow coverage as well as unattended operation that are needed for long-term deployment. ii) Integrate various sensing dimensions (such as pressure, humidity, crevice movements, high precision deformation and movements) in terms of sensing and processing hardware, software and sensor fusion algorithms. iii) Extend the spatial scope from local (microscopic) measurements to large scale information based on satellite radar remote sensing and fuse the resulting information to achieve an unparalleled degree of precision in space, time and accuracy. iv) Utilize this new measurement technology to advance applications in science and society: geophysical research and early warning against landslides and rockfall, thereby securing people in their homes, during recreational activities, in public transportation and cars.

All these activities are guided by thorough geophysical modeling and simulation as well as by demands from early-warning scenarios. The project has also the objective of developing and testing rugged electronics to be used in harsh environments, and can be scaled up to major environmental problems beyond the Alps region.

Fig. 6. Reference Station on the Matterhorn. Courtesy: A. Geiger

V. Technology platforms

Research and development of some technologies impact various projects in the health and environment domains. Examples include various sensing means, ranging from using Silicon Nano Wires to coherent optical sources in the visible and infrared spectrum. New materials, such as CNTs, are studied as both mechanical devices (e.g., tunable resonators) and electronic mediators in sensor structures. The crossbreeding of technologies at the device level is instrumental in creating the underlying physical basis for system building.

In electronics and computing, the two ends of the performance spectrum are investigated. High-performance multi-processing systems, realized as 3-Dimensional Integrated Circuits, require dealing with the excess heat generated as a byproduct of computation. Liquid cooling of such systems requires specific competences in thermodynamics as well as in mechanics of materials, beside mastering dynamic power management in various forms. These activities are part of project *CMOSAIC*.

Low-power electronic systems, and specifically autonomous systems, are crucial for both health and environment application. A technology platform, called *PlaCiTUS* researches mixed-signal platforms, such as those embedded in biomedical electronics, sensor wireless networks. The platform envisages a system consisting of many sensors and actuators interfaced to micro-power data acquisition and driver circuits, respectively. These acquisition circuits can either be supplied by battery or by remote power coupled inductively. A short range wireless network links the sensor nodes together and manages the data flow to the outside world centrally. A wide area network wireless modem, with power consumption commensurate with wearable applications, periodically communicates with remote health centers, transmitting data that require analysis. With this construction, the platform is widely applicable in the medical domain.

VI. Summary and Conclusions

Advances in health and environment monitoring benefit society and improves the security of individuals and communities. Research in these areas is multifaceted, and can only be achieved through the collaborative effort of various groups with diversified competences. The Nanotera.ch program has spearheaded some important challenges in these domains and it is unique as a research funding program because of creating a unique fabric of scientists and engineers whose combined effort can meet the various challenges. Although scientific results are numerous and important, the development of the field requires a sustained effort, including a seamless interaction with industry and medical providers. The future phases of Nano-Tera.ch will focus both on research and on increased industrial awareness.

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