Nano-Tera.CH: Nano-technologies for Tera-scale Problems

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ABSTRACT — **The Nano-Tera.CH initiative is a broad engineering program in Switzerland for health and security of humans and the environment, currently funded by the Swiss government. The program rationale is rooted in advances in engineering nano-scale materials and their exploitation in a variety of systems, requiring extreme integration and coordinated control of diverse micro/nano-scale components. Embodiments of such systems can be found in lightweight, mobile and personalized products embedded in the environment and on/in the body. These products will enable us, for example, to detect in real time different health risks and conditions through integrated bio probing, to reveal security risks through smart buildings and environments, to save energy through ambient sensing, and to detect and monitor environmental hazards such as floods and avalanches from space and/or inaccessible positions on earth. The outstanding novelty and power of these systems stem from their connectedness and the integration of heterogeneous components.**

Index Terms — **Nanotechnology, nanoelectronics, MEMS, NEMS, VLSI, sensors, software, systems.**

I. INTRODUCTION

The mission of this program can be summarized as the *research, design and engineering of complex (tera-scale) systems and networks* to monitor and connect humans and/or the environment. The underlying enabling technology is provided by *micro/nano-technologies* and their applications to distributed and networked embedded-system design. Thus, this research program is built around a technology kernel that supports embedded system applications. Beyond the mere straightforward integration, the program aims at identifying and fostering the potential synergies between micro/nano-component technology and large-scale system design technologies (ranging from hardware to software and networking). Indeed, the availability of sensing, computing and communication technologies enables and constrains the design of embedded systems. Conversely, the stringent requirements of embedded systems on size, weight, power dissipation and communication range demand major innovation in micro/nano-technologies.

The objective of this paper is to outline the scientific vision, the application areas and the technologies of the program. Detailed technical information of the current projects is available on line [1].

II. APPLICATION AREAS

The Nano-Tera.CH program addresses three application areas described next.

Wearable Embedded Systems

As diverse as tomorrow's society constituent groups may be, they will share the common requirements that their life should become safer and healthier, offering higher levels of effectiveness, communication and personal freedom. The key common part to all potential solutions fulfilling these requirements is wearable embedded systems with longer periods of autonomy, offering wider functionality, more communication possibilities and increased computational power. As electronic and information systems on the human body, their role is to collect relevant physiological information, and to interface between humans and local and/or global information systems. Of particular relevance to Switzerland, the potential of the watch, as the most commonly used wearable system, to interface between humans and information systems will be investigated. Specific application targets of wearable systems are in the areas of: i) monitoring, diagnosis and/or treatment of patients; ii) monitoring of professional and recreational sportsmen; iii) supporting the elderly and disabled citizens, iv) enhancing the security and safety of the individuals.

Ambient Systems

The notion of ambient systems captures the idea of large-scale heterogeneous systems used to sense, network, inform, actuate, or interact with the physical environment and the humans present in the environment. These systems are at the heart of the next generation information technology, which will no longer be limited to dedicated infrastructures, such as the Internet, but will be embedded in artifacts and the environment and will consist of highly distributed, networked, heterogeneous, and largely self-organizing devices. Ambient systems research addresses three specific fields, namely: i) environmental monitoring, ii) ambient intelligence embedded in smart buildings, iii) virtual world applications.

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Remote Systems

Remote systems are characterized by autonomous or semi-autonomous behavior, as exemplified by space applications. To date, most commercial satellites range in mass from 500 kg to 5 tons, with electric power of up to 18 kW. Development cycles are very long (10-15 years) and, because of the need to guarantee 15-year lifetime under harsh conditions with no possibility of repair, the technology used is generations behind what is found in current consumer electronics. A specific objective is the study, development and deployment of pico/nano-satellites. Indeed, major advances in microelectronics, in particular microprocessors and MEMS, are making smaller satellites (1-10 kg) a viable alternative. These pico/nano-satellites provide cost-effective solutions to traditional problems and, especially when grouped into networks or constellations, they offer new possibilities to improve our safety, quality of life and understanding of our environment. In this perspective, remote systems address the following goals: i) environmental monitoring; ii) local and worldwide disaster monitoring; iii) demonstration of novel micro-system technologies in space.

III. TECHNOLOGIES

Nanoelectronics

Today's micro/nano-electronics is characterized by migration of research from pure down-scaling to new functionality and combined technology-system innovation. This is mainly required in order to manage power dissipation, variability and complexity issues that are associated with tera-systems that exploit nanotechnology. While this new functionality and technology-system innovation will exploit the properties of future nano-scaled technologies, the aggressive scaling will also play a fundamental, but not an exclusive role. New research drivers, such as ultra-low power technologies, bio-inspired circuit and system design and ambient intelligence applications are expected to play an increasingly important role in the next years.

Within the last decade, the nanotechnology and nano-device evolutions have been dominated by the aggressive scaling in the sub-100nm zone and the related cost-effectiveness of silicon technology. Today top-down nano-lithographic based approaches are challenged by bottom-up nanotechnology. We consider that a smart combination and developments of the two approaches will be needed in the future and the choices will be dictated by complex system performance and functionality.

Both *silicon nanowires* (SiNW) and *carbon nanotubes* (CNTs) offer tremendous possibilities as computing, storage and sensing elements. Within this program we are particularly interested in the hybridization of these technologies with standard ones (e.g., CMOS) in the search of both evolutionary and revolutionary architectures.

3-dimensional (3D) integration of nanoelectronic devices, memory elements, and interconnect layers is considered as a very promising technique to increase the overall integration density as well as the performance of complex systems, mainly due to the significant shortening of connection paths between layers. However, a number of very challenging issues need to be resolved in order to enable widespread adoption of 3D integration for large-volume production: realization of high-density *through silicon vias* (TSVs), multi-level wafer bonding techniques, addressing the thermal management issues for intermediate layers, development of effective 3D layer assignment, placement and 3D routing algorithms – to mention a few. True 3D integration is expected to open the possibilities for very-small-form-factor multi-processing and memory units which can be used in wearable / ubiquitous systems as well as implanted devices. This 3D integration aspect will also become one of the central technology drivers of the Nano-Tera.CH initiative that will be utilized to merge many technology layers.

Sensors

Sensors create an interface between the environment and an electronic system by converting physical, chemical and biological parameters of the environment into electrical signals. Up until now, sensors have been usually developed as stand-alone devices with the notable exception of imaging devices (as seen in digital cameras and mobile phones) and in automotive applications. By far the most success has been made with mechanical sensors (starting with the commercial success of airbag sensors in automotive design), and image sensors. Others, such as chemical and biological sensors, have been mainly developed for large scale laboratory analytical instrumentation with very few integrated applications. These include chemical gas sensors, liquid sensors, glucose-level sensors and large-scale bio-assays used for high-throughput bio-medical measurements.

The *More than Moore* platform sums up the expectation from the next generation of integrated systems. Additional value and applications beyond the down-scaling of electronic devices must be achieved. The "key" element in the More than Moore platform is integrating a series of novel sensors into electronic systems, thus enabling these new integrated systems to interact directly with the environment. The electronic revolution has brought the computation power that was only available to super-computer systems to the common household. The expectation from More than Moore is to bring the sensing and detection capability that is only available in specialized laboratories to the common household as well.

There are a number of challenges for sensing. First of all there is the problem of sample preparation. This involves obtaining, transporting and pre-processing the sample. In the past, this has been the limiting factor for integration. Sensors that require little (image sensors that require focusing, filtering) or no preparation (mechanical motion sensors) were developed much faster than biological sensors that require extensive preparation. As part of the Nano-Tera.CH project, we aim to refine current methods and develop new solutions to come up with viable and affordable sample preparation methods that can be integrated into next generation devices.

The second challenge for the sensor applications is performance. Sensor performance can generally be categorized in three components: *sensitivity, specificity* and *repeatability*. The most obvious parameter is sensitivity, which essentially defines the accuracy of the sensing system. Especially for bio-chemical sensors, where the sample contains multiple similar substances, specificity is a very important parameter that defines how selective the sensing system is to the target substance. The third parameter, repeatability, measures how reliable the sensing result is. The goal of sensor design is to find ways for designing reliable, accurate sensors and integrate them in electronic systems without sacrificing key parameters like sensitivity, specificity and repeatability.

The third challenge is to integrate these new sensors into systems with practical applications. Key application fields include implantable sensors and bio-sensors for health applications, environmental sensing and stand-alone sensor nodes, and ambient intelligence. These projects require solutions in packaging, digital post-processing, communication and security.

MEMS/NEMS

Micro/nano-technologies enable the fabrication of complex and miniaturized functional systems, called MEMS and NEMS (i.e., micro/nano electro-mechanical systems). MEMS/NEMS provide interface functions (sensors and actuators) between micro- or nanoelectronics and the environment and human beings. Thus, there is a strong relation between sensors and MEMS/NEMS. Prominent microsystem examples from the past are automotive safety sensors (crash sensing, driver assistance) and projection systems (DMD™). In MEMS/NEMS we will continue substituting functional micro-scaled structures (e.g. silicon based surface micro-machined capacitive transducers) by new functional materials and nano scaled elements for better performance. Today's prominent examples are macro-molecular carbon nanotubes, which have already been explored in MEMS/NEMS for displacement, force, pressure and gas sensing. New functional materials based on graphene layers, or molecular layers and structures applied for functionalization of surfaces and transducers are envisioned. MEMS/NEMS in general are considered enabling devices for all kind of tera-scale systems, which are proposed to interfaces the environment and the ambient of human beings with autonomous, widely distributed and interacting systems. MEMS/NEMS will also become parts of micro- and nano-electronic systems (systems-in-package) providing functions like resonators, filters, switches and RF MEMS/NEMS in general.

Novel functional materials include SiNW, CNTs, graphene, and materials to achieve components and MEMS/NEMS that integrate micro/nano mechanical, thermal, fluidics and optical structures and structures for chemical and bio-chemical sensing into silicon-based semiconductor processes and alternative material groups (e.g. polymers). Examples of specific activities are using SiNW and CNTs for MEMS/NEMS as well in devices that their excellent properties in sensing mechanical, optical and (bio) chemical quantities.

Novel fabrication and process integration technologies address the integration of nano-sized structures as functional elements in MEMS/NEMS with the goal of forming structures with predictable and controllable characteristics. A new generation of nano sized devices will most probably depend on non-photolithographic placement or structuring techniques like self-assembled growth or assembly of pre-fabricated structures on wafer level.

Systems and Software

Large-scale distributed information processing involves huge sets of nodes performing information acquisition, processing and communication, often in a self-organized manner, to achieve an ambitious overall system objective. Compounding the technological challenges, such processing must occur at high speed and with low power consumption. At the large scale envisioned in this proposal, our understanding of the process of building the architecture of complex systems is still in its infancy.

The large number of devices in the resulting systems, the complexity of their structure, and their distributed nature pose significant system-level challenges, such as designing algorithms for self-organizing large-scale communication and computation.

Algorithms and software play a major role in integrating the distributed components and guaranteeing the desired overall system behavior. In the past, software for such complex systems has been developed in a trial-and-error process that often caused large delays and cost overruns. In order to create products around such devices, we need to improve the development process to make it more predictable. We are on the verge of making fundamental advances in automating the production of software, from its design to its verification and deployment, including the ability to formally prove its correctness and security. We are also in the midst of a fundamental change in the way information is stored, distributed and processed: instead of the current static and relatively inflexible systems, we are moving towards more sophisticated interfaces, more powerful data manipulation languages, and an increasing ability to cope with the enormous amount of data including real-time streams.

The software infrastructure addresses questions of self-organization, reliability and resource usage of large distributed systems. At the system infrastructure level, questions raised by large systems for processing, storing and retrieving the vast amounts of data are very important roadblocks to overcome.

Information and Communication

Tera-scale distributed information processing systems generate unprecedented amounts of data, which needs to be processed, stored and efficiently transmitted over large-scale highly heterogeneous wireless networks. This poses tremendous challenges, detailed below, in various areas of information processing.

Tera-scale networks need to cope with large scales of small and unreliable components. The traditional methods that successfully helped engineers to design small to moderate size networks are not suited for such large scale systems. Techniques that can deal with massive scales, unreliable components and device heterogeneity encompass, for example, large-deviation analysis, percolation theory, large random matrix theory and network information theory. These techniques will be used to establish the communication-theoretic performance limits of large-scale wireless networks under realistic modeling assumption. In addition new signaling strategies, distributed signal processing and control algorithms need to be developed.

Within this context, wireless networks require high-end nodes acting as (cellular) infrastructure centers of the network as well as communication schemes that lead to cheap transceivers suitable for short-range communication. While for the first category there is little doubt that these types of nodes will be based on *multiple-input multiple-output* (MIMO) technology, we expect that for the second category *ultra-wideband* (UWB) communication may be a suitable technology. For both technologies, major challenges remain in the areas of antenna miniaturization and realistic test bed design, crucial to demonstrate systems engineered within Nano-Tera.CH.

Wireless sensor networks allow fine-grained measurements and thus provide more precise spatial and temporal data, e.g., for model verification in environmental science or for building monitoring and control. A first generation of platforms (motes) is now industrially available and deployed for a variety of applications. A number of problems however make scaling up beyond a few hundred of nodes very hard, if not impossible. In the context of the envisioned ambient/environment systems, we address the problems of: i) autonomously deploying, maintaining and administering large-scale wireless sensor networks; ii) enabling, supporting and exploiting mobility of wireless sensor nodes (most current deployments assume static nodes); iii) designing realistic test beds for testing wireless sensor networks at large scale to overcome the evident shortcomings and fallacies of today’s simulation tools.

IV. SUMMARY

The Nano-Tera.CH initiative is a collaborative engineering program that fosters research and crossbreeding of hardware and software technologies in the areas of wearable, ambient and remote systems. The scientific outcome is expected to better the quality of health, security and environmental systems, to foster a vision of engineering with social objectives and to promote a corresponding educational program.

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