Perspectives

Nano-Tera.ch: Information Technology for Health, Environment, and Energy

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Bettering human health care and creating a sustainable environment through monitoring and smart energy usage are primary goals of advanced societies. To this purpose, the Swiss Government, through the State Secretariat for Education, Research, and Innovation has been funding the Nano-Tera.ch program for about nine years with an overall budget of approximately 250 MUSD, half in cash, and half in matching instruments by public research entities. The program aims at establishing embedded/cyberphysical systems through the synergy of various disciplines within collaborative research projects, the design of applied demonstrators, targeted educational programs, and the transfer of acquired research results to industry and hospitals.

Nano-Tera.ch funds projects on a competitive basis and evaluates with the help of the Swiss National Science Foundation (SNSF). The funded projects range from large, 3–4 year research projects (RTD projects), carried out by consortia of 3 to 10 research groups from various Swiss institutions (federal polytechnics, universities, and research/innovation centers) to smaller research projects (NTF projects) focused on technologies, as well as various educational actions (ED projects). The Nano-Tera.ch research community represents today a network of about 50 Swiss research institutions and involves about 1300 members that constitute a large coverage of the Swiss scientific community in the program's fields.

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The funded research strategy evolved through the years. During the phase 1 of the program (2008–2013), the research projects focused on enabling technologies for nanosystems (e.g., sensors and 3D integration), and/or various health and environmental applications (e.g., environmental sensing of air and alpine movements, metabolic and biological cell monitoring, circuit design, and cryptography). In the phase 2 of the program (2013–2017), the research projects are exploring various topics combining engineering with life sciences, medicine, and energy. In the final part of the program, emphasis is given to technology transfer and to the creation of a new funding instrument—called BRIDGE (under the stewardship of SNSF) and to the pilot program Gateway. Nano-Tera.ch also fostered international research collaboration, as for example, by funding joint projects with the Chinese Academy of Science.

At the educational level, Nano-Tera.ch has supported advanced courses, workshop, and international exchanges of researchers. The "NextStep" action was designed to help PhD students explore different ways of increasing their potentials after graduation. In particular, Nano-Tera.ch has provided coaching to PhD students to incite them to consider economic exploitation of their scientific results, has opened research grants to fund collaborative research exclusively involving PhD students, and has organized "My Thesis in 180 Seconds" contests to train PhD students to present their research to a larger audience outside their field.

From a technology transfer perspective, most RTD projects received support from industrial partners and/or hospitals. The impact on the Swiss industry has been further strengthened by the Gateway pilot program. Concretely eight new projects have been funded each with partners from technology transfer institutions (e.g., EMPA and CSEM) and an industrial partner. The goal of these projects was to convert the laboratory prototypes resulting from Nano-Tera.ch research projects into industrial demonstrators with high economic potential directly exploitable by the involved industrial partners.

Detailed information about Nano-Tera.ch can be obtained on the Nano-Tera website (www.nanotera.ch), which represents one of the main dissemination channels for the program, with typically about 100,000 page views per year from more than 140 countries.

Health care

The rapid expansion of distributed communication and computing systems, with low-cost terminals (such as smart telephones) in parallel with recent discoveries in biology and medicine that have made these sciences more quantitative, provide us with new means to improve health care in its broad sense [1].

Electronic health can address various social and market segments with different requirements, ranging from devices and systems for monitoring and enhancing the well-being of active people (e.g., sportspeople) as well as the weak sectors of the population (e.g., elderly, handicapped, and chronic pathologies) to therapeutic means for diagnosing, monitoring, and treating peoples with infirmities. Within these three sectors, barriers to adopt new technologies vary widely, as risks, costs, and projected success rates change.

Nano-Tera.ch projects have targeted many health related topics that can be loosely arranged in three distinct thematic clusters: *smart prosthetics and body repair*, *health monitoring*, and *medical platforms*. A brief description of recent RTD projects is presented next.

Smart prosthetics and body repair

Projects address tactile prosthetics and other sensorimotor functions (in particular, after spinal cord injury), smart muscles for incontinence treatment or micro surgery. More specifically, the following challenges have been addressed.

Image-guided micro surgery for hearing aid implantation. The project HearRestore has been developing novel robotic technologies to drastically reduce the invasiveness and improve the outcome of cochlear implant surgery [2]. The project specifically aimed at increasing the safety of the procedure through the implementation of advanced surgical planning/image analysis, non-invasive registration, modeling/prediction of bone drilling, neuromonitoring, and nanometer tracking. A recent highlight is the successful transfer of the base technology to clinical use. The project was able to achieve regulatory clearance from both the local institutional review board—ethics commission—and the regulatory body Swissmedic for a first clinical trial. The project has proudly reported the first successful stereotactically guided robotic cochlear implantation in man worldwide. To the team's knowledge, no other group in the world other than theirs has produced sufficiently safe and accurate robotic microsurgery technology to enable microsurgical interventions at this scale and in a patient clinical trial.

High-performance spinal cord neuroprosthesis for restoration of locomotion after spinal cord injury. The mission of the SpineRepair project is to develop and optimize the enabling technologies to implement a cutting-edge spinal cord neuroprosthesis, allowing victims of paraplegia to recover partial mobility. Prototypes of the novel integrated devices are evaluated in animal models. The findings pave the way toward fundamentally new technological solutions and treatment paradigms to improve functional recovery in severely paralyzed individuals in a timely manner. So far, the research team has demonstrated a chronic, wired, soft spinal cord neuroprosthesis for a rat model, developed novel stretchable wiring based on silver nanowires, defined the layout of the implantable electronic hardware and the CMOS stimulator, and conducted the first characterization of locomotion enabled by multielectrode array implants in spinal rats.

Use of superparamagnetic nanoparticles for the detection and treatment of cancer.

MagnetoTheranostics has been developing a nanomedical system utilizing nanoparticles for the detection and therapy of lymph-node metastasis by applying iron oxide nanoparticles as contrast agents for metastatic lymph nodes and at the same time as a heat source for thermotherapy (Hyperthermia). The team was able to functionalize the particles with FDA accepted processes and materials, and a transfer to clinical tests should be feasible.

Cutting-edge technology for next-generation of artificial muscles. The application being targeted in SmartSphincter is smart muscles for incontinence treatment and involves hundreds of thousands of low voltage, dielectric, and electrically activated nanometerthick polymer layers. The researchers have found two promising alternatives to conventional stiff metal electrodes for the polymer actuators and shown that they are able to power them for 10 days without recharge from available lithium ion cells. The team has also successfully applied to their local ethical committee for a full pilot study involving 10 male and 10 female participants.

Wise skin for tactile prosthetics. Amputation of a hand or limb is a catastrophic event resulting in significant disability with major consequences for daily activities and quality of life. A sense of tactility is needed for providing feedback for control of prosthetic limbs and to perceive the prosthesis as a real part of the body, inducing a sense of "body ownership" and a natural sensation of touch. The idea of the WiseSkin project is to provide a noninvasive solution for restoration of a natural sensation of touch by embedding miniature tactility sensors into the cosmetic silicone coating of prostheses, which acts like a sensory "skin." A prosthetic hand integrated with tactility sensors and tactile feedback actuators was evaluated on an amputee with a hand phantom map (Figure 1).

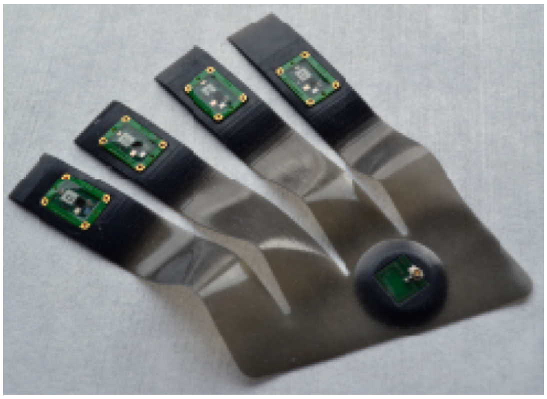

Figure 1. Prosthetic hand.

Health monitoring

Projects address personalized health management through the use of implanted devices, smart textiles, and intelligent drug monitoring systems. Application targets are in the fields of monitoring of obesity and neonatology, among others.

Monitoring the consequences of obesity. Project ObeSense is building integrated wearable body sensors networks to monitor obese patients at different stages of the disease. The physiological sensors include respiratory rate and volume, energy expenditure, blood pressure, and cardiac output and are to be integrated into stand-alone comfortable systems using both low-power electronics and smart textiles. Regarding the monitoring of the respiratory rate and volume, transparent flexible polymer-optical fibers have already been integrated in a smart T-shirt and have been successfully tested. Moreover, near infrared spectroscopy is being developed to measure the arterial and venous oxygen saturation, important parameters to determine energy expenditure. An application for mobile phones and tablets has been developed.

Monitoring of the healing of chronic wounds. The research consortium of FlusiTex has fabricated a sensing wound pad that can be used for noninvasive wound monitoring based on integrated fluorescence coupled biosensors, and which is likely to find broad applications in strongly growing fields such as health care and medtech. Namely, the associated Gateway project FlusiGate produced a functional prototype able to sense and indicate the pH of the wound via fluorescent measurements. Such a sensor is suited for a range of users/applications: at-home use for self-evaluation by the patient, or clinical use by a clinician for a precise measurement of pH evolution of chronic wounds. In particular, the team has developed a sensing patch consisting of a modified commercial wound-pad containing the fluorescent molecules: spots of either textile fibers or hydrogel containing the fluorescent molecules are incorporated into the commercial pad. The fluorescence

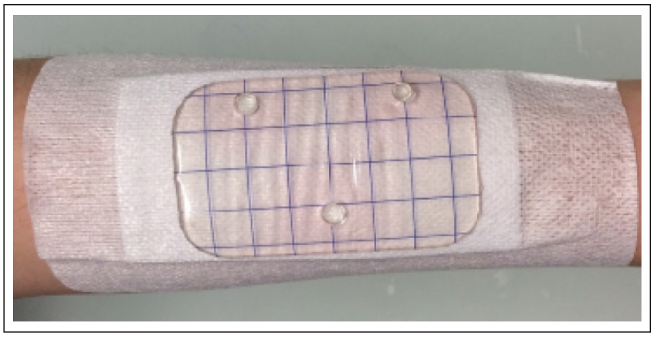

Figure 2. Remote wound monitoring through fluorescence.

intensity of the spots changes according to the pH of the underlying skin model [3] (Figure 2).

Newborn monitoring based on multiple vision sensors. The increasing number of parameters to monitor and the sensitivity of current sensors to body movement are responsible for unacceptably high rates of false alarms in newborn monitoring. NewbornCare seeks to drastically reduce the false positive alarms using a computer vision-based approach to estimate accurately the heart and respiratory rates in a contactless fashion (Figure 3).

Therapeutic drug monitoring for personalized medicine. The overall benefit of this research is to develop a technological platform to improve medical practice by enabling personalized medicine via therapeutic drug monitoring, while reducing healthcare costs. This ISyPeM II project has explored new sensor technologies, hardware and software data processing means, and drug release mechanisms based on silicon membranes [4]. This will provide a comprehensive integrated approach to Therapeutic drug monitoring which combines innovative point-of-care compatible assays, prescription decision support, and interoperability in a complex data-sharing scenario.

Figure 3. Newborn monitoring.

An SoC to make medical devices wearable. For both inpatient and outpatient applications, the electronic interface to typical sensors and electrodes still has a size and weight that prevents it from being used in a convenient and flexible way. Integration of the plethora of functionalities required in a wearable medical monitor, including the management of wireless connectivity, holds the key to the breakthrough required for clinical and user acceptance. This is why WearMeSoC has been developing a chip that will enable very small wearable medical monitors with wireless connectivity to small phones and tablets.

Medical platforms

Research covers engineering systems servicing various fields of medicine, such as oncology.

Wearable ICT for zero power medical applications. The BodyPoweredSenSE project aims to demonstrate that smart medical diagnostics can be performed using ergonomic, efficient, and energy harvesting-based sensors. Specifically, the scientists are developing smart, energy aware, user-friendly wearable sensors, and associated medical algorithms for the early diagnosis of Alzheimer's disease and childhood epilepsy, where the sensors derive power from the user's body energy (heat and motion) as well as from ambient light. The project has significantly contributed to the medical community understanding of the human brain and how brain rhythms and other biomarkers change as a function of ageing. The demonstrators of this project are extremely low-cost devices that can be manufactured as mass consumer products, thus accessible to the elderly and young for medical monitoring. These devices will offer early warning of diseases, thereby improving the immediacy and efficacy of treatment, and assessment of recovery, while all focusing on the pharmacological intervention; these outcomes are important contributions to wearable medical informatics and advanced ICT in health.

Novel semiconductor disk lasers for biomedical and metrology applications. In a follow-up to the original MIXSEL project (in phase 1), MIXSEL II is consolidating its high-power ultrafast semiconductor laser technology. The goal is to develop prototype demonstrators for end-user demonstration in biomedical imaging, compact efficient white light generation for general high brightness illumination, and frequency metrology applications. The project enabled world-record achievements in the development of femtosecond semiconductor disk lasers and their applications in frequency metrology and biomedical microscopy.

Rapid sensing of cancer. PATLiSci II is developing rapid diagnostic tools for cancer by paralleled mechanical cantilever sensors to investigate the elastic properties of biopsy samples in a fast and reliable way. Such a cantilever array approach reduces diagnosis times from 3 hours to minutes, allowing faster decision on the appropriate therapy. Rapid biomarker tests based on cantilever sensors complement information on the status of the tumor. The project is benefitting from its predecessor (PATLiSci in phase 1), where basic concepts of parallel force spectroscopy and nanomechanical biomarker sensing were validated. The approach here is to combine two complementary methods (force spectroscopy mapping for cell stiffness and nanomechanical cantilever sensing for biomarker detection) into a single instrumental platform, which can be handled easily. First, conclusive results on discrimination of breast cancer cells from unaffected cells in tissue using a single cantilever have already been demonstrated. For melanoma patient samples, RNA is extracted and investigated using nanomechanocal sensing with an array of cantilevers. Results make it possible to distinguish mutated melanoma cells from wild type tumor cells by detection of specific BRAF mutations, being essential to choose the appropriate treatment.

High performance portable 3D ultrasound platform. While ultrasound imaging is ubiquitous in medicine due to its low cost compared to other imaging techniques such as MRI—whose own challenges are addressed below—its image quality is usually poorer, and the high-quality devices that exist are expensive and aimed at hospital operation only. This is the reason why UltraSoundToGo is developing a prototype of next-generation, high-quality, and mobile ultrasound imaging device, while operating at a level of power consumption compatible with battery-powered operation on the field [5]. So far, an early version of compressive sensing applied to ultrasonic imaging was developed, as well as a novel image reconstruction technique that reduces pressure on the hardware memory interface. Regarding software implementation, a QoS-aware flow and a parallel beamforming algorithm were prototyped.

Wearable MRI detector and sensor arrays. The final outcome of the WearableMRI project is the introduction of wearable detection to MRI and thus to one of the most widely used imaging techniques in medical diagnostics and basic research. For MRI, the advent of wearable detection marks a pivotal transition away from its current paradigm of rigid, bulky detector arrays, which limit the technology in several ways. The new system has been successfully used for actual MR imaging of test objects and humans.

Environmental monitoring

Projects address both air and water pollution monitoring, as well as environmental sensing in mountainous areas, as described below. Three of these projects have extended over the two NanoTera.ch phases, by engineering novel enabling technologies established in the beginning.

Crowdsourcing high-resolution air quality sensing. OpenSense II addresses air-quality monitoring in urban settings, impacting the health of millions of individuals. It is innovative because the measurements happen *in situ*, essentially sampling the very same air volume citizens breathe. Leveraging mobile networks anchored to public transportation vehicles and deployed in the cities of Zurich and Lausanne, the project has produced highly original results on high-resolution urban air quality mapping. The two deployments were continuously improved over the project duration and they currently represent the longest-running testbeds of their type with the probably largest accumulated urban air quality dataset in the world. Furthermore, in the sustained effort to ensure data quality through cross-validation, the team implemented a highly innovative dispersion multilevel modeling framework which was applied to both cities, producing a collection of modeled air quality maps over a large temporal span. Finally, to

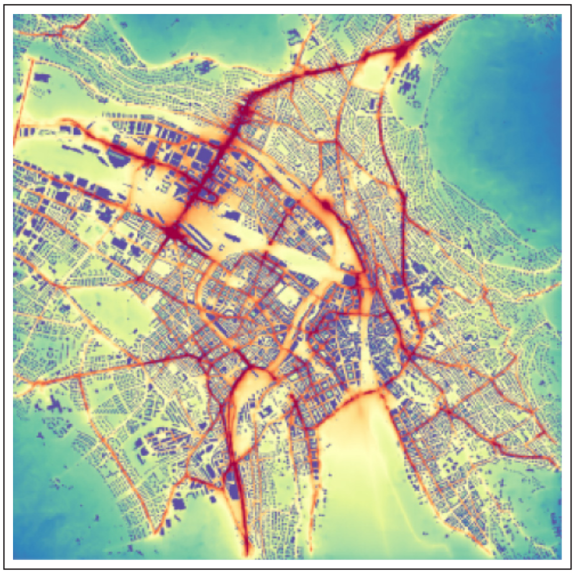

Figure 4. Air pollution monitoring plot.

enable the inclusion of crowd-sourced measurements, OpenSense II developed two novel algorithms: a rewarding mechanism for incentivizing good-quality measurements and an algorithm for characterizing sensor accuracies, while minimizing sampling cost and maximizing data utility. The impact of this project has gone beyond the research domain. Indeed some project outputs have already been recommended or adopted by authorities in the city of Zurich (Figure 4).

An aquatic robot that can "smell" polluting substances in water. The Envirobot project has built a swimming robot with environmental sensing facilities and combines novel sensors with aquatic motion. This enables both sensor data recording/transmission to a remote observer during predefined missions, as well as a form of self-guidance based on real-time sensory input. The self-guiding aquatic robot integrates physical, chemical, and biological measurements of water quality parameters. The robot consists of a 1.0-m segmented snake/eel with anguilliform movement, which causes less turbulence to the sample measurement. The latest self-localization systems permitted the Envirobot to follow a 1-km remote programmed track to within 2-m accuracy at cruise speed of 0.42 m/s on a lake. Prototypes of other sensor systems were fabricated (e.g., miniaturized pH and oxygen measurement), ready to be connected to the robot. Developed biological sensor modules for the robot include general toxicity measurements by Daphnia and fish cell lines, as well as light-emitting bacteria reactive to specific toxicants (e.g., mercury). Overall the Envirobot system is the first self-guiding aquatic robot capable of performing water quality measurements during short sampling missions (Figure 5).

Figure 5. The Envirobot anguilliform robot.

MEMS acoustic detectors for natural hazard warning systems. The X-sense II project, and its predecessor X-Sense, provide safety measures for communities living in alpine environments where rock and ice movement provides a threat. X-Sense II investigates a complete data acquisition chain from sensor technology over networking, data storage, and processing toward new discoveries in environmental sciences and new, more effective technologies for early warning from natural hazards [6]. The interdisciplinary team of X-Sense achieved major breakthroughs on several axes. The team investigated MEMS technology allowing for the partial relocation of signal processing and decision-making from the computing domain to the sensor itself. With this approach, for the first time, close to zero standby power is possible, which is a prerequisite for long term, unattended monitoring of spurious events. The monitoring system produced by the project provides data on slope movements and environmental conditions in mountain permafrost that is worldwide unique with respect to temporal resolution, coverage, and observation duration. The long-term, autonomous, and dependable operation of sensor networks in harsh environment mountain areas is unparalleled in the scientific community and it gathers important input for novel geophysical discoveries and early warning signals (Figure 6).

An all-in-one detection platform for air pollutants and greenhouse gases. Project IrSens II is a sensing platform for gas monitoring, specifically analyzing nitrogen dioxide as well as major air pollutants and greenhouse gases. The final gas spectroscopy setup allows us to simultaneously measure the concentration of 10 highly relevant greenhouse gases (CO_2, H_2O, CH_4, and N_2O) and pollutants (NO, NO_2, NH_3, SO_2, O_3, and CO) with ultrafast data acquisition. The setup reaches a precision comparable to state-of-the-art instrumentation, while reducing the footprint thanks to the use of dual-wavelength laser sources. The spectrometer produced can replace many power consuming and expensive conventional environmental gas sensors in air pollution monitoring and research stations. Moreover, the compact and portable gas detection is selective, fast, autonomous, and can be maintained via remote access. This is particularly valuable for obtaining temporally and spatially resolved data needed for future (urban) climate modelling and health studies. A first demonstrator for nitrogen dioxide detection was installed and operated on top of a tramway in Zurich, yielding hitherto unreached precision, selectivity and time resolution. City-wide air pollution maps were simulated using 1000 hours of unique spatially and temporally resolved data.

Figure 6. Rock movement detector and station.

Energy management

Energy management is deeply linked to environmental protection, namely, energy production and distribution as well as parsimonious use of energy for computing and communication.

Cost-effective and integrated solar-hydrogen generator. SHINE's goal is to develop the design principles and experimentally demonstrate a continuously operating solar-hydrogen generation system with an optimal working point in terms of fuel production cost. The key outcome of the project is the demonstrated 14.2% solar to hydrogen conversion efficiency based on commercially available, abundant, and affordable components. In the long term, the innovative designs for the electrolyzer, fuel cell, and self-tracking concentrators reported in this project can potentially lead a new class of electrochemical reactors and solar concentrators which are less expensive, long lasting, and more efficient. The development of economically viable technologies to produce fuels such as hydrogen, solely based on sunlight and water is one of many potential solutions, on a global scale, to transition from a fossil fuel economy to a renewable energy economy.

Systems for ultrahigh performance photovoltaic energy harvesting. The cost of photovoltaic (PV) modules recently dropped drastically, such that the overall PV system costs are dominated by nonmodule costs [7]. Improving the efficiency of the modules at only moderate additional costs therefore is the most straightforward pathway toward lower PV electricity prices. However, many established PV technologies reached efficiencies close to their practical limits. A promising, disruptive approach is to combine an established PV technology, such as a crystalline silicon or CIGS cell, with emerging technologies, including III–V nanowire and perovskite cells, to form a tandem device with the potential for ultrahigh performance. Project Synergy led to the demonstration of infrared-transparent perovskite cells with high efficiency to the realization of mechanically stacked and monolithically integrated tandem cells and to several efficiency world records in that research domain (Figure 7). The companion Gateway SynergyGate project has focused on bringing perovskite/silicon and perovskite/CIGS tandems closer toward commercialization by upscaling from the typical laboratory size (smaller than 1 cm^2) to 5 × 5 cm^2 substrates, using lightweight, flexible substrates, as well as by developing metallization, interconnection, and encapsulation schemes that are compatible with industrial processes.

Real time monitoring and management of smart grids. The project SmartGrid seeks to optimize the power grid through a hierarchical vision, from the individually monitored power consumption of electrical appliances, across the mid-scale "Microgrid" that optimizes small pools of consumers and at high level with high-speed electronics for power system dynamic emulation [8]. The team has developed and validated an online monitoring infrastructure for the grid. The research team demonstrated the feasibility of supporting phasor measurement unit deployments with standard TCP/IP technology while being secure and real time. This paves the way to an online control and monitoring for intelligent and renewable energy systems. The socioeconomic and technical barriers to this technology introduction were identified and solutions for several of those were provided. The study of the smart-building as a system beyond domotics and Internet of Things (IoT) technologies paves the path for sustainable smart cities and smart grid.

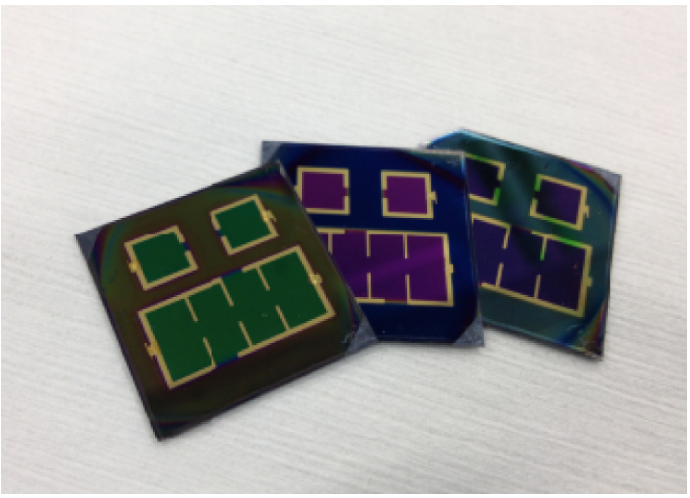

Figure 7. Tandem solar cells.

Thermal storage control. The project HeatReserves deals with the use of thermal loads as additional means for electricity grid ancillary services to account for the expected increase in renewable energy sources. The team has developed an integrated framework to enable the introduction of reserves from two types of thermal loads: heating, ventilation, and air conditioning systems of an aggregation of several office buildings, and a very large number of small household appliances. The economic and marketing case for both types of thermal loads was also investigated; in particular, thermal deviations acceptable by users and incentive schemes for enticing users to participate in demand response schemes were determined.

Green servers and datacenters. The YINS project aims at reducing energy consumption by introducing specific computing/storage server nodes and new cooling technologies, as well as improving system performance by accelerating inter-server communication [9]. Energy-efficient datacenters are strategic for Switzerland, as 75% of the Swiss economy is service based and depends on the datacenter infrastructure cost. Overall, YINS enabled datacenter providers, like BrainServe, to improve their energy efficiency by 30% on average, while guaranteeing reliable operation. Similarly, the energy consumption of Credit Suisse's datacenters was reduced by 35% on average in daily operation through the synergistic application of various techniques. Furthermore, larger energy reduction figures are expected in other businesses in Switzerland, where datacenter operations are less constrained than in the banking industry.

Inexact subnear-threshold systems for ultralow power devices. Project IcySoC targets

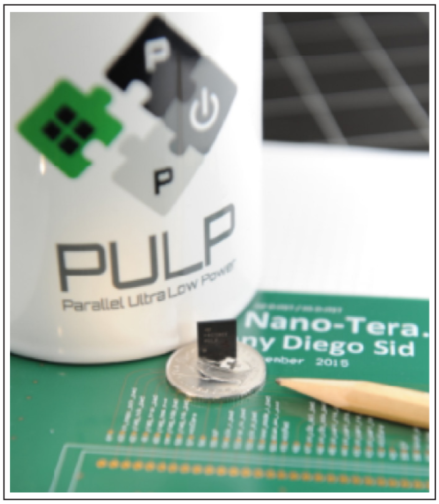

Figure 8. Ultralow power processor.

ultralow power near-sensor processing as a key requirement for many applications such as watch ICs, radio frequency identification tags, sensor interfaces, and emerging IoT applications. The main outcome of the IcySoC project is a toolset with a wide range of techniques and a platform that facilitates the design of such systems and alleviates the issue associated with low-voltage operation. As such, the technologies and building blocks developed in the project solve key problems in the design of a variety of different devices for different process nodes ranging from 180 nm down to 28 nm. Some technology building blocks and design tools (including the PULP platform) are also available as Open source hardware and therefore provides immediate benefit to industrial and academic R&D organizations (Figure 8).

This survey covers the most recent research activities of the Nano-Tera.ch program. These activities have demonstrated that cyber-physical systems—through the combination of sensing, electronics, computation and communication—can significantly improve health management, environmental protection, and energy consumption. Whereas most research projects have produced demonstrators that pave the way to commercial development and use, this research has just scratched the surface of a wide body of activities that give a new meaning to engineering sciences as enablers for a better society. ■

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