Nanosensors for industry, heart and bladder

The digitalisation of our daily lives and workplaces would be inconceivable without progressively smaller and more affordable sensors. At ETH Zurich, several research groups are working on new sensor concepts. Some of these might revolutionise medical technology.

TEXT Samuel Schlaefli

Christofer Hierold has been working in the field of microsystems technology and sensor integration for 30 years. The advances promised by Industry 4.0 don't really sound like anything new to him. “One of the goals is to enable the seamless monitoring of industrial production processes, but the semiconductor industry has been doing that in process technology for years,” the ETH Professor of Micro- and Nanosystems says. After all, it requires hundreds of process steps over several weeks to construct a silicon wafer with integrated circuitry – and a great many sensors are already employed to monitor the machines as this takes place. “The new and exciting thing about the ideas for Industry 4.0 based on digitalised processes is that we are increasingly seeking to achieve uniformly high quality for very small batch sizes, possibly even for batch sizes of one.” That means being able to guarantee that a single customised item can be produced to the same high quality standards as mass produced components. Such flexibility in production is made possible only by the smart linking of sensors in conjunction with the use of sophisticated algorithms. These algorithms are required so that the data recorded can be translated into information that is useful for process control. Hierold is convinced that factory floors will therefore become increasingly filled with sensors. Going forward, this might even apply to the goods produced. “In future, it's probably not just machines that will be fitted with additional and smaller sensors,” the researcher says. “Some day, the products, too, might have sensors on them to monitor quality during manufacturing.” Temperature or pressure sensors would then transmit data in real time about the current state of the product and potential faults in the production process. Production would certainly be more comprehensively monitored than it is today.

> “Production will be more comprehensively monitored.”
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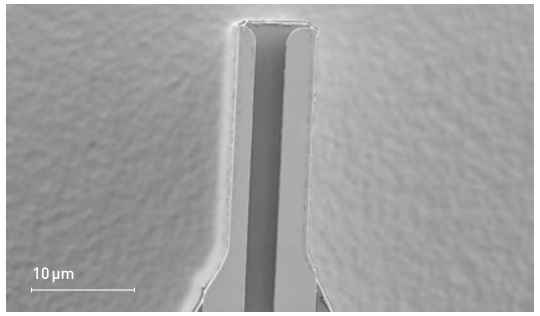
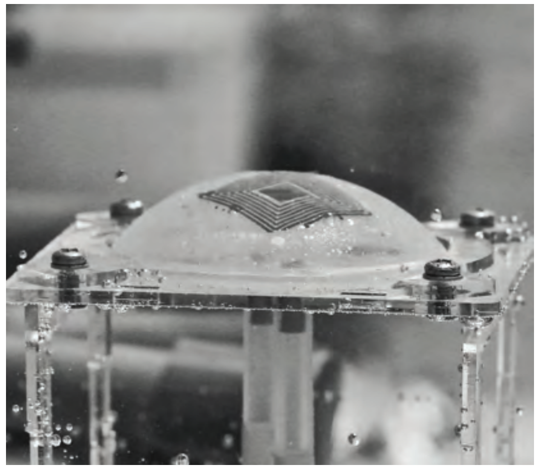
> CHRISTOFER HIEROLD

Superior sensitivity

If the above scenario is to become a reality, it will be underpinned by sensors that are smaller, cheaper and more efficient. That's exactly what Hierold is working on. One section of his research group is focusing on the development of nanoelectromechanical systems (NEMS). Sensors based on these are no longer visible to the human eye. Instead of using semiconductors, as is standard in sensor technology, Hierold builds his NEMS using carbon nanotubes. These are tiny tubes, typically two nanometres in diameter, which are made of graphene and very robust. They are characterised by their large surface area, which makes for highly efficient interaction with other molecules. Gases such as nitrogen oxides, which contribute to smog and ozone formation, can therefore be detected at very low concentrations. If single carbon nanotubes are used as a gas sensing material, only three microwatts of power are needed to take a measurement instead of the one to ten milliwatts previously required. “We can take measurements using a thousand times less power,” Hierold explains. As far as he is concerned, this opens up completely new possibilities. The sensors could use what is known as an energy harvester to derive the energy needed from their surroundings – by taking advantage of a temperature gradient, for instance, or by converting kinetic energy. “That would be especially practical for mobile applications such as smartphones, or for taking environmental measurements with widely distributed sensor networks,” Hierold says.



TINY BUT EFFICIENT Function module for carbon nanotube sensors to detect gases



BIOSENSOR The bladder sensor stretches along with the bladder and sends a signal to indicate the urine level

Nanosensors for health

Tiny, efficient and affordable sensors will also play a key role in the health system of the future. This is demonstrated by the vision of an “internet of humans”. Under the leadership of EPFL, ETH Zurich and a number of other universities are promoting the vision of a personalised, sensor-based healthcare and disease-prevention system in Europe. EU research funding is to be sought for such a flagship initiative. The aim is that, in future, sensors worn on the body will continuously record and evaluate health-related data such as blood pressure or heartbeat. In this way, it would be possible to recognise and treat symptoms of illnesses at an early stage. Those behind the initiative see digitalised prevention not just as a contribution to long-term health, but also as a potential means to reduce healthcare costs.

Microsensors will also play a central role in the inter-university Zurich Heart project. At present, researchers are developing new concepts for artificial hearts that can be used as an alternative to human heart transplants. Hierold's group is working on the system integration of a microsensor for monitoring and controlling such artificial hearts. “The performance of the heart must be able to adapt automatically to a patient's age, health and level of activity,” Hierold explains. To achieve this, his team is working with a standardly available pressure microsensor. However, they have to use biocompatible materials to protect the sensor because it starts to “drift” (i.e. its signals fluctuate over time) when it comes into contact with blood and other physiological fluids. Some day, they aim to integrate the pressure sensor into the in-flow cannula of the newly developed heart pump.

Stretchable bladder sensor

Researchers at the Laboratory of Biosensors and Bioelectronics (LBB) are also working on biosensors. As part of a collaboration with the University of Zurich and other partners, Professor Janos Vörös' group has recently developed a flexible sensor that one day might be used by patients with spinal cord injury to control the level of urine in their bladder. “For many patients, not being able to control their bladder is a more serious impairment than not being able to walk,” says Vörös. If patients have an overfilled bladder without being aware of it, urine flows back into the kidney and can cause devastating damage there.

Vörös' group is developing stretchable sensors, which are enclosed in a soft shell made of a biocompatible rubber (polydimethylsiloxane). The sensor is attached to the surface of the bladder, and, when the bladder fills with urine, it is able to stretch along with it. Stretching the sensor results in a measurable change of its electrical properties, which can be measured using RFID technology from outside the body, meaning that the sensor inside the body does not need its own battery. Researchers are currently testing the system on pig bladders, and testing

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Images: Sebastian Eberle, Micro- and Nanosystems Group; Laboratory of Biosensors and Bioelectronics

on live animals (incontinent dogs) is planned before applying the system in humans. In future, patients themselves should be able to use an app to monitor whether their bladder is full.

The "smart cable"

Vörös' work on sensor development gave rise to an unexpected by-product: unbreakable cables. In 2016, members of his group founded nanoleq, a spin-off which takes the stretchable, conductive polymer composites and adapts them for commercial use.* "Cables like these are particularly in demand for automated manufacturing processes – where robots repeat the same movement thousands of times every day, and the wear on cables is very high," Vörös says. He adds that nanoleq is already in contact with several major cable manufacturers. The young entrepreneurs want to take it a step further: they are thinking of a "smart cable", which will be in a sleeve fitted with microsensors so as to detect problems with materials in real time. Vörös still collaborates closely with the spin-off, and he says that the first prototypes are under development.

In the future, micro- and nanosensors might do more than oversee the way single items progress through the production process, as Hierold predicted. It may be that these sensors will soon monitor every single cable involved in that process. ○

Micro- and Nanosystems Group
→ www.micro.mavt.ethz.ch

Laboratory of Biosensors and Bioelectronics:
→ www.lbb.ethz.ch

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* The founders, Vincent Martinez and Luca Hirt, are Pioneer Fellows. Pioneer Fellowships are funded from donations to the ETH Zurich Foundation.
→ www.ethz-foundation.ch/pioneer-fellowships

3D printing unlimited: From tooth enamel to 4D printing

ETH scientists are constantly pushing the boundaries of additive manufacturing processes. They are mimicking production concepts found in nature and adding a fourth dimension to 3D printing technology.

TEXT Peter Rüegg

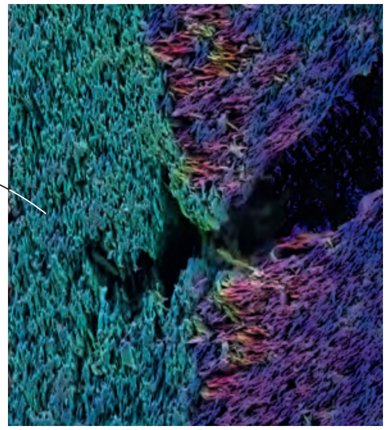
When asked which natural material he finds most fascinating, there's no hesitation in André Studart's reply: "Bone." He is Professor of Complex Materials, and he explains his fascination with bone by saying that it is tough and extremely durable, yet it also remains dynamic over the course of a whole lifetime since fractures or cracks always heal by themselves. Studart would love to replicate bone in his laboratory: he and his group specialise in biomimetic materials, which he prefers to produce using additive manufacturing processes (i.e., 3D printers).

In some ways, additive manufacturing processes simulate production concepts found in nature. "Basically, 3D printing and living cells construct material in the same way," Studart says. He explains that cells are constantly secreting organic or inorganic material, thereby building up a composite material layer by layer. In doing this, they produce materials in which the properties of individual layers change gradually. That is the way intervertebral discs are constructed, for example. These soft, gelatinous structures between the vertebrae allow for spinal mobility and act as shock absorbers. They have a tough outer shell that becomes softer as it goes in. "Additive manufacturing can replicate material gradients like this in a way that traditional processes just cannot do," the ETH professor emphasises.

He has already used additive manufacturing processes in his laboratory to simulate all kinds of natural materials, from mother-of-pearl to pine cones. One of the big successes is biomimetic tooth enamel, which Studart's colleagues produced using a combination of additive manufacturing and traditional casting techniques.

The researchers filled the plaster cast of a tooth with a suspension containing magnetised aluminium oxide platelets and glass nanoparticles as mortar. Using a magnet, they aligned the platelets perpendicular to the surface of the tooth. Once the first layer was dry, the scientists poured a second suspension without glass particles into the same mould. The platelets in this second layer were aligned horizontally to the surface of the tooth using the magnet. As a result, the researchers managed to produce an artificial tooth with the same layered structure as a natural tooth.

Studart's research group puts its success down to precise observation of natural models, an eagerness to experiment, and special printer inks. "We put our effort into developing print-ready inks, not machines," Studart says, and the 3D printers in his laboratory are commercially available machines. The researchers have recently adjusted this strategy, however, to include the development of new printers. This allows the group to fully exploit the potential of the unique inks that they have developed – which include a special ink that Studart has used for the 3D printing of extremely porous ceramic material. The ink is a ceramic suspension full of air bubbles or oil droplets, which is extruded using traditional direct ink writing techniques.



ARTIFICIAL TOOTH USING ADDITIVE MANUFACTURING
(cross-section) Ceramic platelets are aligned vertically in the enamel, but diagonally to horizontally in the dentine

This approach enabled the material scientists to print a multi-layered and close-meshed lattice structure, and so to produce a foamy yet robust ceramic material. This material could some day be used as a catalyst in the chemicals industry, in biomedicine, or indeed in the energy sector.

Enabling self-repair

Yet even with additive manufacturing processes, replicating bone has remained a hard nut to crack. "It's one of my greatest ambitions to produce a bone with a 3D printer," the professor says.

He also says that one problem with imitating bone is that, unlike the genuine article, artificial structural materials usually do not contain any living cells – cells like osteoblasts and osteoclasts that are responsible for the exceptional ability of bone to heal itself. One possible remedy is to incorporate microcapsules into the ink. These could contain a solution that leaks out when exposed to high pressure and repairs any structural damage. Unfortunately, this approach only works once. That is why Studart is conducting experiments with special inks capable of releasing "healing" substances in the printed material more than once. However, he is still a long way from having found a solution to the problem posed by bone. "The challenge is enormous," he says.

THE FOURTH DIMENSION
This object is printed flat and can later be reconfigured into other stable and load-bearing forms

4D printing is the next step

How to imitate natural materials is not a research focus for Kristina Shea, Professor for Engineering Design and Computing. Instead, she is looking to add a fourth dimension to 3D printing: time. The objects developed in her laboratory are printed in two dimensions by multi-material 3D printers that can print up to 40 different materials at the same time. Although printed flat, these objects can be reconfigured into three-dimensional forms at a later point. "The objects do not change their configuration randomly, but rather

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Image: Hortense Le Ferrand, Professorship Complex Materials; Tian Chen, Engineering Design and Computing Laboratory