ETH GLOBE

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Robots ahead!

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Main building of ETH Zurich (Photo: ETH Zurich)

ETH Zurich – Federal Institute of Technology Zurich

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Dear readers

Roland Siegwart, Vice-President of Research and Corporate Relations (Photo: Giulia Marthaler)

Will robots soon be our companions in daily life? Look after us when we're old? Improve or take over our lives? All these questions were already a central theme in the literature and especially science fiction films of the mid-1900s.

In science fiction, robots are primarily the product of the imaginations of creative authors and film-makers. The technical fascination with humanoid machines, however, dates back to the 18th century. The first automatons emerged around 1750 in the workshops of clockmakers in Grenoble and the Jura mountains in Switzerland and still capture our imaginations to this day. These machines were not intelligent as such, but they could play music, write or draw. The ultimate automaton, called "Pouchkine", was unveiled last autumn by the world's premier automaton-maker, Swiss François Junod. Thanks to "mechanical" intelligence, he can write over 1,400 poems.

After the introduction of the first industrial robot, Unimate, and the subsequent incorporation of robots into industrial production, intelligence took the centre stage in robotics. For many years, the research focussed on classical artificial intelligence, which endeavours to model the full complexity of a system, but it was unfortunately unable to live up to the high expectations. Then, in the mid-1980s, a group of nerds headed by Rodney Brooks triggered a minor revolution with the idea of behaviour-based artificial intelligence and neuronal networks. Unfortunately, however, these approaches did not bring about the rapid progress in artificial intelligence and robotics they had hoped for, either.

Nevertheless, intelligent autonomous robots have come on in leaps and bounds in the last fifteen years – largely thanks to advances in sensor technology (laser distance sensors, digital cameras) and the exponentially increasing computing power. This meant that the probabilistic methods of Thomas Bayes from the 18th century suddenly became applicable and computationally implementable on complex systems. Coupled with new methods from machine learning, robots that can drive autonomously in road traffic or perform basic tasks in everyday life are now feasible. However, we are still a far cry from robots whose intelligence is anywhere near that of humans.

ETH Zurich is one of the leading universities in robotics. Indeed, Switzerland in general is excellently positioned in this field – not least with the new National Centre of Competence in Robotics, which ETH Zurich is closely involved in with various projects. The aim is to develop robot technology with humans in mind that will improve our quality of life.

This issue of ETH Globe visits researchers and their robots in the lab and features the smallest robots in the world, intelligent mini-helicopters, bio-inspired walking robots and much more. Delve into the fascinating world of robotics!

Roland Siegwart
Vice-President of Research and Corporate Relations, and professor of autonomous systems at ETH Zurich

ETH Zurich's robot "Europa" on a test run through Zurich's main railway station. Passers-by may one day use him as a tour guide or flexible helper by giving him instructions via a touchscreen. Where's the nearest ATM? No problem for "Europa": he'll lead the way – and even carry your heavy shopping bags if need be. (Photo: Roland Tännler)

Robots – our clever helpers

Christine Heidemann

They make coffee, milk cows and mow the lawn; work as teachers, actors and therapists. They scout hostile territory, rough terrain and distant planets: Robots are the unsung heroes of everyday life. They have slipped out of the robotics labs and into our lives almost unnoticed to relieve us of monotonous or dangerous tasks or go where we cannot.

Science fiction? No. Robots were already used to look for people buried in the rubble of the World Trade Center. They are deployed as scouts in Iraq and Afghanistan and step in wherever society has reached its staffing limits, such as in care for the elderly for instance. Often, we don't even know we're surrounded by them: Who would have thought automatic distance regulators in cars were actually robots, for example?

Some of them are so tiny they are invisible to the naked eye; others look so human it's uncanny. But like it or not, we have to make friends with them. After all, gone are the days when we just needed them in industry, tirelessly bolting and welding away on the assembly line; nowadays, we require flexible, dynamic service machines that can respond to the unexpected like humans and display a certain degree of intelligence. This is where the really exciting part of robotics begins – the area that's the focus of this issue.

Surgeon and partner substitution

Almost 80,000 service robots are currently in commercial use all over the world. They inspect turbines, perform minimally invasive surgical procedures or sweep for mines. This figure is expected to double in two years. In the private sphere, umpteen million already crawl, roll or totter their way around our homes as autonomous vacuum cleaners, lawnmowers, toys and learning aids. The machines are even available as a partner substitute these days.

Consequently, the work these metal servants do can't exactly be called slave labour. Even if that is precisely what the word "robot" means: It comes from the Czech for serf labour (robota) and slave (robotnik). The word was introduced by Czech author Karel Čapek in the early twentieth century. He wrote the play *R.U.R.* (Rossum's Universal Robot), in which intelligent machines created by humans as a workforce rebel against their creators and wipe out the human race. Čapek called these machines "robots".

However, people were dreaming of robot-like entities long before Čapek's time. Take Hephaestus, the god of fire and blacksmiths in Greek mythology, for instance, who built artificial maidservants out of gold. Then, in the last century, robots frequently appeared as protagonists in the world of fantasy and science fiction and became famous the world over – such as the droid R2-D2 in the space epic *Star Wars* who could repair spaceships like a mechanic.

Every culture has its robots

However, the robots created for the real world sometimes enjoy a cult status, too – especially in Asia, where society is the least afraid of coming into contact with the machines. The cuddly robot seal Paro from Japan, for instance, has taken retirement homes all over the world by storm. With its big, moving eyes, soft fur and heartrending whimper, it reduces – as studies have proven – stress, boredom and loneliness: a robot as a therapist and family substitute all rolled into one. As of recently, robots are no stranger to the visual arts, either: Renowned roboticist Hiroshi Ishiguro from Osaka University, for instance, created the lifelike actress Geminoid F for a play. Prior to this, he had even built a clone of himself – an android twin made of metal and latex which he likes to send off to lectures and meetings in his place. And Korean schoolchildren now already are being taught by electronically controlled teachers.

Robots can't get human enough for Asians. And so robotics researchers there are increasingly perfecting humanoids. In the US, however, the topic of artificial intelligence is right at the top of the research agenda. Robotics research is thus primarily carried out in the artificial intelligence labs at prestigious universities like Stanford or the Massachusetts Institute of Technology.

It's a very different story at ETH Zurich: The robotics engineers here have specialised in designing robot systems, which focus more on the function of the machine than its appearance. This seems to be less important to European users, as a recent survey shows: Robots don't have to resemble humans, just so long as they serve their purpose. And they do so in multitude of ways, as a glimpse into the labs at ETH Zurich's Institute of Robotics and Intelligent Systems impressively reveals. In the following, ETH Globe takes a peek over the roboticists' shoulders and asks one of the most renowned robotics researchers in Europe about his visions – a thrilling foray into the world of the robots of today and tomorrow.

This fragment is a microrobot. He moves into the eye and administers medication locally. (Photo: Roland Tännler)

Minirobots passing through

In the past engineers primarily built bridges and other monumental constructions. Nowadays, however, they build machines on a micro- and nanometre scale. The minirobots developed as a result could one day revolutionise medicine.

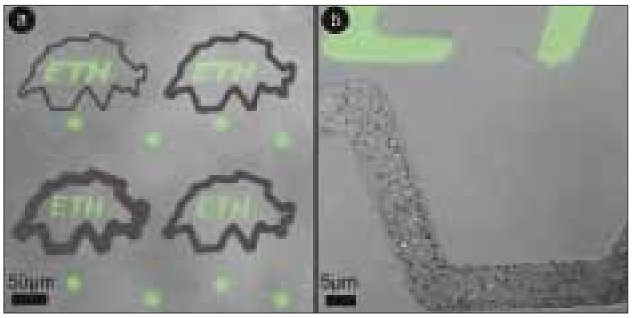
Samuel Schläfli

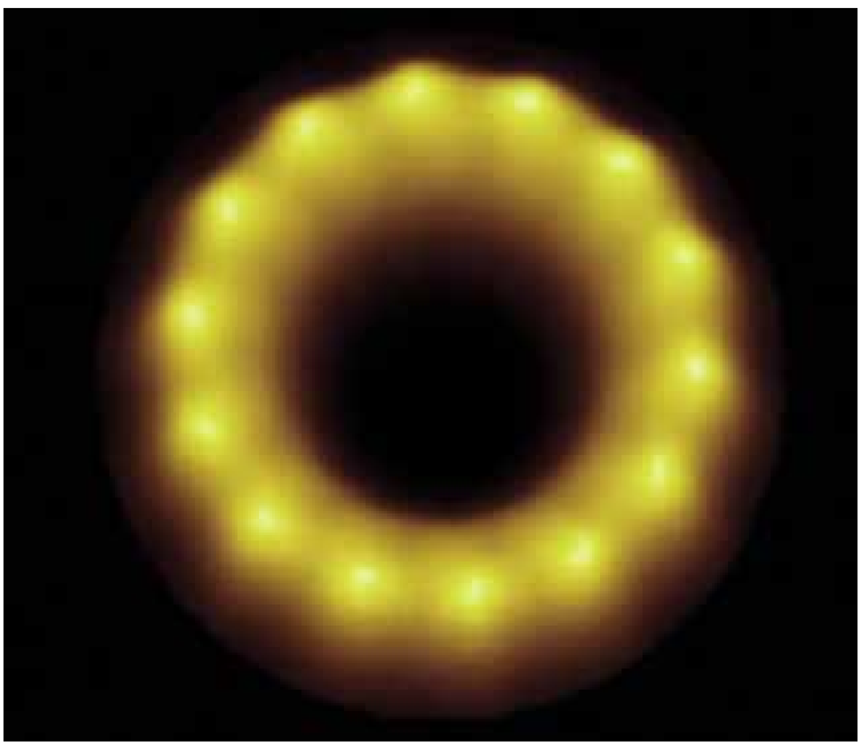
Only a few micrometres in size, the robot has an adventuresome mission ahead of it. It begins in the urethra. The tiny machine then swims until it reaches a wide opening: the bladder. It crosses a major part of the bladder cavity before arriving at the ureter, which departs at an oblique angle. It drifts along the ureter and into the kidney, where it crushes the located kidney stone by means of ultrasound. Mission accomplished. This is more or less how roboticists today envisage the medicine of tomorrow. Microrobots barely visible to the naked eye could one day provide an alternative to invasive surgical or catheter-based procedures. And they could reach parts of the body that surgeons can't get at today with their tools – such as the brain. They would be injected into the spinal chord and move up the spine towards the head. Apart from the safety requirements one of these robots would have to meet, the physical challenges on the way through the body are tremendous: "If we develop robots on a microscale, the basic physics to control it remains the same but the significance of certain effects like viscosity and electrostatics changes greatly", says American Bradley Nelson, who has been involved in microrobotics for 14 years. In 2002 he was made a professor of robotics and intelligent systems at ETH Zurich and has built up an interdisciplinary team of engineers, computer scientists, biologists and chemists. He describes himself as an engineer; his work should help solve practical problems.

Manoeuvring active substances through the eyeball

Nelson is convinced: "The first applications for microrobots will be in medicine, particularly for eye diseases." Part of his 25-men team is currently perfecting a microrobot which should help surgeons treat age-related macular degeneration (AMD). The disease is currently the biggest cause of blindness in over-50-year-olds in industrialised countries, with 30 million people affected by the disorder. The most famous active substance against AMD, Lucentis, is injected straight into the eye and has an effect for several months; non-specific and more or less effective. However, too big a dose increases the eye pressure and causes unpleasant side effects. The chances of recovery would be better and the risks fewer if the substance could be administered locally on the damaged part of the retina. Four years ago Nelson's team presented a new system that can be used to inject pharmaceutical substances into individual small blood vessels in the eye. The microrobots – tiny cobalt/nickel splinters that are barely visible to the naked eye – are controlled by magnetic fields applied outside the eye. Here's what a typical scene in the scientists' lab looks like: A synthetic eye or a cow eye fresh from the butcher's is clamped under a microscope with eight copper magnetic coils arranged around it. Once the microrobot has been injected into the eye, the researchers can control him via the direction and gradient of the magnetic field.

The researchers have the controls down pat by now. However, many issues are still unresolved as far as biocompatibility is concerned. How tolerable is a splinter like this in the eye? This is particularly important if the metal splinter is supposed to remain near the *Macula lutea*, the point of the greatest acuity of vision, on the retina to administer the active substance it contains at intervals. However, the researchers are severely limited in their choice of biocompatible materials. They have to be sufficiently magnetic so the robot can still be controlled externally. An internal drive via batteries is not an option; on this scale, they would not be able to generate enough power for the controls. Consequently, part of Nelson's team is looking into other potential "motors" on a micrometre scale. The scientists are looking to microorganisms for inspiration. After all, to guarantee their survival in the competition among species, they have developed techniques to move with the minimum expenditure of energy. In studying bacteria, for instance, the researchers have come across flagella, a kind of tail which bacteria use to swim through cellular fluids by rotating them: "When we took a closer look at the fluid dynamics of these flagella, we suddenly realised how efficient this motor is in propelling tiny items through liquids", says Bradley Nelson enthusiastically. As it stands, the researchers are still unable to build a 45-nanometre motor like the one bacteria use to move their tails. But using semi-conductor metals, they have managed to recreate flagella measuring 25 to 60 nanometres. If a piece of





Glimpses into the nanoworld

(Picture top) Together with her doctoral student, Claudia Schmidt, Viola Vogel has proved that loading and unloading molecular shuttles works on a glass slab only a few square micrometres in size. She placed gold nanoparticles along the edge of a map of Switzerland. Molecular shuttles then transferred the particles across Switzerland and unloaded them on the site of the imaginary ETH Zurich. (Photo: Viola Vogel)

(Picture bottom) Shot of the proton-powered rotor of the ATP-synthase made of spinach. The rotor uses the energy of the proton gradient to turn mechanically, thus driving other processes in the cell. The rotor has an outer diameter of about six nanometres. (Photo: Daniel Müller)

magnetic nickel is vapour-deposited at the tip and an external rotating magnetic field applied, the spiral begins to turn and the body swims. Using the magnetic coils mentioned earlier, the tiny bodies can be navigated through liquids – and with a considerably weaker magnetic field than with cobalt/nickel splinters at that. According to the scientists' vision, in future shoals of artificial flagella loaded with active substances could be manoeuvred to the point of application – such as in the eye. Nelson and his team opted for semi-conducting metals because their processing steps can be controlled the best on a nanometre scale. As far as their compatibility in the body is concerned, however, synthetic materials would be better suited. The scientists are currently working on this in the hope that they'll be able to test the system for the first time in animal experiments in two to three years.

Nanoscale rail cargo

Although researchers have been recording their first successes in engineering microrobots and their motors in recent years, it's still early days yet for the nanoscale. The smaller robots and their motors become, the more scientists rely on the existing elements and principles from nature. Viola Vogel, a professor at the Laboratory for Biologically Oriented Materials Science, thus extracts "motors" for engineering nanorobots from biological cells. "Millions of biochemical nanomotors propel people and every other living thing on Earth", explains Vogel. The energy is produced by splitting adenosine triphosphate (ATP) with water (hydrolysis), whereby chemical energy is converted into mechanical energy. Our bodies use such motors to form biomolecules needed for life, such as DNA or proteins. At the same time, they transport vital substances within the cell with an enormous degree of temporal and spatial precision. Vogel's team extracts such motors – molecules measuring about 70 nanometres in length – from bovine brains as they are found in particularly high concentrations in nerve tissue.

Last July the scientist presented a possible application for the extracted biomotors in a hybrid system: Using so-called "molecular shuttles", Vogel succeeded in transporting gold pellets measuring 40 nanometres in size. Her team prepared a kind of carpet made of motor proteins (known as kinesins) that had been isolated beforehand. These are propelled with chemical energy released during ATP hydrolysis. Microtubules were carried across the carpet with the mechanical energy of the motor proteins. On a specially prepared loading station, they took a gold particle and deposited it on an unloading station. The loading and unloading mechanism is based on two DNA strands that interlock like hands. Vogel's team succeeded in manipulating the DNA in such a way that the hands grasp at the right moment and let go again in time. For this to work, the researchers first had to understand the dynamics and kinetics of the loading and unloading mechanism down to the last detail and calculate the necessary strengths of the bonds exactly.

Vogel describes the system as "nanoscale rail cargo". In future, entire manufacturing chains only a few nanometres in size could be formed with such nano-assembly lines, the researchers believe. Another idea is the development of self-constructing or "self-healing" robots. The assembly lines could autonomously transport synthetic components from depots to the target sites, such as to defective sections, in order to repair materials. "We understand the physics of the nanomotors relatively well by now. However, which molecules are best suited for particular applications is still largely unclear", says Vogel. In order to gain inspiration for new ideas, she and her team are following the current literature from physics, chemistry and biology.

The doctor in the nanocell

Promising impulses for nanorobotics are also coming from synthetic biology at the moment, including from the Department of Biosystems Science and Engineering (D-BSSE) founded in 2007. Daniel Müller has been a professor of biophysics there since last year. He also heads the EU project "Nanocell", in which researchers from all over Europe are involved. The aim of the project is to build a nanorobot that is entirely composed of existing biological machines – none of them bigger than two to five nanometres. Like Bradley Nelson's microrobots, Müller's "nanocells" are one day to be manoeuvred towards any number of points in the body to administer medication, suck away toxic pollutants or activate particular biochemical processes. Müller is looking to isolate components that perform precisely this kind of tasks from biological cells. "It makes no sense to build completely new machines on a nanoscale. Nature has developed hundreds of thousands of them over millions of years that are far more efficient than any machine humans have ever built", explains Müller. So-called vesicles should one day serve as the carrier for the machines. These are football-shaped lipid bubbles with a diameter of 50 to 100 nanometres that are loaded differently depending on their medical assignment. The ball is driven and controlled by proteorhodopsin, which the researchers extract from sea plankton. This carotene-containing protein absorbs light and uses the energy to pump protons within the vesicle to places richer in energy. This gives rise to a "proton gradient", not unlike a water gradient in reservoirs. The "machines" in the vesicle are propelled with the built-up energy to move the nanocell or perform medical tasks, for instance. In simpler terms, we can imagine it as follows in practice: As soon as you hold a torch to the point in the body where the nanocells have been injected, the proton pumps start up and the tiny doctors head towards the light. There, they carry out the task they have been pre-programmed to do, such as remove toxins or produce active substances to fight an infection. If the light is switched off, the nanodoctors become inactive and are broken down by the body without any harmful by-products.

But we are still a far cry from this: During the three-year EU project, purely basic research is to be carried out. "We want to work out the engineering principles, so we can use them to construct cells like these with systems-biological tools in the future", says Müller.

The boundaries between robots in the original sense and high-tech medication is thus increasingly disappearing. Micro- and nanorobots have to combine approaches from biology, physics, chemistry, materials science and engineering to find new solutions. In this, they are inspired by the wonders of evolution, which after all is not exactly new: "In the whole of nature, there isn't a single thing to be taught; it's full of masterpieces", as the German writer Johann Peter Hebel once said.

→ www.iris.ethz.ch/msrl/research/
→ www.nanomat.mat.ethz.ch/research/
→ www.bsse.ethz.ch/biophysics/research/

No, not a visit from outer space, but the test flight of a flying robot developed at ETH Zurich's Autonomous Systems Lab. One day, it could well be a common sight in our skies along with other "hexacopters", as the six-rotor aircraft are called, as they monitor major events, for instance.
(Photo: Roland Tännler)

Autonomous highfliers

The days of the inflexible robot, stubbornly following a plan, are over. The future belongs to autonomous machines that interact with their environment, learn from experience and adjust their behaviour accordingly; an enormous challenge that ETH Zurich's engineers have also set themselves – with smart ideas that are already giving us a taste of how robots will change our lives one day.

Christine Heidemann

The idea sounds tantalising: Instead of battling your way through the evening rush-hour traffic jams in your car to get to the nearest shopping mall, all you need do is hop on your little private helicopter, tell it where you want to go and it'll take you there.
A dream of the future? Yes. Impossible? Certainly not; for this service is what the scientists involved in the EU project "myCopter" have in mind. They are looking to develop autonomous flying vehicles that everyone can use to get to work or down the main shopping streets comfortably. No chorus of car horns, no fuss – all to reduce congestion on roads and the strain on the local traffic. Along with one British and three German research facilities, EPF Lausanne and ETH Zurich are also involved in the project. The latter is represented by the Autonomous Systems Lab – the lab at ETH Zurich where this type of independent, autonomous machines is being developed and built: robots that know where they are, what lies in store for them and how they have to react.
Millions of autonomous robots are already in use all over the world, and the expectations for the future are high: supposedly, robots will look after us when we're old or sick; relieve us of irksome household chores; carry out inspections; operate, treat and teach; give advance warnings of danger; deactivate bombs and mines; and track people after disasters.
Much of this they already do; but sometimes they still find these tasks quite hard. After all, a machine acts differently to a person. And so roboticists all over the world are busy making the electron brains even smarter. But just how clever and human can, should and need robots be? One thing is certain: If they are to live up to the expectations placed upon them, they have to be able to interact with the real world. First of all, they must be able to navigate reliably in an environment – a skill also needed for "myCopter". The experts at ETH Zurich will be focusing on how the private aircraft of the future can park in urban canyons without crashing into a building. The team under Roland Siegwart, robotics professor and head of the Autonomous Systems Lab, is responsible for the especially critical moments in the project: the autonomous take-off and landing of the flying objects.

The ideal path

In particular, the interaction with a constantly changing environment is an enormous challenge in robotics, says Martin Rufli. The doctoral student from ETH Zurich is the planning expert at the lab. He makes sure an autonomous robot reaches its given destination as quickly as possible without injuring anyone or crashing. In addition, he programmes the machines so they can constantly make proper use of the information they receive via their sensors, such as cameras or distance meters – which is easier said than done: How do I tell a person from a wall? What things can or can't I run across? Problems that humans solve instinctively pose major difficulties for robots – especially outside, in unknown territory. After all, unlike for navigation inside buildings, where the environment is structured by straight walls, doors and level floors, outdoors robots come up against considerably more complex obstacles and objects: The shape and surface of trees or bushes is irregular and changes with time, and influences like the wind are difficult to describe with clear mathematical models. What's more, plans are available for every building; in dense woodland or underwater, however, there often aren't any maps. The robot has no access to GPS. In order to find its bearings, it has to determine its position by itself.
One successful method is called SLAM (Simultaneous Localisation And Mapping), where the robot uses its sensors to get an idea of the surroundings by identifying particularly prominent features of the landscape and creating a map. Simultaneously, it estimates its own position in relation to the mapped objects with the aid of a mathematical model. The researchers' aim is for the robot to recognise these specific landmarks on subsequent missions and be able to use them as a guide. "Europa", the robot featured on the cover of this issue of ETH Globe, also takes its bearings from a SLAM module. One day, he should serve people as a clever tour guide and flexible helper; help old ladies across the street, carry crates of beer or give directions to the nearest ATM: With its touchscreen, "Europa" provides a service at the touch of a button.

Approximately one and a half metres tall and weighing in at 50 kilograms, the robot is the culmination of the eponymous EU project named after its star. The somewhat conventional-looking metal assistant on wheels is the dominant figure in the office of the two ETH Zurich engineers Rudolph Triebel and Jérôme Maye. Together with the planning expert Martin Rufli and other members of the team, they both breathe something approximating intelligence into the machine. The main challenge here is that "Europa" is one day supposed to be able to find its way in extremely dynamic environments – especially in pedestrian precincts or at airport terminals and railway stations, where people, bikes and cars will constantly come into contact with it and muddle its algorithms.

Robot confused by people

"Suddenly, all it sees is moving objects and no longer knows what belongs on its map or not", says Rudolph Triebel, explaining the problem. When a person stands in one place for any length of time, such as in front of a shop window, for instance, the robot registers them as wall and already his map is wrong. Therefore, it has to learn to recognise and gage people and the direction they are going in correctly if it is to avoid bumping into them. For the time being, however, "Europa" will mostly be confined to the Autonomous Systems Lab. The ETH Zurich engineers are testing, among other things, a new sensor combination made up of three cameras, a 3D laser and three 2D lasers, which even enable "Europa" to look behind itself. "The robot can follow what it has seen with the cameras on the laser scan and see where a person is going", explains Rudolph Triebel. At the same time, using a special algorithm it can predict where someone it has detected might head several seconds in advance and then avoid them accordingly. It does so by using their line of vision or present path as input.

The metal tour guide is also supposed to learn which objects are important for planning its journey, such as traffic lights, curbs or crosswalks, and where they are.

If, using its sensors, the robot registers especially heavy flows of pedestrians on a grid square on its map it should conclude: I have to cross the street along with everyone else. "Europa" is also supposed to delete errors and irrelevant information from its electron brain. After all, Rudolph Triebel says, "Even a robot needs to be able to forget." Otherwise, it would end up correcting faulty information unnecessarily later on. "We're trying to make it as intelligent as possible so it'll be accepted by the users", adds Jérôme Maye. Robots that can only make coffee, for instance, would quickly be branded boring. The savvier it is, the more attractive it will be.

Function before beauty

The Zurich engineers let the task to be performed dictate the appearance of their service machines. "We always try to define the design of our robot systems by their role", says Lab Head Roland Siegwart, explaining ETH Zurich's philosophy for building autonomous robots. And the researchers are on the right track, at least in Europe: According to surveys, unlike the Japanese, Europeans don't have quite such a soft spot for humanoid robots; the main thing is that the machines do their job.

The flying robot experts in the offices next door to the "Europa" team are also perfecting a design that's just the ticket for what they need. Among other things, they are developing autonomous mini-helicopters designed to check the combustion chambers in coal-fired power plants for defects as artificial inspectors, for instance. Power plant inspections are labor-intensive and costly; a prime example of the possible areas where the artificial workers might be used – and the enormous demands upon their designers.

What the private vehicle of the future might look like: Scientists involved in the EU project "myCopter" are perfecting flying objects that may one day fly their users autonomously to work or the shops.
(Photo: Prof. Gareth Padfield, Flight Stability and Control)

"We want to demonstrate for the first time that a helicopter can approach a surface in a controlled fashion", says doctoral student Christoph Hürzeler, describing the major challenge the EU project "AIRobots" faces. After all, if they are to be able to inspect combustion chambers for cracks using special sensors, the robots will need to fly right up to chambers. Christoph Hürzeler and his colleagues are trying to achieve this controlled approach with so-called coaxial helicopters – helicopters with two contra-rotating rotors mounted one above the other – which should give the flying inspectors the composure and stability they need.

The four-legged robot a.l.f. (an autonomous walking robot with springs), which was developed at ETH Zurich, during a field trial in a crater in Tenerife. Mobile machines like this could one day explore Mars, for instance. The robots wear cuffs to protect them from dust. (Photo: ETH Zurich)

Intelligent drone fleets

Yet another form of machine intelligence is the order of the day for the colleagues working on the EU project "sFly". The aim is to enable mini-helicopters to monitor major events as a drone fleet or provide information on the magnitude of disasters. The "sFly" hexacopters with their six tiny rotors look more like flying saucers than helicopters. After all, they need to be small, flat and light to enable them to manoeuvre their way through narrow passages when they are in towns, flying low. Consequently, for weight reasons, instead of having distance sensors on board like larger robots, they are only fitted with a little camera. The flying saucers thus have to calculate the distance to potential obstacles or objects solely using camera information. Moreover, one day they are supposed to communicate with one another and/or a base station in order to deliver the data required to their clients as quickly and accurately as possible. But how many mini-choppers do you need to cover the area in question as fully as possible? And how will the system react to changing lighting conditions? These are just two questions the "sFly" experts are looking to answer within the next year.

Meanwhile, at the neighbouring desk Stefan Leutenegger is preparing for a long stint: The ETH Zurich doctoral student and two-time Swiss gliding champion is developing an autonomous solar aircraft the size of a model airplane that could one day look for people who've been in accidents or monitor areas at risk from forest fires around the clock. Stefan Leutenegger also wants to make his robots "more intelligent", as he puts it – among other things by fitting them with a thermal imaging camera which the robots can use to recognise terrain at night, avoid obstacles and at the same time identify fires or people in good time.

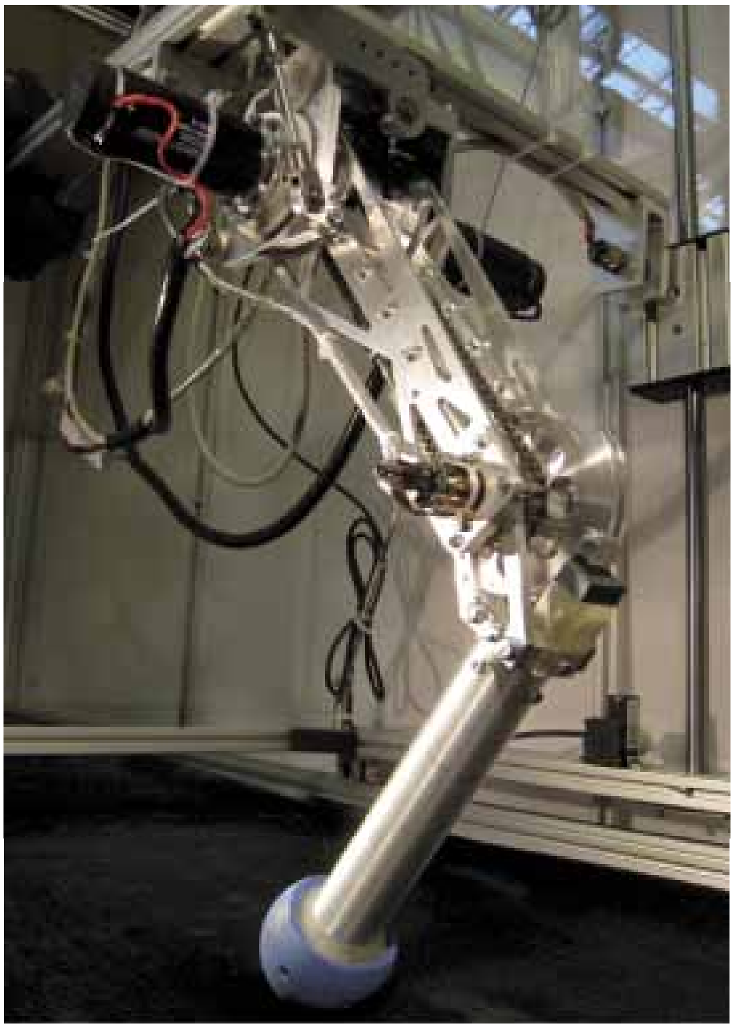
Giving the robot a leg up

A couple of offices further on, a leg runs back and forth in a glass case. The same scene greets the onlooker as in every room at the Autonomous Systems Lab: Next to the computers lie cables, wires, plugs and slips of paper; all over the place, people are testing, assembling and adjusting things. In this case, for a new, highly flexible, energy-efficient leg for walking robots – according to Lab Head Roland Siegwart, the most advanced electrically driven robot leg in the world. With the aid of built-in spring elements, as the experts responsible, David Remy and Marco Hutter, explain, it can store energy – much like the muscles and tendons in a human leg – and thus walk much faster and jump higher than other robot legs. Moreover, due to the sophisticated knee and hip design, the leg can also bend fully, thus making it ideal for climbing over even difficult obstacles.

And it can move along in a force-controlled motion, as it is known in the technical jargon. This means it reacts flexibly when the ground changes, just like its human counterpart: The sensitive leg senses obstacles and adjusts its position accordingly. In the near future, the ETH Zurich researchers want to make legs for a dog-like walking robot.

Such flexible companions could one day provide emergency aid in rough terrain, deactivate mines or explore distant planets. The leg principle can also be used in prosthetic limbs or flexible robotic arms for industry.

The example shows that robot intelligence is not just based on sophisticated algorithms but also as perfect a robot body design as possible, which saves the machines a lot of brainwork and therefore computing power. This is also the credo of roboticists who take their inspiration from biology. One of their most famous representatives is Rodney Brooks, who ran the Artificial Intelligence Laboratory at the renowned Massachusetts Institute of Tech-



The most advanced electric robot leg in the world: Thanks to built-in spring elements and a sophisticated knee and hip design, it can conserve energy, much like the muscles and tendons in a human leg, and even negotiate difficult obstacles. (Photo: ETH Zurich)

nology, or MIT for short, in Boston until 2008. How else, he argues, can you explain the behaviour of insects, which are able to move quickly and skillfully despite having tiny brains, if not through a good body design? They often don't need a map or representation of their environment; they simply act instinctively. By the same token, robots could also act directly according to their sensor data.

Instead of painstakingly serially connecting different mathematical modules, in the late 1980s Brooks built the first robot whose behaviour was determined by the interaction of many relatively simple behaviour patterns with each another and the environment – a method that is still the talk of the roboticist community to this day.

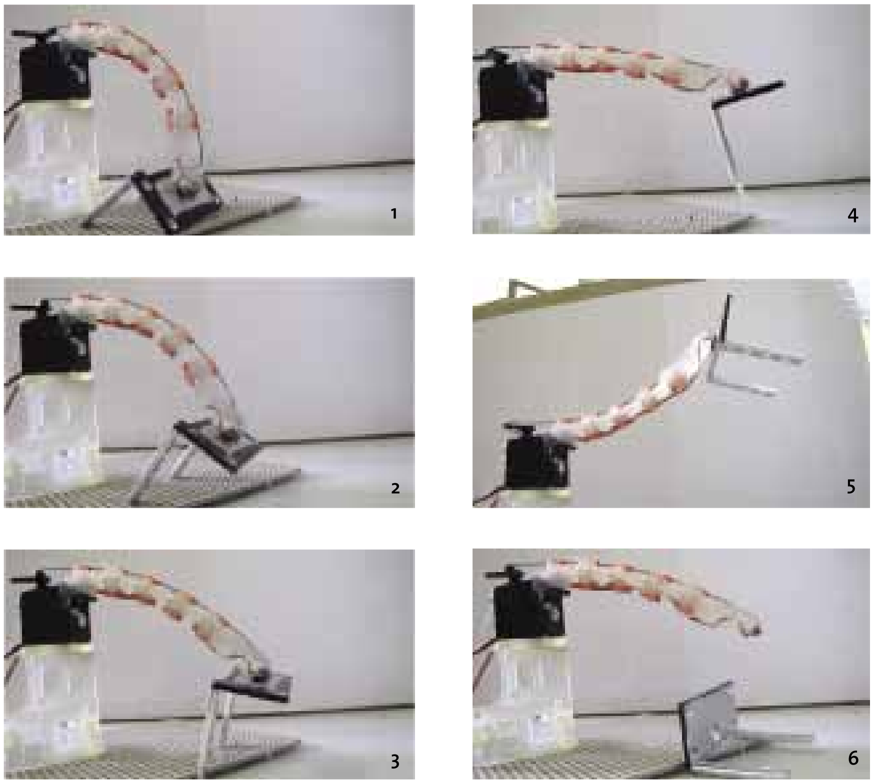
Inspired by nature

Professor Fumiya Iida spent two years at MIT in the office right next door to Brooks'. Today, he runs ETH Zurich's Bio-Inspired Robotics Lab. He, too, is busy perfecting the robots of the future with his team. Unlike his "autonomous" colleagues, however, the Japanese scientist draws his inspiration entirely from nature. Under the motto "Nature is the best teacher", on the one hand Fumiya Iida wants to design robots more efficiently based on nature's model; on the other hand, however, he is also looking to understand nature better through abstraction of the design principles of biological systems and recreating them using robots.

For example, he wants to help biologists find out more about the role of muscles in locomotion. "We're not interested in walking in general but rather how nature does it in detail." Why exactly this insight might be useful, Iida doesn't yet know. His research focuses less on the application than understanding and giving things a try: basic research that might come across as a bit loopy at first glance, chuckles Iida.

After all, the engineer has a fantastic vision: He wants to develop machines that grow autonomously and reproduce themselves. "That's the Holy Grail for biologically inspired roboticists", says Iida enthusiastically. We may well still be a far cry from robots that follow their model, Mother Nature, and grow and reproduce; but the scientist and his team have certainly set the ball rolling – among other things, by creating little four-legged robots that, along similar lines to David Remy and Marco Hutters' robotic leg, don't just move with the aid of springs and are thus extremely energy-efficient. Some also have a kind of trunk made of a special synthetic material that can change shape when heat is induced – the first small step towards growth.

One storey below in Iida's lab, another robot is building a little ETH Zurich logo out of components that are also coated in the "growing" synthetic material. Next to it, more "puppies", as the little prototypes are called, wait to be used. The mechanical builder has already finished the "E" and the "T" with a steady hum by sticking the individual little blocks together. "The idea is to teach the robot to repair itself autonomously and build other robots", ex-



Vision: Growth

Like in this experiment, biologically inspired robots could one day "grow" by joining up with other objects, thereby changing their shape. The "trunk" is made of a special synthetic material that enables it to stick to almost anything with any part of its "body" and detach itself again. The idea is that it's not just biological cells that can grow by joining up with other cells; robots can also strengthen their bodies and use them more effectively if they link up with tools, for instance. (Photo: Bio-Inspired Robotics Lab / ETH Zurich)

plains Iida. Reproduction science-fiction style. For machines to grow and reproduce autonomously, however, they also have to be able to provide food, i.e. energy, for themselves, which Fumiya Iida and his team are also working on. Hungry puppies latch on to simulated loading stations made of orange-juice containers on a platform on the floor. They are supposed to learn to interrupt their exploratory tours whenever their batteries are running low.

Endowed with these characteristics, Iida's puppies could one day live on Mars as fully autonomous exploratory robots, for instance. So much robot self-sufficiency may already be a bit unnerving for some people. However, the ETH Zurich researchers don't share the fear fuelled by numerous fantasy and science fiction thrillers that autonomous robots might one day seize power and annihilate us: Mankind's worst enemy is and will remain Man himself. Only humans can programme robots incorrectly. But of course, says planning specialist Martin Rufli, things can still go wrong with autonomous machines, too. A module might malfunction, for instance. Then it could well be that a robot fails to recognise a person or recognises him too late and causes an accident, just as it can happen between two people. "At the end of the day, it's up to society to decide how and whether it can deal with potential risks like this." That said, according to an ETH Zurich survey a large proportion of the Europeans interviewed could imagine enlisting the help of robots in old age. And as soon as the first aircraft from the "myCopter" project lifts off for a private shopping spree (if not before), autonomous robots in Europe are bound to catch up with Japan in the popularity ratings.

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After a stroke, routine movements have to be relearned: Therapeutic robot ARMin helps the patient's impaired arm perform the task set on the screen as virtual reality.
(Photo: Roland Tännler)

Gentle therapists

They are patient, indefatigable and scrupulously accurate. Therapeutic robots can help stroke patients and people with movement disabilities to regain some of their movement capabilities. They are remotely reminiscent of the machines at the fitness center; but they can do much more.

Martina Märki

Hannes S.* sits on a chair, looking intently at the monitor in front of him. His left arm is strapped from the upper arm all the way down to the finger tips into a machine skeleton called "ARMin", which looks like a cross between an industrial robot and a fitness machine. "Armin activated", says a voice from the machine, and Hannes S.' arm forms an arc out to the side before returning to its original position with a gentle swivel. On the screen, a virtual puppet mimics the movement. "Watch carefully", encourages the therapist, Anja Kollmar, adjusting the patient's position.
The mannequin repeats the movement on the monitor; again, Hannes S.' arm reaches out in front of him and back to his thigh. "Now both arms together! Do the same movement with the healthy arm!" The patient opens both his arms and slowly closes them again; the mannequin on the screen continues to demonstrate the motion with one arm, over and over. A pause. Then the same again – well, almost the same. After the passive mobilisation session, it's time for actively assisted gaming. The therapist changes a setting on the computer "Can you feel you're getting less help now?" asks the therapist. Hannes S.' first arm movement by himself is a little shaky; a thick, bright yellow stripe appears around the mannequin's arm on the screen.

Sensorimotor assistance
"That's the space Mr. S. can now move his arm in independently on this setting", explains Kollmar. The movement is supposed to be autonomous but still on the right therapeutic track. ARMin, the therapeutic robot developed by ETH Zurich and the University of Zurich in Professor Robert Riener's Sensory Motor Systems Laboratory, prevents the arm from veering off uncontrollably, which can potentially be harmful, with gentle but firm blocks. Hannes S. has been impaired down his left side since he had a stroke almost a year ago. Until recently, his left arm was completely paralysed. For a number of weeks now, he has been attending the therapy programme at Balgrist University Hospital in Zurich, where ARMin is used. His development was largely funded out of the strategic fund of the ETH Zurich Foundation – a fund private donors such as the Walter Haefner Stiftung pay into to finance strategic ETH Zurich projects like the therapeutic robot. ARMin is currently being road-tested in four hospitals throughout Switzerland and is soon to be launched on the market; a fifth is in use at the National Rehabilitation Hospital in Washington D.C. ARMin is a robotic arm that is attached to a patient's arm and hand. Sensors measure the activation of the muscles and ARMin uses motors to support the movements if necessary and wanted by the therapist. Now, after eleven intensive sessions, Hannes S. can move and lift his elbow halfway up to shoulder height again. "After my stroke, I thought that was it", he explains. 24 sessions have been scheduled in all, during which Hannes S. won't just be performing therapeutic movements; with ARMin's help, he'll also be practicing routine movements and hand grips, such as grabbing and opening door handles or putting coins into ticket machines.

The virtual world as a training camp
Everyday situations show up on the screen: a door with a handle plus the virtual model of an arm. The patient moves his arm with ARMin's assistance and can check how successful the movement was on the monitor. Lift your arm, knock on the door, grip and press down the handle; push open the door: a seemingly straightforward sequence of movements. Hannes S. pushes his arm out in front of him – bingo: it knocks! Now lower the arm and grab the door handle. The virtual double on the monitor says "missed". Again: This time everything falls into place and the virtual door swings open. The patient walks across a virtual room to the next door. This time, the door handle is pointing to the left; the door has to be pulled open. Hannes S. groans then moves his arm determinedly. Last time he made it as far as the red door; today, he'd like to go further.
"The problem with robot-assisted therapy is that patients have to stick to one task for quite a long time. They are supposed to be involved and motivated but not overstrained. That's where the virtual reality technology comes in", explains Professor Robert Riener. Robot-assisted therapy as such is already quite common worldwide. The inclusion of virtual reality, however, is still rather new. Much of it is reminiscent of computer games; but it's about more than just

*** Name changed by the editorial team**

Connecting robots up to the brain

In the CA2ST project, robot-assisted therapy is supposed to be regulated autonomously and optimised with the aid of neuroimaging and physiological signals. The hope is one day to be able to transmit impulses from the brain straight to robot interfaces in order to animate prosthetic limbs or movement aids. (Photo: courtesy of Roger Gassert)

motivational games: “Our experimental design gages and evaluates the patient in real time during the exercises. We know exactly whether he or she is involved motorically and cognitively and can have the system respond in such a way that the patient is always stretched just to the right extent”, explains Marco Guidali, an engineer responsible for ARMin’s technical side. And it’s precisely this combination of motivation, cognition and movement exercises that’s crucial for the success of the therapy, stresses project manager Verena Klamroth.

The physician is currently conducting a medical comparative study that Hannes S. is also involved in as a patient. The study compares 44 patients who are being treated with ARMin with 44 who are receiving a conventional course of therapy. Already, more or less at the half-way mark, ARMin is showing promising results. One reason for this is that robot-assisted therapy repeats movements far more often and precisely than a human therapist. However, the cognitive components are just as important: “First, the brain relearns to execute the movement”, says Klamroth.

Impulses from the brain

Roger Gassert, a professor at the neighbouring Rehabilitation Engineering Lab at ETH Zurich, would like to look into the relationships between movement and the brain in rehabilitation in more detail. How do we learn movements? And what happens in the brain? “If we could answer these questions in more detail, we could help paralysed or movement-impaired patients more effectively”, Gassert is convinced. Physical exercises that essentially move the patient passively would not be of much use to someone whose hand is completely paralysed. “We know the effects of mental training from sport”, he says. “If we could now measure the impulse to execute a movement from areas of the patient’s brain, we might even be able to use it to animate a robotic interface that helps them to open the paralysed hand for instance.” One such ambitious project, CA2ST (Cortically-driven Assistance Adaptation in Sensorimotor Training), is newly launched and brings together specialists from various different labs. Apart from Roger Gassert and his team, Robert Riener and the Sensory Motor Systems Laboratory, the Biomedical Optics Research Lab at the University of Zurich, the Institute of Neuroinformatics of the University and ETH Zurich are also involved. Gassert and his fellow researchers have not achieved their goal yet. However, there is a series of robots at Gassert’s lab that help treat hands that have lost the ability to move – and with great success, as the “ReHapticKnob”, a kind of sensor- and computer-controlled, ball-shaped joystick for grip and turning exercises, shows. Another robot permits extremely precise opening and closing exercises with the thumb and forefinger. By developing such a robot out of non-metallic materials, Gassert has moved another step closer to his ultimate aim, namely the perfect combination of neuroscience and robotics. After all, it can easily be exposed to any magnetic field, which means test people can now be placed in a MRI machine to record their brain activity as they exercise finger movements. “We have already demonstrated that other areas of the brain can step in to compensate for inoperative parts of the brain in elderly people and stroke patients.” However, Gassert explains that another of his research group’s aims is to develop equipment for rehabilitation in the home. For this to work, it would have to be small, simple and quite literally handy. “Patients could be treated even more effectively if they were able to do exercises by themselves at home”, stresses Roger Gassert. Patient Hannes S., whose only contact with computer games used to be watching his grandchildren playing them, would welcome these ideas. Only today, he asked his therapist whether there were virtual games like the door opener for the home computer.

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Students present their project: the ballbot "Rezero". (Photo: Thomas Baumgartner)

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