3TU. Federation

JOINING FORCES TO SHAPE THE FUTURE

3TU.RESEARCH HIGHLIGHTS
The three universities of technology in the Netherlands - Delft University of Technology, Eindhoven University of Technology and the University of Twente - have joined forces to establish the 3TU.Federation. Its aim is to maximise technology innovation in the interests of the Dutch knowledge economy and to enhance the country’s competitive global position. This is achieved by combining and concentrating the strengths of all three universities in research, education and technology transfer. The 3TU.Federation wants to boost the value of the three cooperating universities for both students and researchers as well as industry and society as a whole. One of the key underlying objectives of the federation is to strengthen the focus and mass of research, and to this end the federation started joint 3TU.Centres of Excellence in research domains that are central to national and European research agendas.

This book contains highlights of the research performed by the six joint Centres of Excellence, with special attention paid to applications in industry and society. The ethical aspects of technological innovations are an integral concern in all our research domains.

Top researchers tell enthusiastically about their top-notch projects that will make our expectations for the future come true. These same researchers look to intensify partnership with industry to promote the social and economic application of the technology knowledge developed within the universities. They also play a leading role in encouraging supporting new business start-ups by young technology entrepreneurs. The time has now come to roll out and develop these successful joint activities and to form a united front for the interests of the Netherlands as a high-tech country. We will raise the level of the research through partnership and coordination, creating a more internationally competitive environment.

Joining forces to shape the future.

A.H. Lundqvist, Chairman of the Executive Committee 3TU.Federation

prof.dr.ir. J.T. Fokkema, Chairman of the Managing Committee for Research 3TU.Federation
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In the past decades, a wave of miniaturisation has rolled through technology - and this wave is not coming to an end. In addition, a ‘convergence’ of physics, chemistry and biology is following in the wake of nanotechnology research due to the fact that the relevant building blocks at molecular/nanometre scale can no longer get uniquely assigned to a particular discipline. Furthermore, at this point in time, the applications in electronics, nanofabrication and genomics and life-sciences are starting to overlap.

The 3TU.Centre for Bio-Nano Applications focuses on these next steps in miniaturisation and in convergence towards applications in life sciences. We assist in the development of revolutionary technology for medicine/pharmacology, instrumentation and treatments. It is our ambition to valorise the leading position held by nanotechnology in the Netherlands into valuable applications.

With the 3TU.Centre for Bio-Nano Applications the three universities of technology unite their relevant excellent research. A mild form of self-organisation, based on reinforcing existing expertise, allows us to leverage synergy and develop sufficient momentum to deliver high-quality education and research. Together we aim to develop this research field through a balance of competition and complementarities. This 3TU strategy is founded on the awareness that we are competing on a global rather than domestic level. The choices made in recent years, in terms of personnel and infrastructure, have given our three technology universities, through this 3TU.Centre, a very strong global position.
“Seeing how atoms and molecules move in living and non-living matter”, is how Henny Zandbergen, professor in Electron Microscopy at Delft University of Technology, describes the research he and his group conduct. They use the electron microscope not just to see things but also as a tool to build things on the nanoscale.

In collaboration with the Delft University of Technology researchers, the Dutch company Philips was the first to have a serial production line for electron microscopes. The fact that electrons have much smaller wavelengths than even X-rays allows you to see things with much more detail than with a light microscope. The electron microscope can even now be used as a tool, for example to move atoms around. The Delft University of Technology has played, and is playing, an important role in the further development of these instruments and in finding new applications. One of these new applications is using the electrons to create holes a few nanometres in diameter in thin membranes. A nanometre is one millionth of a millimetre. Technology developed for microchip manufacturing can be used to make thin membranes of around 100 nanometres in size. In this ‘big’ membrane, a hole of, for instance, 5 nanometres can be sculpted with a focused electron beam in an electron microscope. Such a hole can be used as a single molecule detection system. Eventually it might be used to determine the sequence of a DNA-molecule, or other long polymers.

“These nanopores are being used, for example, in the department for Bionanoscience to research the interaction between DNA and enzymes”, says Zandbergen. “My colleagues Cees Dekker and Nynke Dekker are for instance using the pores to study how a single DNA molecule coils and uncoils. For this they use a DNA-molecule that is trapped in a pore on one end and to a magnetic bead on the other end. By playing around with the magnetic field strength you can make the molecule coil up, not unlike the cord on a telephone. If you then thread the DNA molecule through the nanopore, you can see if and, if so, how fast it uncoils under the influence of a given enzyme.”
This research, which is carried out in the department of Bionanoscience, does not just provide insights into the fundamental workings of DNA, but also helps to figure out the method of action of anti-tumour drugs. You can see the activity of the uncoupling enzyme being inhibited by the drug. This in turn stops cell division and thereby the growth of tumours.

The passing of a DNA molecule, or another polymer, through the pore can be measured by observing a change in current. The length of the molecule and the shape in which it passes through the pore is reflected in the time and amplitude of the change in resistance. Zandbergen: 'The next step is to not just measure the change in resistance, but to determine which DNA bases pass. This would allow the direct determination of the DNA sequence and be a giant step towards the sequencing of individual genomes.' Such a characterisation is one of the holy grails of the National Institute of Health of the USA, a large funding organisation for medical research, that is investing large amounts to get the '1000 dollar genome' within reach – having a person's genome sequenced for 1000 dollars.

Electron microscopes are not just useful for the study of biomolecules, they are also still used to study non-living materials. Catalysts, for example, compounds that when added in tiny amounts, can make reactions that normally don't happen, happen quickly; like the conversion of crude oil – and to an increasing extent, green source materials – into useful chemicals. Together with Fredrik Creemer, assistant professor of Micro-Electro-Mechanical Systems, Zandbergen has developed a nanoreactor in which the working of catalysts can be studied with atomic resolution. Zandbergen: 'Using transmission electron microscopy you can, as I said earlier, visualise particles with atomic resolution. The problem is that this form of electron microscopy works best under vacuum, so the electron you use for looking at things are not disturbed by gas molecules. In the nanoreactor we got around this by creating a small vessel around the sample and maintaining the vacuum in the rest of the microscope. Using extremely thin membranes we confine gases in this vessel and we can let gases flow in and out and a reaction can take place between a solid – a catalyst in our case – and the gaseous reactants. We can follow this reaction using the electron microscope. One of the reactions one can follow this way is how a metal oxide, like platinum or copper monoxide and hydrogen into liquid fuels. Researchers from the University of Utrecht have used the reactor to work out the reaction mechanism of the Fisher-Tropsch reaction – the conversion of carbon monoxide and hydrogen into liquid fuels.

Zandbergen: 'The nice thing of our research is that we collaborate with researchers from many different disciplines; not only within Delft and the 3TU.federation, but also with medical faculties in Rotterdam and Leiden and the Dutch Cancer Institute. Internationally, we collaborate with other centres for high resolution electron microscopy, both in Europe and the rest of the world. Eventually, we all want to see what is happening at the atomic level, whether we are chemists, biologists or material scientists.'

Currently, the nanoreactor can be used to monitor reactions at the molecular level under pressures of up to 1 bar and temperatures as high as 500 degrees. It has been used to, for example, study the way copper/zinc catalysts work. These are used in industry to convert methane into methanol. Researchers from the University of Utrecht have used the reactor to work out the reaction mechanism of the Fisher-Tropsch reaction – the conversion of carbon monoxide and hydrogen into liquid fuels.

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The whole world is hunting for biomarkers; molecules in bodily fluids such as blood, urine and saliva that give an indication of a person’s state of disease. Finding a biomarker, though, is only half the story. The other half is finding a way to measure it, that is quick, accurate, reliable and practical. Menno Prins and his collaborators are looking for smart techniques to map the molecular state of our body.

On the table in front lies a heart-shaped object about the size of a keychain, with a display and two buttons: the reader. A small strip with a coloured tip has been inserted into the reader: the cartridge. ‘This here is the most used biosensor in the world’, says Menno Prins. ‘The glucose sensor. If you want to know your glucose level, you drop a minute amount of blood on the cartridge. A series of biochemical reactions take place and within five seconds one gets a read-out of the blood glucose level. This allows diabetes patients to determine the exact amount of insulin they need to take’.

The focus of Menno Prins’ research group is on leaps forward in biosensing. ‘The concentrations of biomarkers that we want to measure are very low. If you want to compare it to glucose, it is like measuring glucose levels in an Olympic-sized pool after throwing in a few grains of sugar. The big challenge for us is to develop biosensors that are many orders of magnitude more sensitive, but as quick, reliable, small and economical as the glucose sensor’.

One of the important applications is to test drivers for the use of illegal drugs. Another application is to measure protein levels in the blood to determine the condition of the heart. Biosensors will also play a key role in the development of personalised medicine. Prins: ‘Patients can react very differently to drugs. One person can suffer from side effects much more than the next. For some people the medicine will not even work. Using biosensors you could biochemically determine how a patient is reacting to a drug and adjust the dose of the medication accordingly.’

As is typical for universities of technology, Prins does not just give lip service to finding potential applications. He is actually working on them because he is, in parallel to his professorship,
Combining hardcore physics with medical applications is what Xander Janssen (28), who finished his PhD in Menno Prins’ group in November 2009, finds exciting about his research into next generation biosensors. ‘If I had only been researching magnetic phenomena, I probably would not have been half as interested’, says Janssen. ‘One of my earlier internships was at the Academic Hospital of Maastricht. This strongly motivated me as it really showed me the potential applications of my work. ‘

After school he chose to study applied Physics at the eindhoven University of Technology. ‘Slowly but surely the interest in biomedical aspects crept in and I was lucky enough to eventually work on this topic during my PhD. ‘ That research – broadly speaking – involves the development of second generation biosensors. The aim of this new generation of biosensors is to not only detect biological molecules (so-called biomarkers) at picomolar concentrations and lower but to also unveil functional properties of the biomarkers. Biological tests generally use antibodies that bind to biomarkers with very high specificity. The antibodies that Janssen uses have been attached to micrometre sized superparamagnetic particles, which allows for the direct physical measurement of the presence of the biomarker.

‘Many more things are possible’, says Janssen. ‘Since the particles are magnetic, one can use a rotating magnetic field to turn and twist the whole construct of biomarker-antibody-particle. That way one can deduce how the biomarker binds to the antibody, which in turn can provide information on the biological functionality of the biomarker, hence the name functional biosensor. ‘

Xander Janssen has been given a postdoctoral position to do related biophysical research for an additional three years after finishing his PhD. Not in eindhoven, but at the Delft University of Technology, in the department of Bionanoscience to be precise. The transition will be quite smooth, he thinks. ‘The advantage of the collaboration between the three universities of technology is that I already know the people and what they are working on. This means I can hit the ground running. ‘

employed by Philips Research. This gives him a commercial as well as a scientific radar. ‘To be commercially viable, one needs to develop a technological platform that can serve many applications, starting with a few large opportunities and later opening many smaller applications.’ The biochemical heart of the biosensors are antibodies, molecules that capture biomarkers in a very specific manner in so-called immuno-assays. ‘In traditional immuno-assays the read-out of binding events is often done using a biochemical reaction that generates light, but for the type of sensor we are envisaging that is too laborious.’ An alternative that is being investigated by Prins is the use of magnetic particles. The particles are superparamagnetic, which means that they become magnetic only when exposed to an external magnetic field. This makes it possible to turn the magnetic moment of the particles on and off. Prins: ‘The magnetic particle is decorated with antibodies specific to the biomarker. The particle binds the biomarker through these antibodies. Next, the whole complex is bound to a second antibody attached to a chip. This gives a kind of sandwich wherein the antibodies are the slices of bread and the biomarker the jam sitting in the middle.’

Next to sandwiches with a biomarker topping, empty sandwiches are also formed where the antibody on the magnetic particle is bound to the antibody on the chip, instead of both being bound to the biomarker. By applying a magnetic force to the magnetic particles, the particles bound (loosely) to the antibody on the surface without the biomarker will float off. The particles in a sandwich with a biomarker molecule still stick. Then the number of particles left behind is a measure for the biomarker concentration in the original sample. ‘Working with magnetic particles offers further opportunities’, says Prins. ‘For example, we are looking how the molecular structure of the magnet-antibody-biomarker-second antibody reacts when you use the magnetic field to apply a force and a torque on the complex. At the moment we are studying what the physical effects are and the next stage is to extract the biochemical information. The response to the force reveals important details of the captured biomarker molecules.’

‘The study of molecular interactions using physical techniques is the theme for the collaborative effort within the 3TU Federation’, says Prins. ‘The focus differs – Delft emphasises interactions between nucleic acids and proteins, whilst Twente has a strong interest in the formation of protein aggregates – but the methods and tools are comparable. We are all trying to gain biological knowledge using physics techniques.’
Intrinsically disordered proteins are believed to play an important role in the emergence of neuro-degenerative disorders such as Alzheimer’s and Parkinson’s disease. Using various visualisation and quantification methods, Vinod Subramaniam and his colleagues are trying to work out how the aggregation of these proteins takes place. This research could lead to understanding the fundamental biophysical principles underlying these protein misfolding and aggregation processes, and potentially to the identification of biomarkers for the early detection of these disorders.

For most of his academic career, Subramaniam has been intrigued by the phenomenon of protein folding. ‘Strictly speaking, proteins are no more than a linear chain of amino acids’, he says. ‘The properties of each of the individual links and the order in which they sit in the chain, however, cause it to fold into a three-dimensional structure. This structure often serves as a lock in which a very specific molecular key fits. When the key is put in the lock, this may, for example, cause a particular biochemical reaction to take place.’

The importance of this folding becomes apparent in cases where it goes wrong. One example is cystic fibrosis, a hereditary disease in which just one amino acid is mutated causing the whole protein to misfold and not carry out its function any more. Also the prion diseases, such as the infamous BSE in cattle, are caused by misfolding of proteins.

Most of the proteins in the human body require a three-dimensional fold to perform their function. ‘There is, however, a class of proteins that is intrinsically disordered’, says Subramaniam. ‘They have no well-defined three-dimensional structure. It is believed that these proteins can fold in different manners, based on requirement. This allows them to have multiple functions in the cell. Like a jack of all trades that can be deployed according to need.

We do encounter some of these intrinsically disordered proteins in Alzheimer’s and Parkinson’s disease where they form an important part of the amyloid plaques; protein aggregates in the brains that are characteristic for neuro-degenerative disorders. If you study the brain of
BART VAN ROOIJEN
UNIVERSITY OF TWENTE

The combination of technology and biology is what makes research into fibrillar aggregates and their role in the development of diseases like Alzheimer’s and Parkinson’s so interesting for Bart van Rooijen. He hopes to gain his doctorate in this subject by the end of 2022. "Initially the focus of my project was on developing techniques, most notably the use of Atomic Force Microscopy, he says. "That is kind of obvious because my background is in Applied Physics. My research quickly took a more biological turn and now I am studying the way in which the fibrillar aggregates affect the membrane. The techniques I use are now much more focused on visualising these biological processes. I have now broadened my technological focus beyond using just Atomic Force Microscopy and use all kinds of visualization methods. The biological question has become the focal point of the research, instead of the technique as such.

Van Rooijen also enjoys the fact that neuro-degenerative disorders and the role of certain proteins herein attracts a lot of other research interest. "This has made it a highly competitive area in which you are continually challenged to find and push the boundaries of what is technically possible. At the same time the research is highly relevant. It is to ease their symptoms. My research is very fundamental, but I do keep in mind that I am contributing to the solution of a large burden, both on society and on the individual patient."

Van Rooijen’s patients, you will see so-called Lewy-bodies, which are clumps of aggregated protein. If you analyse those further you will see that for a large part they consist of fibrillar aggregates, which in turn are made up of a specific intrinsically disordered protein. The most important protein in Parkinson’s disease is α-synuclein, which forms wavy structures tens of nanometres in length. Subramaniam is trying to mimic the formation of these aggregates in the laboratory. Using genetically modified bacteria, relatively large amounts (a few milligrams) of this protein can be made. The formation of these wire-like aggregates, how fast or even if they form, is then studied under a range of conditions.

We use a whole host of different techniques to visualise and quantify the process; from electron microscopy to a range of spectroscopic techniques. In that regard we can’t be narrow-minded. One of the big advantages of the 3TU.federation is that you do not just have the different equipment available, but also the expertise to help you push the limits of detection. You could call it a joint voyage of discovery, which by now has mapped large parts of this unknown area of research.

One of the discoveries made is a ‘description’ of the early events of aggregate formation. ‘It is this first phase which is incredibly important’, says Subramaniam. ‘Until a few years ago research into Alzheimer’s and Parkinson’s diseases was focused on the study of large aggregates as a probable cause of symptoms. Recently, however, it has become more apparent that the smaller aggregates, so-called early aggregates or oligomers, which may consist of around 50-70 proteins, are likely to be involved in cell death. The large aggregates may be a defence mechanism of the cell to neutralise these smaller oligomers by turning them into larger clumps.’

An interesting question is what damage these small oligomers do to the brain. Subramaniam: ‘There is an indication that they puncture holes in the cell membranes – the so-called amyloid pore hypothesis. Our results suggest that oligomeric α-synuclein interacts with lipid membranes. We don’t think that α-synuclein interacts with the cell membrane itself but rather with organelle membranes, like those of mitochondria, for example, the cell’s power plants. If these become leaky, the cell no longer gets energy and dies.’

To study what these oligomers do to membranes exactly, artificial vesicles are used. These are small fluid-filled sacks surrounded by a lipid membrane, which behave in an organelle-like manner. By filling such a vesicle with a fluorescent dye, it becomes possible to visualise what happens on the nanoscale. Subramaniam: ‘We hope to figure out what kind of lipids these small protein aggregates bind to, how the lipids reorganise and how holes are then formed. One remarkable observation is that the leakage of the content out of the vesicle can be observed with the membrane itself appearing intact. This could indicate a specific transport mechanism, but we do not understand yet how it works.’

Research into visualising and quantifying biological processes at the nanoscale is of a very fundamental nature. Applications are not within easy reach. They do, however, exist and form an important motivator for this research into intrinsically disordered proteins. Subramaniam: ‘In neuro-degenerative disorders, like Alzheimer’s and Parkinson’s disease, a lot of damage is done at the cellular level before any symptoms become apparent in a patient. If we can map how fibrils form and how they react with membranes, we could start looking for new biomarkers. A small change in the blood, saliva or other bodily fluid which could indicate the process has started.

Type of research is also being performed within the 3TU.federation. A better insight into the mechanism of the disease will also provide new targets for the development of drugs that could nip the disease development in the bud. We are not close to these prizes, but they are important motivators for this research.”

The techniques I use are now much more focused on visualising these biological processes. I have now broadened my technological focus beyond using just Atomic Force Microscopy and use all kinds of visualization methods. The biological question has become the focal point of the research, instead of the technique as such.
Information and communication technology can often be unreliable, as we experience almost every day. For example, when we have to reset the computer or close a programme, that’s usually not such a problem. But it can be more serious if it happens in a traffic control system. Let alone the dangers that ICT problems in an aircraft or a nuclear power plant could cause. ICT systems are so complex that, in many cases, their operation is no longer transparent. These almost organic systems are controlled from different locations, and operate as parts of extended networks. Our society has an extremely high level of dependency on them. If the internet is not accessible for a few hours, the resulting problems are almost impossible to contemplate – almost every conceivable system will be out of operation.

Scientists at universities can carry out research into the causes of the problems we experience today. But this is not sufficient for the 3TU.Centre for Dependable ICT Systems; it aims to raise the bar even higher. The challenge is to really solve this ICT problem.

By itself, a single university has insufficient critical mass and expertise to take an influential position in this research field. But together, it is possible to find good partners with which we can jointly develop fundamental solutions. The professors have been recruited, there are intensive collaborations between the chairs and industry is keen to participate in our research. Together with a large number of European partners, we have recently submitted a proposal to the European Institute of Innovation and Technology (EIT) for a Knowledge and Innovation Community (KIC) in the field of ICT. It is the first time that top European universities, excellent research partners and leading companies have joined forces on such a large scale in the field of ICT.
software is continually evolving in an attempt to adapt to social changes. These changes, however, lead to an erosion of the fundamental structure of the software, eventually resulting in further evolution becoming impossible. Evolution inhibiting future evolution; that is what we call the software evolution paradox’, says Arie van Deursen, professor in the Software Engineering Research Group in Delft. ‘Breaking this paradox is the main driving force behind our research.’

Thousands of software engineers write programs every day to keep a multitude of systems operational: from mega-computers that keep track of bank accounts to the computers in a washing machine that ensure the delivery of soap to the laundry at the right point in the washing cycle. Furthermore, software engineers are working on adjusting existing programs to, for example, fix bugs in older versions. However, more often than not alterations are needed as a result of changes in the environment in which the program has to function.

‘Software is continually being adjusted’, says Van Deursen. ‘A company like ASML, a manufacturer of machinery to make microchips, is the owner of around 10 million lines of code. It is locked in a continuous battle with its competitors to make their product just that little bit better so that the microstructures on a chip can be miniaturised by a few more nanometers.

Or take the Inland Revenue as another example. They too own many millions of lines of software code. If a new law is passed in the House of Commons at least some part of this code has to be altered in order to implement this law.

The changes, which are often introduced under severe time pressure, can lead to the erosion of the original structure of the program. Van Deursen: ‘You could compare programming to laying a mosaic floor. A programmer writes code like the maker of the mosaic puts small stones in rows. Just like the mosaic, the program has a structure. Adjusting the code in a program can be compared to the re-laying of certain stones in the mosaic. If you do this, there is a chance you disrupt the original picture of the mosaic. The same happens in software; if you start playing

THE PARADOX OF SOFTWARE EVOLUTION
The collaboration dates back to 2001 when research groups in Eindhoven, Twente and Delft dependability of ICT systems. This is something we are researching as part of the 3TU federation. Finding an answer to that is not just a question of correctness and performance, but also of how one can prevent the structure, the original mosaic picture, from disappearing completely. 

Not because they are less able, more because they tend to be very transient as a labour. Not because they are less able, more because they tend to be very transient as a football pitches. The problem is exacerbated by the fact that companies often used temporary employees. AsML employs 300-400 programmers to move the small stones in its 10 million lines of code. One of these problems is the maintainability of the programs, a key property of dependability. Research is being done into aspect-oriented software development to improve upon this. Van Deursen explains: ‘a good way to improve maintainability of software is by modular programming. This means that you build a program consisting of various modules, rather than one big unit. If something needs to be altered, only one or a few modules have to be adjusted. Or, so goes the theory. In practice, it is impossible to harness certain cross-cutting functions in a single module. Logging, registering the status of a program at a given point in time, is an example of a cross-cutting function. Security and dealing with errors, the infamous error messages, are also examples of such tangled functions.’

Together with the other technical universities and ASML, we have developed a method to modularise even these general functions by making them like a cassette, which can be slotted into specific modules. If you want to change the program code for such a function, you modify the specific cassette once and it will weave itself into all the modules that require its specific function.’

One of the functions the research group in Delft look at is error handling. Van Deursen: ‘For the complex machines that ASML makes, it is essential that error codes are correct. A reported error 103 has to be a real error 103, otherwise the system makes, it is essential that error codes are correct. a reported error 103 has to be a real error 103, otherwise the system

To them it appears as a normal user. ‘crawljax’, which is the name of this tool, compares each renewed page after a click to the page it should have been according to the requirements. In 2009, the paper that Ali Mesbah wrote with his professor Arie van Deursen on crawljax won the prestigious Distinguished Paper Award at the International Conference on Software Engineering. ‘a once in a lifetime experience, comparable to winning an Oscar or an Emmy Award in film or television’.

Another theme in Van Deursen’s research group is the testing of new versions of existing programs. Among them the Ajax technology, a new way of programming in which a range of functions are bolted onto the Internet browser. Like the e-mail and office functions Google offers that simply run in the browser. ‘Very pleasant for the user, but a disaster for the programmer to manage the complexity,’ says Ali Mesbah (30). In 2009, he completed his PhD with honours on analysis and testing of web applications. He developed a software tool that automatically tests interactive websites as if it were an insist user. If you were to do this by hand, it would take a few million clicks for large applications such as Gmail. This is too much for a programmer to do. One software tool does it automatically. This means you can also test at the right or in the background. Aside from saving time, automatic testing of websites makes them safer and more reliable, as they can be tested exhaustively. Ali Mesbah came to the Netherlands from Iran aged 15, because his father was doing a PhD at the University of Wageningen. When his family returned after four years, he decided to stay here and study Computer Science in Delft. After my MSc in 2003 I started working for a software engineering consultancy firm. Initially, this was very challenging, but after a while it became routine. That is why I contacted Arie van Deursen in 2005 to see if he had any PhD positions available.

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Compared to ten years ago, web applications have become much more interactive. ‘very pleasant for the user, but a disaster for the programmer to manage the complexity,’ says Ali Mesbah (30). In 2009, he completed his PhD with honours on analysis and testing of web applications. He developed a software tool that automatically tests interactive websites as if it were an insist user. If you were to do this by hand, it would take a few million clicks for large applications such as Gmail. This is too much for a programmer to do. One software tool does it automatically. This means you can also test at the right or in the background. Aside from saving time, automatic testing of websites makes them safer and more reliable, as they can be tested exhaustively. Ali Mesbah came to the Netherlands from Iran aged 15, because his father was doing a PhD at the University of Wageningen. When his family returned after four years, he decided to stay here and study Computer Science in Delft. After my MSc in 2003 I started working for a software engineering consultancy firm. Initially, this was very challenging, but after a while it became routine. That is why I contacted Arie van Deursen in 2005 to see if he had any PhD positions available. Luckily he did and it was in the area of my favourite topic, web applications. After gaining my doctorate in 2009 I was able to stay on as a postdoc, which I like a lot.’

The tool developed by Mesbah works a bit like a robot, but neither the applications, nor the browser in which the application is running recognizes it as such. To them it appears as a normal user. ‘crawljax’, which is the name of this tool, compares each renewed page after a click to the page it should have been according to the requirements. In 2009, the paper that Ali Mesbah wrote with his professor Arie van Deursen on crawljax won the prestigious Distinguished Paper Award at the International Conference on Software Engineering. ‘a once in a lifetime experience, comparable to winning an Oscar or an Emmy Award in film or television.’

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Data logging has undergone explosive growth over the last ten years. Not just data about operating procedures in industry and public services, but also data about machines themselves. Wil van der Aalst reckons these event logs, which are mainly generated automatically, are a reflection of operating reality. ‘Those data can be used to check existing models or to automatically generate new models as well as to improve the working of machines and operating procedures. Since the information is about processes, the gathering and analysis of these data are not called data mining, but process mining. Together with other groups, both within and out with the Centre of Excellence, we are developing these tools for this growing industry.’

Van der Aalst uses medical devices of Philips Health care, which are used in hospitals all over the world, as a prime example of the use of event logging. ‘In principle, they are all connected to the internet and are sending a constant stream of detailed information on what is happening with the machine to the home front. Those data can be used to develop a model for the working of the machine. If you then take this model and compare it to the original model, which served as the basis for designing the machine, you can figure out whether the initial assumptions were correct and what changes could be made for the device to work even better.’

Operating procedures of businesses can be analysed in a similar manner. Van der Aalst: ‘Booking a trip on the internet takes about five to ten minutes at most. During that time at least four or five companies are involved in the transaction: the airline, the travel agent, the web host, the hotel, the payment service and a few banks. The whole process is logged in great detail and provides an avalanche of events that in turn can be analysed using tools such as ProM. In the ProM group developers and users work closely together, free of vested interest. It is an open source alliance. On the one hand, process mining can be used to figure out what events exactly took place, and on the other hand the data can be used to deduce a model of the operating procedure, which again can be tested against the existing model – a conformance test – or it
anne rozinat (31) loves solving problems together with industrial partners. this is a very good thing considering that she started the company fluxicon together with her former colleague christian w. gütter in september 2009. they help companies and institutions with innovative tools and services for analysing and improving their processes. with support and guidance from the innovation lab of the eindhoven university of technology, fluxicon is now making its way into the marketplace. during her phd, rozinat experienced how motivating it can be for people when they realise how the processes in their business actually work. ‘information about business processes is in the heads of many employees. using process mining tools and services for analysing and improving their processes. with support and guidance from the innovation lab of the eindhoven university of technology, fluxicon is now making its way into the marketplace. during her phd, rozinat experienced how motivating it can be for 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Society is becoming increasingly reliant on ICT systems, which therefore have to remain functional. At the same time the chance of errors in software, hardware and the combination of the two is rising. ‘Such mistakes could cause rockets to explode, airplanes to crash or the complete disruption of train traffic in the rush. ‘The question we work on is how to keep these systems functioning correctly. And, more importantly, how you can prove this to be the case’, says Jaco van de Pol, professor in Formal Methods and Tools.

It is not something we pay too much attention to, but over the last few decades we have become increasingly dependent on properly functioning computer systems. Take the Maeslandtkering, the intelligent dam in the Nieuwe Waterweg near Rotterdam, for example. If a storm is blowing in South-Westerly direction, there will be a risk of flooding in this area. The system controlling the dam will decide itself whether to close or not, based on the calculated risk of flooding. A wrong decision could have massive consequences. Not closing the dam, when it should be closed, increases the risk of flooding in the polders that lie behind it. Closing it without significant enough risk results in an enormous unnecessary loss of income because ships cannot leave or enter the harbour.

‘The correct functioning of ICT systems has become a matter of life and death increasingly often’, states Van de Pol. His own research focuses on train protection systems, which control the track switches and signals, resulting in orderly and safe railway traffic. ‘A system like that has to function 100% correctly on two fronts. For a start, it must not make errors, as that could lead to fatal accidents. And it has to always work because if it fails, trains can no longer run. For a railway as busy as that of the Netherlands, that would mean tens of thousands of people arriving late at school or work.’

As ICT systems get more complex, the chance of errors increases; not just software errors – error-free software is an illusion according to Van De Pol – but also hardware induced errors. As systems get smaller, for instance, the chance of cross-over and bit flips increases.
The use of wireless communication between systems increases the chance of errors too as data can be lost in transit. Another important source of errors stems from the fact ICT systems are not solely used by experts and human operators can sometimes accidentally introduce errors that make the system unreliable.

In the aim to develop dependable ICT systems, the Fab Four form the important guideline. Not the Beatles, but the Fab Four: ‘F’ stands for fault avoidance: prevent the introduction of faults by improving the design process. The second is fault tolerance: add redundancy to avoid service failure, for example, by using multiple systems. The third is fault removal, both during the design and implementation as well as during operation of a system. The fourth and final ‘F’ is fault forecasting: predict faults and future occurrences. That completes the circle as that leads back to fault avoidance.

The research of Van de Pol and his colleagues is aimed at developing techniques for improving the design process, thereby preventing errors and increasing the error tolerance. The first step is to make a model of the system that is to be designed. Van De Pol: ‘It is the same as what an architect or civil engineer does when designing a house or a bridge. Based on the requirements of the customer we make a model of the system and then calculate how it will behave in a range of different situations.’

Making a model isn’t trivial, as it basically represents the translation of everyday requirements onto the computer system, Van de Pol: ‘Take, for example, the communication system of the emergency services during a disaster in which normal telephone communication has been hampered. To work out the parameters of the model you need to very precisely know what the protocol is of the emergency services under such conditions; how many people need to be able to communicate at the same time, which communications are to be prioritised if the bandwidth is too small. All – and many more – need to be recorded unambiguously and preferably in a way that they can be used to probe the system.’

Based on the list of demands of the system, a model is developed. This model is subsequently challenged by a model checker; a piece of software to test the system requirements. For instance, those requirements – and many more – need to be recorded unambiguously and preferably in a way that they can be used to probe the system.”

For his PhD he does not want to test existing systems, but models for systems that are yet to be built. ‘We are developing mathematical tools to use in the system model to ensure the required standards and how reliable it is. In principle, you would have to test all the states of the system. This involves huge matrices, which is beyond the calculation power of existing computers. Essentially, if these states are not determined by the data alone, but probabilities also play a role. Like in this case, the probability that certain behaviour is avoided is 50 per cent.’

During his first year of his doctoral studies, Timmer developed a formal language that allows the reduction of this enormous number of states – the state space – to a size that makes verifying whether a model meets certain requirements feasible, without compromising on the reliability of the result. ‘This tool, which we are developing further, allows us to efficiently model and verify complex ICT systems in which data and chance both play a part; like a mobile phone network. This is highly useful for improving the reliability of the system.’

Mark Timmer (25) has a very infectious kind of enthusiasm. The subject of his PhD, developing methods to prove that ICT systems are working right, is not the most accessible, luckily, he has no issue with trying to explain it again. And again. Some gentle probing discovers that even during his degree in Computer Science at the University of Twente, he was always happy to help with computer science and still be involved in teaching. This combined with the full marks for his final year research project made his PhD a obvious choice.

During his degree he developed, together with Marjolein Steenstra, a framework to evaluate the reliability of system tests. ‘When you test an ICT system, you have it go through a series of procedures and check whether the outcome of the procedure corresponds to the expected outcome. When you reach a fault, it is a serious concern whether the system is faulty. This would require an infinite number of states – to a size that makes verifying whether a model meets the required standards and how reliable it is. In principle, you would have to test all the states of the system. This involves huge matrices, which is beyond the calculation power of existing computers. Essentially, if these states are not determined by the data alone, but probabilities also play a role.’

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Many technological applications are developed because at first glance they appear to offer benefits. Like the smart electricity meter, which produces energy savings. It’s smart, but not quite smart enough to anticipate objections from society. The roll-out of the meter has been deferred by the Dutch parliament because of its potential threat to the privacy of citizens.

The task of the 3TU.Centre for Ethics and Technology is to consider these ethical and societal issues at an early stage, when changes or adjustments can still be made in designs, materials and products. Not only is it possible at this stage to check whether the desired functionality can be offered but it also allows anticipated moral objections to be addressed. Our work focuses primarily, but not exclusively, on the technology domains of the other 3TU.Centres of Competence and Centres of Excellence. A major theme in our research is value-sensitive design – design that takes into account societal, political and moral values. Other topics that we work on are, for example, the ethics of technological risk, responsibility distributions in R&D networks, human enhancement, technology and the good life, the ethics of technology for developing countries and for future generations, neuroethics, nanoethics and ethical aspects of genomics.

The 3TU.Centre for Ethics and Technology is the world’s largest institute for the ethics of technology. We are very successful in generating external funding for our research. Several of our members hold prestigious VENI, VIDI and VICI grants from the Netherlands Organisation for Scientific Research (NWO). In the first round of a new NWO funding scheme on socially responsible innovation (the MVI programme), the 3TU.Centre for Ethics and Technology obtained funding for seven new research projects, worth more than three million euros. Recently the 3TU.Centre received a highly competitive grant from the NWO for its graduate programme.
The question we focus on is how you can design things in such a way that it will allow people to thrive, i.e., to have the capabilities to lead healthy and meaningful lives. This means that very early on in the design process of, say, ICT systems we question the values informing or shaping the design. This is how Jeroen van den Hoven describes his research into the moral issues of the use and regulation of technology at the Centre of Excellence. As a result of the collaboration between Eindhoven, Twente and Delft, we are not only the largest, but also the most prominent centre for ethics and technology research in the world.

Ethics deals with the Good and the Bad, the right and the wrong. When you translate this to technology, according to Van Den Hoven, this results not just in the study of the values inherent in technical systems, but also in how you can design them so that moral dilemmas are solved or avoided. This approach requires the study of technology and its uses. Van Den Hoven: “Debates in society are often just an exchange of the pros and cons of a given topic. You are pro-nuclear energy or against it; pro-GM or anti. These discussions can take years and usually end in trench warfare. Studying ethics requires us to analyse a topic in depth and find out which values are more or less inherent in, say, the design of a nuclear power plant or the design of a GM-crop. Instead of looking in black and white, we try to find the subtleties, the shades of grey, with the aim of a more refined debate about the values of everybody involved.”

This method of analysis can be applied very well to the Electronic Patient Files (EPF), according to Van Den Hoven. This is the central storage and exchange of patient data by care providers. The setting up of the EPF database has led to some heated debates in the Netherlands, in which the values of privacy and good medical care seem to collide head on. Van Den Hoven: “Repeating the pros and cons does not solve this argument, the disagreement over the value of privacy is too deep to overcome in the context of this debate. The approach needs to be more subtle. For example, by addressing who needs which data and what can they use it for. Is the hospital porter, for example, allowed to see laboratory test results and does he have the right to change these?”
This new role cannot remain without consequences for the modus operandi and the culture in a hospital. When a medical mistake has been made, an individual culprit is still often sought. The whole ethical and legal thinking is still based on this approach, but it is no longer possible to ignore the high-tech and organisational setting of the hospital; the design of the system preempts certain choices of individuals and this affects their capacity to take responsibility. To prevent future errors, it is much better to analyse the error came about than to look for an individual scapegoat, which will only cause everybody to become defensive and prevent valuable information from being produced.

It usually turns out that a medical blunder is the result of an accumulation of systems errors, and joint or collective decisions as well as human errors.

Values can change with time, often under the influence of technological developments. Privacy, for example, appears less important to the younger generations, who display their entire personal lives on Facebook. How can values be taken into account when designing systems, when they continually shift? Van Den Hoven: ‘We could use a meta-system for this, which means that we do not lumber future generations with airtight systems. Or, that we design systems in such a way that they can be altered with the changes in our value systems.’

At the moment ‘security’ appears to be a much more prominent value than ‘privacy’, as high-lighted by the fact that every Dutch citizen applying for a new passport will have their fingerprint data stored. If ‘privacy’ were to become the dominant value again in a few years, the system needs to have been designed in such a way that, at the push of a button for example, all this fingerprint data can be deleted. The same goes for any website carrying personal data; you should be able to delete the data yourself. This way those embarrassing holiday snaps from your Club 38-30 holiday in Spain won’t be on the rest of your life. The 3TU.Centre for Ethics and Technology is not just the largest in the world, but with its research reflects the changing role of the ethics researcher; most notably when it comes to technological developments. Van Den Hoven: ‘In the past ethics research was first and foremost about the analysis of a theoretical problem. We now also see it as our job to be much more technology-driven and the role of the doctor has changed whereby he or she is much more of a highly-skilled team player.’

In a once-through cycle the nuclear fuel is used once and then stored underground. This involves relatively large amounts of waste that remain radiotoxic for 200,000 years. In a closed cycle, the nuclear fuel is reprocessed and re-used. The toxicity is then reduced 20-fold: also the waste volume is reduced considerably. Taebi: ‘The once-through cycle is relatively safe for our generation, as we are transforming the risk for a very long period of time. A closed cycle reduces the burden on future generations, it is even scientifically possible to reduce the lifetime to 500 years. The downside is that we as the present generation are more at risk of a radiation accident or – more importantly – of proliferation as that nuclear material can be turned into atomic weapons.’

Working on the assumption that nuclear fuel is a serious option for our future energy supply is much too complex to judge ‘either black or white’. That is why it is so important to have the understanding of the technology and distinguishing between different production methods, as they bring about significantly different considerations for the present and future generations. In my research I look at the effect of a once-through and a closed nuclear fuel cycle within the philosophical framework of justice between generations.'
Innovation is too important to just leave it to engineers. The aim of our research is to involve ethics researchers, psychologists and sociologists as early as possible in the development of new technologies, says Anthonie Meijers, professor at Eindhoven University of Technology. ‘Technical artifacts are not isolated objects; their function is a result of the way the user interacts with them. This gives rise to moral questions. If you take social, psychological and ethical aspects into account early on in the development, you get better products.’

As a philosopher, Meijers exemplifies this ‘ethical parallel research’ approach with a case study on persuasive technology, technology that is explicitly designed with the intention to persuade people to change their behaviour. His case is the development of an automated braking system for lorries. The project is financed by NWO, The Netherlands Organisation for Scientific Research, and is carried out in collaboration with prof. Maarten Steinbuch of the Department of Mechanical Engineering and prof. Cees Midden of the Department of Industrial Engineering and Innovation Science at Eindhoven University of Technology. DAF Trucks and TNO are external stakeholders of this project. Meijers, who himself is also trained as a mechanical engineer: ‘Car and truck manufacturers are researching systems that can harvest the energy when the car brakes. This recovered energy can be converted to electricity and stored in a battery. The amount of energy that can be recovered is highly dependent on the way the driver brakes. The difference can be as much as ten per cent. This potential energy gain has motivated designers to develop automated braking systems that always brake optimally. This research has been done by the Department of Mechanical Engineering.’

Although technically feasible, an automated braking system carries psychological, legal and ethical implications. To a large extent these result from the so-called ‘reallocation of control’, that is the extent to which control is transferred from the driver to the automated braking system. This reallocation raises questions about the responsibility for the vehicle when it is
going through an automated braking procedure. Meijers: ‘Most kinetic energy can probably be recovered if the automated braking system was to take over completely and automatically stick to the optimised braking curve. If something were to happen though – say the car crashes into the car in front – who then is responsible; morally and legally? The driver? He has transferred his autonomy to the automated system and cannot really be held responsible. But who can? The designer? The manufacturer? The owner of the truck company sending his drivers out with the automated braking system?’

To aid the development of the automated braking system, a simulator is built shaped like the cabin of a truck. Test subjects will try out the system and their behaviour will be studied by psychologists. Meijers: ‘Apart from a system that completely takes over braking, we are also looking into other, less far-reaching ways to deploy such a system. One could, for example, stimulate people to follow the optimum braking curve by showing them how much energy they can save, or by using light indicators to simulate the ideal braking pattern. An ethical issue arising from this is how far one can go to persuade people to behave in a certain manner. When does persuasion become manipulation?’

For projects on a much larger scale, i.e. the construction of large infrastructural projects, ethical issues come into play that should also be discussed from a very early stage onwards. Meijers: ‘When does persuasion become manipulation?’

Derksen, who got her bachelor’s degree from University College Utrecht and obtained her master’s degree from the University of Wageningen, is intrigued by the technological way in which biomedical engineers approach their work. ‘The engineers consider the body as much a machine. Cells to them are a resource for engineering. They do not realize that their work is not only technical but normative too, these technological choices influence the way humans experience their bodies.’

In her PhD thesis, which she defended in 2008, she concludes that biomedical engineers have a professional responsibility for the way they (tissue) engineering influences humans in how they experience their bodies and their possibilities. Derksen: ‘One of the ways in which to take this responsibility is by having more direct contact with patients and with the daily running of the healthcare system. That might lead them to realize that the body is much more than a whole for carrying their technical innovations.’

Like an anthropologist studying an unknown people, that is how Mechteld-Hanna Derksen (30) studied the biomedical engineers working on tissue engineering. In particular those working on growing a living heart valve that can be implanted in newborn babies with a heart condition. What she realized is that the engineers approach the subject primarily from a technological angle. They focus on the heart valve and the technologies they develop to engineer heart valves; the body, and left alone the person, is for removed from the equation. This tunnel vision can be explained by the sheer number of technical difficulties one encounters when trying to grow the cells for a heart valve. ‘But they still need to realize that they are not just working on technological problems, but also on normative ones,’ argues Derksen. A normative perspective is one of the ways in which biomedical engineers can look at that responsibility to be having more direct contact with patients and with the daily running of the healthcare system. That might lead them to realize that the body is much more than a whole for carrying their technical innovations.’

1.5 per cent. The result of this would be that future profits would be projected much higher, thereby making the investment in renewable energy projects much more attractive.

Quite a plausible argument, which was duly embraced by former Prime Minister Tony Blair and formed the basis of his ambitious climate policy. This in itself also raises certain ethical questions on how to deal with uncertainty. Meijers: ‘Climate policy is based on the assumption that anthropogenic CO2 production is causing the atmosphere to warm. This quite small rise in temperature is believed to have a lot of different effects that will push the temperature up even further, maybe even up to 6 degrees over the next century.’

These climate scenarios are all based on models that use algorithms to harness current knowledge of the climate and the mechanisms that play a role in it. Meijers: ‘Since it is impossible to know everything, and since the phenomena we are talking about are probabilistic in nature, we know the model carries uncertainties that can influence the predictions to varying degrees. In this case it is very important that the people who actually build and use these models, the engineers or the climatologists, are very clear about the initial assumptions they used. The ethics researcher then has to take it a step further and has to look for uncertainties and hidden assumptions. That is very important that the people who actually build and use these models, the engineers or the climatologists, are very clear about the initial assumptions they used. The ethics researcher then has to take it a step further and has to look for uncertainties and hidden assumptions. That is very important.'
’The ethics of technology has traditionally focused on the protection of individual rights and interests in the development and use of technology. With our research we want to create a framework from that also looks at the broader implications of technology for the quality of life and the quality of society’, according to Philip Brey, Professor of Philosophy at the University of Twente and Twente representative of the 3TU.Centre for Ethics and Technology. ’The resulting assessments are not necessarily made from any ideological point of view, but are instead based on a thorough insight into the impact of a technology on the individual and on society.’

An example of such a broad approach is, according to Brey, the phenomenon of internet purchasing. This results in people visiting their local shopping areas less and less. Is this a good or a bad development? Brey: ‘The classical approach would state that shopping online is not morally problematic because it does not violate the rights or interests of others. Our approach does not just look at it as an isolated event, but also at the possible consequences of it on the cohesion of the social fabric. If online shopping were to result in the fraying of it– something you’d have to research first – then it might lead to a reduction in quality of life, which is not morally neutral at all.’

Ethics of technology is becoming increasingly important to the social and political debate, according to Brey. This has a variety of causes. ’Society is being privatised; ethical behaviour is no longer being enforced by law alone, but individuals and organisations are required to act responsibly themselves. Companies no longer get away with justifying their actions with the sole argument that they were not illegal. A second important change is caused by new developments in the fields of biotechnology, nanotechnology and information technology. These are high-impact technologies that are having a large impact on society and are generating many new ethical questions. Lastly, there is an increased need for ethical reflection amongst engineers themselves. To achieve the status of chartered engineer in the United States, you need to have
people who work in care are going down. Many institutions and companies are therefore working on the development of care robots. At the same time some ethical questions are looming that deal with the interaction between human and robot. Is it, for example, ethical to lead people to believe they are developing a meaningful relationship with a robot by giving the robot human traits? Does the presence of the robot lead to social isolation because the children visit less as mum or dad is being cared for in the robot? As this seems contradictory, she says. Brother seems to have subsided. Thanks to applications like Facebook and Hyves everybody can choose and maintain contacts with whom they want. Privacy is proving to be a shifting example. Brey: ‘Partly due to the Internet thoughts on privacy are changing. Thirty years ago people would refuse to take part in the census because they were afraid their information would be abused, but amongst the younger generations the fear of Big Brother seems to have subsided. Thanks to applications like Facebook and Hyves everybody can play Big Brother, so it seems.’

That statement fits well within another large research project headed by Brey within the Centre of Excellence, on how to evaluate the way in which information technology changes society and everyday life. Brey: ‘People evaluate the impact of information technology on everyday life both positively and negatively. You could conduct surveys and gather data about which percentages of which groups are positive and which are negative. For ethics research it is much more interesting to figure out the internal frame of reference people use to arrive at their judgement. What is a good life and what is meant by a good society and to what extent is that influenced by ICT?’

Someone for whom the good life means comfort and enjoyment is more likely to think positively about ICT than someone whose core values are based on spirituality. This way you can detect values that are important for the developers of technology and for the designers that make the objects.’

Ethics of technology has undergone an empirical shift in recent years according to Brey. This means that ethics researchers are increasingly resorting to technological and social studies to work out the impact of technological developments on society. As this often involves new technological developments of which you can at best make assumptions on the potential impact, case studies are often used. Brey: ‘When you start talking about those, opinions often become much less black and white about a given technology. You can talk about a “care robot”, a “friendship robot” or a “military robot”, rather than simply “the robot”. The debate then stops being about prohibition of technologies and begins being about what aspects are more or less desirable and how engineers can meet these criteria. It all becomes a bit more pragmatic and a bit less ideological.’

Finally, Brey also has explored the possibility of the so-called value sensitive design. ‘In the Netherlands both students and teachers are pushing for the inclusion of ethics into the engineering curriculum. The founding of the 3TU Centre for Ethics and Technology too shows that engineers are increasingly aware of the ethical and social implications of their work.’

The problem is, of course, that we often cannot envisage the impact of new technological developments. Brey: ‘We are often dealing with technologies that are still in their infancy. For nanotechnology, for example, we cannot begin to fathom what opportunities and challenges it will bring. Brey: ‘We are often dealing with technologies that are still in their infancy. For nanotechnology, for example, we cannot begin to fathom what opportunities and challenges it will bring. It is understandable that this design excludes some users, but it has to be recognised that this is a value-laden choice and that the machine could also have been designed in a more inclusive way.’

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In the future, we will need new solutions that help us to maintain our quality of life. In these new solutions robots will play an important role. For example, robots helping the elderly remain independent for as long as possible. The Intelligent Mechatronic Systems (IMS) centre has a long-term vision of robots that carry out tasks normally performed by humans but with greater precision, using extensive interactive and sensory abilities and with an energy efficiency superior to that of all existing applications.

To put that vision into practice, the TU Centre for Intelligent Mechatronic Systems is focusing today on research into and the design of advanced (movement) systems. For example, microsystems and precision robots for applications in mechatronics and the automotive and medical fields. The qualification ‘Intelligent’ underlines the innovative nature of our work, in which we make use of advanced software and control algorithms.

Research at the TU Centre for Intelligent Mechatronic Systems has four focal areas. Robotics: the development of intelligent robotic/machine systems; Precision Systems: the design of high-end mechatronic systems subject to extreme performance demands of speed and precision; Microsystems: the realization of miniaturised devices with very high precision; Distributed and Embedded Systems: the discipline of control technology to enable the control of complex systems.

The multidisciplinary research field of IMS makes an important and innovative contribution to the high-tech systems industry in the Netherlands. The advanced knowledge of the universities supports and promotes innovation by industry in this field, and also ensures a constant stream of young graduate engineers and PhDs.
A robot can beat you at a game of chess, but if you were to ask it to carry a cup to the kitchen, it would fail. ‘Human-like movement could help robots develop a form of intelligence more like our own’, believes Martijn Wisse, associate professor in Mechanical Engineering, who uses biology as the inspiration of his research into robotics.

A few years ago, Wisse and his colleagues not only made the journal Science, but also the national and international press. The reason for this publicity was Denise, a robot that walks like a human. Where other robots move on wheels or by alternating standing stably on one of two legs, Denise moves - just like us - by falling forward in a controlled manner. Gravity is used to take the next step, which means this mode of transport uses up very little energy. The upper body and arms of Denise move in opposite direction to the legs, making Denise remarkably stable.

Denise models the concepts of what Wisse refers to as ‘biorobotics’, a term which carries a double meaning: ‘on the one hand we want to let biology inspire us. On the other hand it refers to the surroundings in which we want the robots to function. Industrial robots do their work in highly defined surroundings where everything, down to the last screw, is in place. Our biorobots have to be able to function in domestic situations, or even in a hospital, where not everything is so tightly ordered. This means they have to be able to adapt to their surroundings. On top of that they have to be safe for those surrounding them. An intermediate scenario is a greenhouse; where robots can be deployed to, for example, pick tomatoes. On the one hand this is factory-like, but because the tomatoes do not always hang in the same place, it requires the robot to have adaptive ability also.’

Human-like locomotion is not only smoother and more efficient, but could be the key to a type of machine intelligence more closely resembling human-like intelligence. ‘There is a group of developers – myself included – that believes in embodiment. We think that intelligent behaviour stems from the interaction between brain, body and surroundings. You can develop artificial intelligence all you want, but if this intelligence is not grounded by means of a body, it will...’
remain artificial. And with that the communication between man and robot will remain unnatural.’ Wisse does emphasise that embodiment is not a rigid scientific concept. Some indications exist that human intelligence, at least partly, is rooted in our ability to move. If a robot is to carry out domestic or medical tasks independently, where he needs to anticipate human needs and feelings, it would help if he occupied this world in a similar manner. Wisse: ‘You could compare it to humans that have been blind from birth. To them, for example, colours such as green or red have a completely different meaning than they do to us.’

To test the embodiment hypothesis – learning through movement – you need biorobots that move in a similar way to humans. Denise was one of the first examples, but nowadays she has a few offspring, including Tulip, the robot footballer. ‘A big difference is that Denise still had pneumatic muscles, whereas Tulip has muscles based on an electromotor with a spring. It requires a lot more technology to regulate this, but does make the movements much more supple and natural.’

As a straight-up mechanical engineer, it is Wisse’s aim to control the movements of the biorobot with as simple mechanics as possible; so without using sensors and feedback systems. The electronics used for the locomotion of Denise, for example, are no more complex than those in a simple mobile phone. Another example is the robot hand that can pick up bricks without dropping them. ‘Purely mechanical’, says Wisse.

‘That in itself is fascinating’, says de Boer. ‘It gets even more interesting if you translate those analyses to a machine. Man, or even nature, as inspiration for technology; that is what makes it a very challenging field.’

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Demands for increased speed of production and higher accuracy put more and more pressure on the performance of machinery. In order to stabilise equipment at higher power levels they are also getting heavier and heavier. ‘The elephant is moving the mouse’, states Elena Lomonova, ‘more and more heavy equipment is reaching its operational limit. That is why our research is going right back to basics: the underlying physics.’

The research of Lomonova’s research group is divided into a series of different clusters. One of these is ‘power quality’ and looks at the quality of the electricity. Lomonova: ‘This is an important theme for stand-alone systems, such as airplanes, which are controlled pretty much fully electronically (fly by wire). For electrical grids stability is crucial too. Due to the rise of renewable energy, such as wind and solar power, the production of electricity is increasingly decentralised. This implies that the supply is of a much more variable nature, so to align the variable demand with the variable supply a smart electricity grid is needed. Within the ePe group a multi-port converter has been developed to convert electricity from a range of different sources into electricity of a constant quality, with very high efficiencies.’

A second cluster works on contactless energy transfer for, amongst other things, charging electrical vehicles. This simplified design does not need contacts and avoids complex wiring. Therefore, it is becoming increasingly important, especially for newly developed plug-in vehicles that have to be charged in a large variety of circumstances. Furthermore, different vehicle on board workloads, as can be caused by acceleration or deceleration, have to be trapped in storage devices. Lomonova: ‘We are working on bi-directional systems, which allow for the storage of the energy to be released when the car slows down. These energy recovery systems already exist, but are mainly based on conventional technology. As such, we are researching contactless charged new electric drive train configurations to minimise the number of electric conversions.’

The third cluster within the group looks at contactless movement for high-precision production systems to make things like wafer steppers, electron microscopes and other high-precision...
evasive manoeuvres (the moose test).
becoming unstable, or even tipping over, in corners and during sudden
high centre of gravity and a small footprint. This can result in the car
the current suspension systems are not very suitable for cars with
say the riblike road markings at a traffic light. a further problem is that
in the road. In technical terms, they are said to have a relatively low
which costs energy. They also do not respond quickly enough to bumps
The current generation of cars with active suspension is usually fitted
on a circuit instead. ‘We hope to be ready to
to SKf. Gysen: ‘We hope to be ready to
stabilise an item weighing 3 grams, an apparatus weighing 3000 times that amount is required.
energy levels are necessary to power the processes. as acceleration is equal to the force divided
This challenging concept is being developed because current high-precision manufacturing
to deliver the required forces and torques. Lomonova: ‘Classical linear actuators have limited force
to do anything else, even if just to breathe… Using model-based design we
have accurately modelled. This allows for active control
of the system. The invention has been patented.
Another example of a current project proposal, in a completely
different field, is the development of high bandwidth systems, which can anticipate the behaviour of the actuator as accurately as possible and use it to make
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‘We’re at the dawn of a robotic wave’, says Stefano Stramigioli. ’It is no longer a question of ‘whether’ but a question of ‘when’ robots will populate our houses, hospitals and care homes to lend a helping hand. Together with our colleagues in Delft and Eindhoven we are working on the concepts and underlying technologies that will allow robots to move safely in a constantly varying environment.’

The whole world knows the story of little Hansje Brinkers, the boy that saved the Netherlands by putting his finger in a hole in a dyke. This is of course a fairy tale. In reality the dykes in the Netherlands are guarded by levee patrollers, but only when the water levels are high. Stramigioli: ’This inspection of the dykes would be a perfect task for robots. We are currently working on a project where a swarm of robots, similar to the Mars rover, continually monitors the strength of a dyke.’

Using robots as levee patrollers is just one of numerous examples of robots working at providing services. Another example of this is the Pirate, a robot that can check gas pipelines for leakages. These kinds of inspections need to be carried out every five years. Stramigioli: ’Normally, this inspection is done on the surface using sniffers that detect escaped gas. It would be much better to be able to inspect the pipelines from within for weak spots before a leak has even sprung. An additional advantage is that when you know exactly where the weak spot is, you can dig a much smaller hole to repair it. Checking for leakages is quite a complex task and the robots need to be able to travel independently through long stretches of pipeline. That means that it has to be recharged by induction. It also has to be able to recognise and navigate bends in the pipe and T-joints.’

Pirate and the Levee Patroller are two examples of robots leaving the highly organised industrial domains and venturing into the public arena, where not everything is fixed in place. They are part of the new robotic wave that will lead to robots populating our personal lives too. In terms of the interaction between human and robot, it is important for robots to behave as humanly.
as possible; these robots are referred to as humanoids. Stramigioli is developing a humanoid head, which will be one of the parts used in the 3TU project Bobby, a robot that can be used in its eyes are not looking past its conversation partners but at them. The head can also be used as part of a complete humanoid. One that can walk, make coffee, clean and, for example, program the DVD player. The next step is the development of the limbs. The three universities of technology are also collaborating intensively on this. Each of the universities is in possession of a TULip, a 4-foot tall lightweight robot that walks like a human and is taking part in the Robocup, the football world cup for robots. Football-playing robots may sound frivolous, but the competition is generating a lot of knowledge that can be applied elsewhere. For example, in robots that are used in healthcare. Stramigioli: ‘One of the applications considered a challenge for me is the Reflex Leg, a prosthetic leg for people who have lost their own leg. The Reflex Leg gives patient feedback on the position of the leg using vibrations or electrical signals. This means they do not have to continually check the position of the leg visually. Aside from that we are also trying to make the prosthetic automatically remove the need for batteries. Stramigioli thinks that the switch robots are making from an industrial setting to the public and private space has led to an exponential development in robotics. ‘It has not always been this way’, he says, ‘but robotics is hot right now with both students and – not unimportantly – financers. When the robots will actually be assisting us in everyday life, I can of course not predict, but I think it will be much sooner than we think’.
The objective of the 3TU.Centre for Multiscale Phenomena is to achieve a better understanding of the macroscopic behaviour of gases, fluids and solids on the basis of the underlying structure and forces on the mesoscopic and microscopic scales. Linking experiments and models at different scales into integrated simulation tools is considered to be an important scientific challenge. We need this knowledge to better understand the behaviour of wide-ranging but essential topics concerning us all: from the flow of gas and particles in a reactor to the mechanical behaviour of flexible displays.

One example is the flow in a fluidised bed, a chemical reactor used in the process industry. In this reactor gases are passed under pressure through a catalyst particle bed. At the most detailed level the flow of the gases is calculated at a much smaller scale than that of the particles. The results provide information about the interaction between the gas phase and the particles. This information is used to calculate the interaction between the particles at a larger scale. Finally the information is used in the continuum model, which describes the flow in the entire fluidised bed. The exchange of information based on the phenomena at different length scales makes it possible to predict the flow behaviour of gas and particles in the reactor accurately.

The centre’s research will lead to models and computer programmes for use in practice. Knowledge transfer also takes place through doctoral candidates who, after completing their studies, find employment in companies and technology institutes. An important added value of the 3TU.Centre for Multiscale Phenomena is a further strengthening of the collaboration between the groups working in this field.
Multiphase flow systems are encountered regularly in industry. In process industries, for example, various combinations of gases, liquids and solids can be found that need to be mixed. Also in pipeline transport, when gases and liquids travel through pipelines together. ‘Our studies into multi-phase flow lie on the interface of theory and application’, says Rob Mudde, professor in Multiphase Flows at the Delft University of Technology. ‘Using experimental and numerical techniques we try to develop tools for the design of efficient and safe installations.’

Through the 3TU.Federation, Mudde’s group owns a unique installation to map flows in so-called fluidised beds where a fluid or gas can be passed through a powdered solid, such as finely ground coal or a powdered catalyst for the cracking of crude oil. This can be done at high pressure. Gas flows from the bottom of the vessel upwards, resulting in the powder starting to behave like a fluid. The main advantage of this fluidised bed technology is that the contact between the powder and the injected liquid or gas is much better than in a fixed bed reactor.

‘In order to optimise the reaction conditions, we’d like to know exactly what happens in such a fluidised bed’, says Mudde. ‘The problem is that mixtures of powders and gases or liquids are not very transparent. One-phase flows have been beautifully imaged using lasers and high-speed cameras, but normal light doesn’t penetrate further than about 3 particles into a two-phase flow. That is why we use X-rays to record the movements of the mixture.’

Recently – funded by the 3TU.Federation – a room was made with floors, walls and ceilings consisting of 5 mm lead plates. The room contains three industrial X-ray sources, which are set up in a triangle. At the centre of the triangle is a glass tube containing very fine sand. By blowing air or water into the vessel from below the sand will begin to float, which results in a fluidised bed. Mudde: ‘As the system is in motion, you cannot rely on single photos, but instead you need to take a continuous stream of pictures. The experiments are a bit like taking CT scans of the fluidised bed, where we measure direction and flow speeds every ten milliseconds.’
trying to model on the computer. And small-scale phenomena, a fully turbulent flow, all of which I am trying to model in the computer.

These elements combined lead to a complex combination of large and small-scale phenomena. Mudde: ‘Combining experimental data and numerical models provides information that can really help the people that design the installations. They do still need to use their vast experience, as there is still very much an art to designing these installations.’

The matter is complicated further by the fact that micro-organisms convert the sugar into carbon dioxide, the product and biomass (more micro-organisms). Günyol tries to incorporate these conversions into his models for predicting sugar concentration and oxygen levels. ‘In principle I could use my models to calculate the sugar concentration and oxygen level at any point in the reactor at any time after the start of the reaction. In practice, this requires too much computer power, which is why I make use of approximations. The eventual goal is to establish the parameters required for designing an industrial scale reactor, such as inlet positioning, shape of the vessel, stirring power. By choosing these parameters correctly, you could prevent cloud spots, areas where sugar concentrations and/or oxygen levels are too low, as this is where the yield of the process is limited and unwanted side-reactions may take place.’

The high-level industrial X-ray sources used to make the CT-scans are like those used to scan luggage at airports. Mudde: ‘The X-ray equipment used in hospital isn’t quick enough to image the motion of the mixtures; at least, not with the level of detail that we require. We have to detect perturbations in the paths of the X-rays with a series of detectors instead of taking a picture. Using these we make a three-dimensional computer model of the flow patterns in the fluidised bed reactor.’

Using this computer model, Mudde and colleagues try to answer questions with regards to, for example, the effect of the speed of the inflowing gas on the progress of the reaction. Or what the exact shape of the reaction vessel and/or the gas phase is to be to prevent so-called hot spots, areas where insufficient mixing occurs. Mudde: ‘Combining experimental data and numerical models provides information that can really help the people that design the installations. They do still need to use their vast experience, as there is still very much an art to designing these installations.’

The demand for optimising reactors has increased, especially in the bulk chemistry sector. Mudde: ‘The investments needed there are large, but the profits per kilogram are small. The margins are very narrow, meaning that there is a real need to get the most from the installations and the source materials. The chemical industry is also subject to very tight environmental regulations, which could be met by end-of-pipe purification. It is usually cheaper and more efficient to prevent emissions in the first place through a well-planned reactor design.’

Since the end of the 19th century, when the Gist and Spiritus factory was founded in Delft, a lot of research time has been dedicated to bioreactors and the flow phenomena herein. This mainly involves the multi-phase flow of gases and liquids. Mudde: ‘One of the classical processes is the conversion of sugar into alcohol using baker’s yeast. This is performed in reactors a few hundred cubic feet in size. The yeast cells are suspended in water to which sugar is added continuously as molasses. At the same time air is blown into the vessel from the bottom. These air bubbles need to be distributed evenly throughout the vessel otherwise oxygen-depleted pockets will form in which unwanted by-products can be produced. We try to model these processes too so the designer can improve them.’

Another application that is being researched in Delft is the transport of liquid-gas mixtures through pipelines. Natural gas, for example, consists of a mixture of gases and so-called condensates, compounds that condensate when the gas is transported from deep in the well to the surface. During horizontal transport, for example to get the gas to shore, the gas will flow faster through the pipe than the liquid does. This difference in speed can cause slugs to form; large plugs of mostly gaseous or liquid materials. Some slugs will grow as they travel the pipeline, evaporate or dampen out and disappear before they reach the outlet. If large slugs reach the outlet of the installation at the end of the pipeline, it can become overloaded and possibly damaged. A slug catcher can be used to prevent this by catching the slug before it reaches the installation. Mudde: ‘Slug catchers are basically big barrels, usually of quite excessive dimensions as the size of the slug is unpredictable. They take up a lot of space, quite often in space-constricted areas such as drilling rigs. It would therefore be worth a lot to the oil and chemical industries if they could prevent, or at least predict, slug formation.’

The Group in Delft owns a 400-foot pipeline that can be used to study the slug phenomenon. Mudde: ‘We measure flow speeds, in this case those of a mixture of air and water. When the difference in speed gets too large we start to see waves forming. At a given point the wave amplitude gets so large that the waves touch the top and the sides of the pipe and cause a – temporary – blockage. The pressure from the gas rushing through, however, is so high that this liquid plug is blasted through the pipe at very high speeds. We try to model this process and use the models to suggest measures to prevent slug formation. For example, the application of ridges in the pipe can break up the slug. Again, the designers can use the knowledge we have gained to their advantage.’
Mechanical properties of materials, like stiffness, strength and damage tolerance, are not simply determined by their chemical composition, but also by their underlying microstructure; the way the crystalline and amorphous phases are arranged, how they are connected and how they deform in relation to one another when the material or product is subjected to strain. Understanding and, more importantly, predicting the behaviour of materials and high-tech products based on this underlying microstructure is the aim of the Mechanics of Materials research group.

‘Prediction of the mechanical behaviour of materials and constructs is usually based on conventional testing techniques like tensile, compression, shear or bending tests’, says Geers. ‘These experiments basically rely on deforming, loading or even breaking individual samples in a commercial testing machine. Those classical tests are widely used in industrial practice to determine strength, stiffness, ductility, resilience, etc. They typically allow engineers to quickly assess the properties of materials as they are used in our day-to-day lives, ranging from sophisticated components in aircrafts and engines to commonly-used domestic devices.

From a materials science perspective it is more common to investigate materials using different microscopy methods.’

‘In trying to bridge microstructures to properties, we aim to construct a bridge between materials science and the mechanical engineering application of materials’, continues Geers. ‘In doing so, we established a marriage between mechanical testing and microscopic visualisation, complemented by advanced computational models to achieve the desired predictability. Our multi-scale lab is equipped with different small test frames that can be used in combination with different microscopic visualisation techniques, like electron microscopy, optical microscopy, atomic force microscopy and 3D micro-CT scanning. The observations and measurements carried out at different scales enable us to translate our understanding in advanced models of the materials studied, in which we integrate the explicit role of the microstructure.’

**BRIDGING SCALES**

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The resulting models enable predictions that are very interesting for a wide range of applications. One example is the research carried out in the Materials Innovation Institute on Corus’ polymer-coated steel, which is typically used in the packaging industry for food and beverage cans. Corus supports its clients by providing detailed models that enable them to simulate the manufacturing process. Geers: ‘One of the problems in this process is hidden delamination, whereby the polymer coating comes off the underlying steel layer at a small scale, making the cans vulnerable to corrosion. We are analysing what happens here on different scales, resulting in a numerical model of the delamination allowing us to predict the occurrence and extent of delamination events.

With properly determined material parameters, these models can be used in process simulations to improve the process, the product or the material itself.’

Another example, whereby the combination of testing and visualisation has potential is in preventing cracks in paperboard packaging materials. ‘It may sound low-tech,’ says Geers, ‘but at a small scale, paper has a rather complex unstable microstructure that raises interesting research questions. ‘To make a box from corrugated paperboard, you need to fold it. To do this, the paperboard is creased first along its folding line. During folding, the creased paperboard may present cracks that compromise the integrity of the resulting box. The prediction of the occurrence of such cracks is quite difficult: the underlying paper has an exciting fibrous microstructure, the behaviour of which strongly depends on environmental factors, such as temperature and humidity.’ The ability to predict the mechanical behaviour based on the underlying substrate or initial microstructure is also important for the development of a variety of new products. Examples of such applications can be found in ongoing collaborations with companies located on the High Tech Campus Eindhoven: flexible displays, photonic textiles, stretchable electronics and alsorollable solar cells.

Geers: ‘A new generation of electronic devices and applications are being developed by mounting the electronics and wiring on a flexible or even a stretchable substrate. The resulting products are therefore exposed to mechanical forces during their normal service life, which emphasizes the critical influence of their mechanical properties. To determine the reliability and product lifetime, it is important to predict the behaviour of these new generation devices under realistic service conditions, including the role of temperature, humidity, incidental impact loads, etc.’

The mechanical properties of a product are in part determined through the processing history of the material used in making that product. Each manufacturing technique alters the underlying microstructure in a substantial way. Within this context, the Mechanics of Materials research group has developed a reconfigurable computer-controlled discrete die that consists of small discrete pins that can be repositioned individually and automatically in order to give the die various possible shapes in a minimal time. Geers: ‘This development was part of a PhD project researching to what extent the microstructure is influenced by different deformation routes leading to the same final product shape. The technique allowed us to validate a fairly complex model for metals that accounts for their evolving mechanical properties. What is quite nice is the fact that the PhD student successfully continued this development in a spin-off company that aims to commercialise and upscale the technique.

Switching between micro-structural and macro-scale properties is not only important for the materials as such, but also the products they are used in. ‘Bridging the fields of mechanics and materials science in a mixed-numerical-experimental approach is the way to go,’ says Geers. ‘As a result of the ongoing miniaturisation, products or components therein are made smaller and smaller. At these small dimensions one, among all other factors, is the influence of the microstructure; scales, making the two disciplines inseparable’. The focus on multiple scales and multiple disciplines naturally steered Geers’ group in maintaining intensive external contacts: first and foremost the other two universities of technology, but also other universities both within the Netherlands and abroad. Close collaborations with industry are also well in place, Geers: ‘Our strength is integrated fundamental research: experimenting, modelling and predicting the behaviour of materials towards products. Our links with industry are indispensable to manifesting a direct practical impact.’
‘Everything flows’ said the Greek philosopher Heraclitus around 2500 years ago. But what exactly happens when things flow and how macroscopic events like vortices relate to the properties of microscopic particles is the subject of the ‘Physics of Fluids’ research group at the University of Twente. Together with colleagues in Eindhoven and Delft they look at heat transfer and the behaviour of droplets in turbulent streams. This may sound highly theoretical, until you realise that these are phenomena taking place in combustion engines, printers, oceans and clouds.

One of the subjects the group of Detlef Lohse studies, together with the Eindhoven University of Technology, is heat-induced turbulence. ‘If you heat a vessel – say a reactor vessel in industry – from the base of the vessel, the heated fluid will rise as it becomes lighter than the colder fluid above it. In reverse, the cold fluid will move to the bottom due to gravitational pull. This results in a lot of, apparently random, convection currents.’ These convection currents can be influenced by rotating the whole vessel around its axis. This creates turbulence: the convection no longer happens in layers – it is not laminar – but moves in vortices. These systems are ubiquitous according to Lohse, as in the Earth’s atmosphere, where the movements of warm and cool air happen turbulent, but also in oceans and even the Earth’s crust, where turbulent convection currents cause the movement of the tectonic plates.

Lohse: ‘In collaboration with the universities of Eindhoven, Rome and California, we have studied how and why heat transfer improves when you heat the vessel from below and spin it round its axis with increased velocity. You can observe the plumes of warm liquid rising and plumes of cold liquid sinking thereby forming a vortex; little whirlpools that get stretched further and further in a vertical direction, thereby drawing liquid away from the bottom as well as the top of the vessel. This results in the heat convection increasing by up to thirty per cent for optimised rotation speeds. We now understand the mechanism and can simulate it on the computer where the flow patterns we calculate fit the experimental data exactly.’
That knowledge could, according to Lohse, be used to reduce the drag ships experience when they were the first to describe the way in which it happens. Turbulence. It was known before that bubbles can reduce friction in a turbulent stream, but was from eight to – in some cases – twenty to thirty per cent, depending on the level of words less force was needed to keep the inner cylinder spinning at a given speed. The difference in drag exerts on the cylinder for a given rotational speed. Excitingly, this drag was reduced, or in other words less force was needed to keep the inner cylinder spinning at a given speed. The difference was from eight to – in some cases – twenty to thirty per cent, depending on the level of turbulence. It was known before that bubbles can reduce friction in a turbulent stream, but we were the first to describe the way in which it happens. That knowledge could, according to Lohse, be used to reduce the drag ships experience when sailing. One could, for example, try to inject micro bubbles at the hull of the ship, allowing them to sail faster or use less energy. Two per cent less drag would mean two per cent less fuel. Further research, performed together with the Delft University of Technology and the Maritime Research Institute Netherlands (MARIN) showed that just the injection of bubbles, only has a short-term benefit. Lohse: "The roughness of the ship’s outer wall is most important in reducing drag. If it is very smooth, drag can go down by up to eight per cent. As soon as the wall gets rougher, for example by barnacle growth, the beneficial effect of the bubbles disappears completely. They do not even partly compensate for the increase in drag caused by the ship’s rough wall. To be able to utilise the effect of the bubbles – and a lot is to be said for it, due to the need to save energy – we must therefore also look at the microstructure of the metal the hull is made of and to the anti-fouling paints used." As well as looking at bubbles in turbulent flows, Lohse’s group, together with colleagues in Eindhoven and Delft, has recently started studying the behaviour of drops in turbulent gas flows.
It’s a very topical question: what is the sustainable energy source of the future? Will it be solar energy, wind or biomass? And will hydrogen be an important part of the energy mix in the future? In other words, how will we be able to meet the explosively increasing demand for energy while save the environment at the same time.

Unfortunately, nobody yet knows the answers. The fact is that there is quite still not a technology available that will provide an extensive and sustainable energy supply. Fundamental breakthroughs are necessary.

The 3TU.Centre for Sustainable Energy Technologies has therefore set itself the goal of making the entire spectrum of energy sources and storage systems sustainable. Solar cells, hydrogen production, wind energy, storage in batteries, nuclear fission and fusion, refining of biofuels, fuel cells, energy saving... all of them are subjects of the centre’s interest and attention.

A lot of scientific research will be required if we are to play a significant role in the coming energy revolution. As universities, we can best do this together. Because none of the universities by itself possesses knowledge about all the possible sustainable solutions. But together we can cover the whole energy supply domain.

The combination of all three universities has many top researchers and professors. The extra effectiveness that gives us has, for example, already enabled us as 3TU.Centre together with ECN (Energy Research Centre of the Netherlands) to set up the large scale ADeM (Advanced Dutch Energy Materials) project. Another significant achievement is the joint Master’s programme in Sustainable Energy Technology, which is developing into a highly popular 3TU course.

prof. dr. ir. Tim van der Hagen
Scientific Director
3TU.Centre for Sustainable Energy Technologies
It is a story we all know: the Earth receives more solar energy in a day than 6 billion of us would use up in about twenty years. The question remains, however, how to harvest this solar energy cheaply and efficiently in a form that our society can utilise. According to Laurens Siebbeles, professor in optoelectronic materials at the Delft University of Technology, a lot has already been achieved with conventional silicon solar cells that show an efficiency of around 15 per cent. ‘But’, he states, ‘if we want to meet a much larger chunk of our energy needs with solar energy, cheap and efficient solar cells have to be developed. To realise this, fundamental research into the interaction between light and new materials for the next generation of solar cells is needed.’

The interaction between light and matter and the electrical properties of materials are the research theme of Siebbeles and his group. They do not just look at materials for solar cells. Their research is also important for the development of energy-efficient LED-lamps and FETs (field effect transistors) and so-called nano-electronics.

‘Light is made up of photons’, states Siebbeles, ‘small units of energy of a given wavelength. When one of these photons bumps into a semi-conducting material, like silicon, it can give a kick to an electron in the material. This will convert the electron from a bound to a conducting state where you can extract and harvest it. The electron has a negative charge and removing it leaves a positively charged ‘hole’. These holes can also be harvested.’

Even though the present generation of solar cells is far more efficient than the first ones developed in 1946, Siebbeles believes the process can be made even more efficient. ‘First of all, conventional solar cells only use a small segment of the light spectrum, only the photons of certain wavelengths. A minimum amount of energy is needed to get an electron from a bound state to a mobile state. If a photon has got too little energy, nothing happens and the photon passes through the material. If a photon has too much energy, then the extra energy is lost in the form of heat.’
Quantum dots are tiny crystals, a few nanometres in size (a nanometre is a millionth of a millimetre) made up of a few thousand atoms. What is interesting about quantum dots is that their optical and electronic properties are dependent on their size. As the size of a quantum dot is varied by slightly changing their size, if you can stack several layers of quantum dots with different colours they will absorb the different wavelengths of light. This increased efficiency comes from the fact that the colour of quantum dots can be varied by changing their size. Houtepen has succeeded in making crystals between 2 and 10 nanometres in size. These well-defined crystals will be used to build two and three-dimensional structures. Or, more correctly, they self-organise into these structures.

Quantum dots have gained a lot of attention for their potential for application in solar cells, tens of nanometres in thickness, that can be applied nearly invisibly to roofs, cars and other surfaces. ‘To say that you could spray-paint them onto a wall is probably a tad exaggerated, but we are talking about a new generation of solar cells, which are much easier to make and install in principle and therefore much cheaper than current generations. Again, this is all far into the future; a lot of basic research needs to be done before we get there.’

One issue is how to harvest the mobilised electrons and holes from a quantum dot. In other words; how do you get the charges out of the quantum dot. ‘One of the possibilities is to combine quantum dots with conducting polymers that can act as molecular wires for charge transport. Our research has shown that charges can move along such polymers very rapidly, which would mean we could separate the electron and the hole before they recombine. At the moment we are building a novel electron accelerator, so we can see in more detail exactly what is happening with the mobile electrons and holes and how we can use this to convert sunlight into electricity.’

It will take a long time before we can expect to see solar cells based on multi-exciton generation in quantum dots. ‘It could be ten years, but also fifteen or twenty. We must first learn to control the process of multi-exciton generation and learn to harvest the charges. Once we can do that we have to then design a solar cell that is easily handled and does not degenerate when exposed to air and light. It is very basic research from which we are learning a lot, also for other applications such as LED-lights and novel transistors.’
The chemical industry in the Netherlands as well as the rest of the world depends to a large extent on oil. Imminent shortages and growing demand, mainly from up and coming industrial nations, are forcing chemists to look at other, preferably green, source materials. ‘Heterogeneous catalysis will play a key role in the conversion of green source materials into useful products’, says Emiel Hensen, professor in Inorganic Materials Chemistry at the Eindhoven University of Technology. ‘With catalysts, you can convert wood into plastics and liquid fuels.

Catalysts are materials that, when added in small amounts, can speed up a particular chemical reaction. ‘They are used extensively in chemical industry and have’, so says Hensen, ‘a large multiplier effect. The turnover of the Dutch chemical industry is around 50 billion euros per year. This is largely made possible by catalysts, whose turnover is only a small fraction of this amount. It is therefore not surprising that the Netherlands is one of the leaders in the field of catalysis research. The ‘Dutch School of Catalysis’ of which the three universities of technology form a key part is renowned worldwide in the field of catalysis.’

The end of catalysis is by no means in sight. Hensen: ‘Over the next fifty years the world energy consumption is estimated to double. It is highly unlikely that we can meet that demand using solely renewable resources. The primary task of society now is therefore to use existing fossil fuel sources as efficiently as possible and with as little environmental damage as possible.’

One of the possibilities is to not burn natural gas directly in power plants and in central heating, but to first convert it to hydrogen. The traditional method for this is steam reforming where natural gas (mainly methane) is reacted with steam and, using a metal-based catalyst, is converted to carbon dioxide and hydrogen. The carbon dioxide – a greenhouse gas – could be trapped and stored underground, whilst the hydrogen could be used to generate electricity, for example, by means of a fuel cell. The process could be made a lot more efficient and environmentally friendly if the carbon...
disappearing and the hydrogen could be separated straight after or even better during the reaction. The reason being that the starting materials and the products are in equilibrium; by removing one of the products the equilibrium will shift and nearly all of the natural gas will be converted to hydrogen. Hensen: ‘Together with the Netherlands Centre for Energy Research (ECN) we are working on a procedure for the simultaneous production and separation of carbon dioxide and hydrogen. The ECN has developed a membrane, whereby the actual reaction takes places within a membrane – a molecular sieve – which allows for the removal of the hydrogen from the carbon dioxide straight after their formation. Using spectroscopic methods we are trying to visualise how the reaction actually happens when using different catalysts. We are especially interested in the role of the structure of the metal nanoparticles on the reaction. The surface structure of these particles has drastic effects on the efficiency of the conversion and the stability of the catalysts.

As well as using fossil fuels more efficiently we need to consider switching to biomass as an energy source and fuel. This is already happening on a small scale. Ethanol is made from plant starch and edible oils is not considered sustainable. A lot of research is therefore focused on the use of the inedible parts of plants. Hensen: ‘One of the most ubiquitous, and therefore cheapest, green materials is cellulose. It makes up 40 to 80 per cent of agricultural and forestry waste and humans cannot digest it. If you use cellulose as a chemical feedstock or fuel you are not competing with food production.’

A large worldwide research effort focuses on the conversion of cellulose into ethanol using micro-organisms. This ethanol can then be used as feedstock for the chemical industry or as a liquid fuel for vehicles. Hensen: ‘We, together with some other research groups, are opting to use catalytic conversion – not microbiological, but chemical – because we think it is more efficient and yields better building blocks (basis of materials for chemical production).’

Chemically, cellulose is converted into HMF, hydroxymethylfurfural, in two steps – in future a one-step conversion may become possible – using metal chlorides as catalysts. Starting from HMF building blocks can be made for the production of plastics, or for liquid fuels. The efficiency of the conversion lies around 70 per cent which means that this proportion of the cellulose present in the source material, wood or agricultural waste, is converted into HMF. Hensen: ‘We are looking at what exactly is happening during the reaction. It appears that the catalysts ‘grab’ the glucose building blocks of the cellulose in a certain way and very rapidly converts them to fructose – a molecule related to glucose – followed by a conversion of this molecule into HMF. We can visualise this process using X-rays and other imaging techniques. On top of this, we can use quantum-mechanical calculations to make computer models of the process at the molecular level.’

The goal of all these efforts is to increase the efficiency of the reaction and to improve the quality of the final product. HMF. Hensen: ‘Catalysts used to be more of an art than a science. Nowadays, we have reached such a level, however, that we can design catalysts with desired reactivity. For this reaction, for example, we can improve the process by attaching the catalyst to a solid-phase carrier material. The advantage of a carrier is that you can easily remove the catalyst from the reaction solvent, in this case an ionic liquid (a liquid salt), and use it again. A second advantage is that the right choice of solid-phase carrier can increase the surface area on which the reaction can take place, which subsequently boosts reaction yields.’

In ‘normal’ catalysed reactions, like those used for refining crude oil, zeolites are often used as carriers; a packed bed of solid particles, in which the reactants are mixed, in the reactor. But with the catalysts currently being used as a feedstock for a wide range of industrial processes, it is also one of the fuels of the future. Ligthart: ‘When you work with catalysts with which you can use the hydrogen to generate clean electricity in a fuel cell, the CO2 could be stored but can also be used as a reagent in other petrochemical processes where methane is converted into hydrogen and carbon dioxide. Ligthart: ‘The process he is concerned with is ‘steam reforming’, a classical petrochemical process where methane is converted into hydrogen and carbon dioxide. Ligthart: ‘A second advantage is that the right choice of solid-phase carrier can increase the surface area on which the reaction can take place, which subsequently boosts reaction yields.’
The central theme of the Laboratory of Thermal Engineering is ‘playing with heat’. This ranges from the development of efficient methods to convert biomass and waste into useful fuels for producing e.g. electricity to the development of an intelligent reactor that uses heat much more efficiently. Theo van der Meer: ‘By using heat more efficiently, we can save a lot of energy.’

One of the research themes is the conversion of waste into oil that can be used in small power plants and ship’s engines. This process is called pyrolysis, which is the breaking-down of materials in absence of oxygen. It is a bit like making charcoal from wood, except that in Twente they are using it to produce liquid fuels. This is not a new thing but, according to van der Meer, ‘the amazing thing about this process, which is being developed by professor Gerrit Brem, is that the oil produced is exceptionally clean. It does not contain carbon particles and is also less acidic. This prevents complications during combustion. The process can also be performed on a small scale, so you could picture it being used in developing countries to make fuel from waste. This fuel can then be used to run a generator.’

Pyrolysis is especially useful for relatively dry waste streams. Van der Meer: ‘For more damp waste streams, like stems and leaves of plants we are developing supercritical gasification technology whereby biomass and water are brought together under such pressures and temperatures that the water becomes supercritical. This means that it is no longer liquid, nor is it gaseous. Under these circumstances the biomass and the water will react to form a gas that is rich in hydrogen, methane and carbon monoxide. This gas is an excellent fuel for a gas motor.’

The group looks not only at making new types of fuel, but also at the burning of them, for example in a gas turbine, furnace or boiler. This study forms part of the nationwide ‘Clean Combustion Concept’ research programme. Its aim is to develop new concepts in combustion technology that are more efficient and produce fewer oxides of nitrogen. One of these new concepts is flameless combustion. Van der Meer: ‘Normally you try to mix fuel and air as
It could still be a while before a chemical factory the size of a container (reactor plus supply systems) becomes reality. Roestenberg: ‘My research is aimed at the thermodynamics and heat transfer of the reactor. You can imagine that the materials begin to expand when temperatures rise this quickly. If this expansion is different for the cylinder and piston, it can result in a leakage, or the piston getting stuck. If we know more about the thermomechanics, we can design the reactor in such a way that this is prevented.’ Roestenberg, who obtained his Master’s degree in mechanical engineering, did not hesitate one moment when he was asked about this PhD position. ‘The group is good, the people are nice and – not unimportantly – I get to work on and study this revolutionary design. What may be the most fun about the project is that I get to collaborate with the inventor of the design.’

The group is part of a project that is aimed at the thermodynamics and heat transfer of the reactor. You can imagine that the materials begin to expand when temperatures rise this quickly. If this expansion is different for the cylinder and piston, it can result in a leakage, or the piston getting stuck. If we know more about the thermomechanics, we can design the reactor in such a way that this is prevented.

‘Another line of research focuses on heat transfer in stationary systems. A recent example is aDeM, produced quite a few PhDs over the years.’

The proof of principle of this new type of reactor was successful. ‘In order to improve heat transfer, we are developing a coating made of carbon nano-fibres; tiny hairs between 2 and 10 micrometres in length and with a diameter of 60 to 100 nanometres. These measurements are the data used by detailed computer models of the combustion process. These models in turn are used to optimise combustion processes and develop new ones. Another line of research focuses on heat transfer in stationary systems. A recent example is aDeM, the Advanced Dutch Energy Materials Innovation Lab, a large research collaboration between the three universities of technology (T3TU federation) and the Energy Research Centre (ECN). One of the themes within that programme is the development of an improved heat pump. Van der Meer: ‘In order to improve heat transfer, we are developing a coating made of carbon nano-fibres; tiny hairs between 2 and 10 micrometres in length and with a diameter of 60 to 100 nanometres. These vibrations are so large that they can cause the wall of the combustion chamber to rupture. It was first observed in the Netherlands about fifteen years ago in a power plant where coal gasification was used. Here a mixture of hydrogen and carbon monoxide is used mixed with air. The problems presented here formed the basis of our very successful research programme. It has produced quite a few PhDs over the years.’

Another project focuses on improving the heat transfer inside a chemical reactor. An interesting spin-off of this project is a new type of reactor, which slightly resembles a combustion engine. ‘The concept was developed by a Swiss professor in the 1960s, and then taken up in the Netherlands by Timo Roestenberg. The concept is based on complementary oscillating cavities. These are chambers in which the reactions proceed so rapidly that it needs to be roughly the size of a moped engine to still have an enormous production capacity. It works a bit like an engine.’

‘It works a bit like an engine,’ Roestenberg tells us. ‘Inside a cylinder, a free-moving piston moves up and down. This creates very high pressures alternately in the upper or the lower cylinder chamber depending on the position of the piston. This causes the temperature to rise rapidly, the so-called bicycle-pump effect. Reactions in the compressed chamber take place. Where current systems are big and slow, this reactor is superfast and very small. So fast, in fact, that you need to deliver the reagent streams at nearly the speed of sound to keep up with the reaction. ’