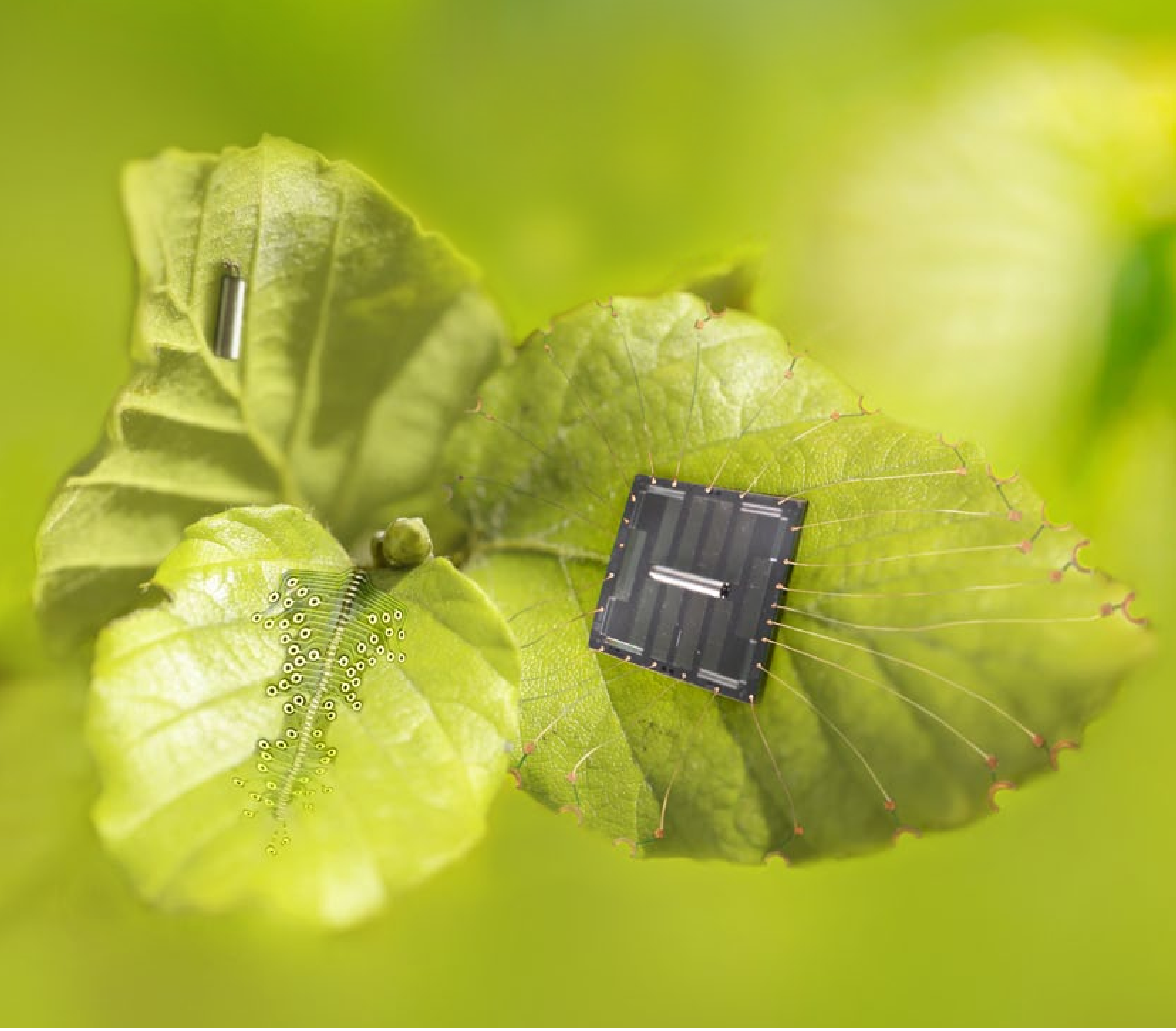

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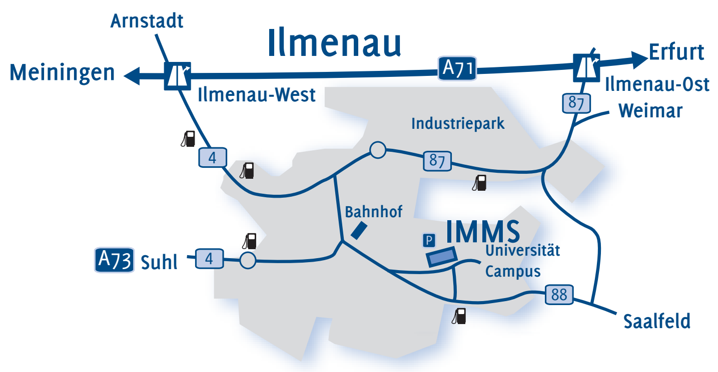

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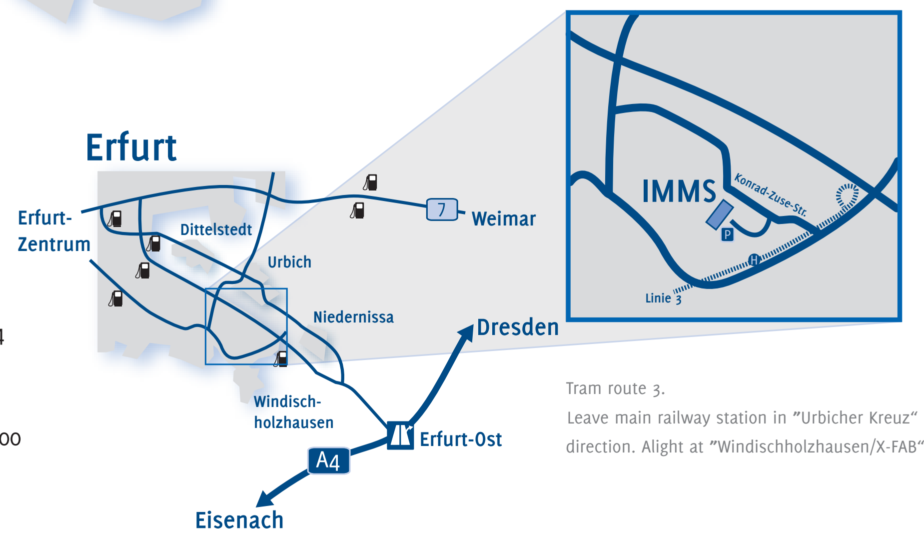

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IMMS

WE CONNECT IT TO THE REAL WORLD.

Contents

Abbreviations

ADC *Analog-to-digital converter*
ASIC *Application-specific integrated circuit*
BMBF *Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)*
BMWi *Bundesministerium für Wirtschaft und Energie (Federal Ministry of Economic Affairs and Energy)*
CAN *Controller area network (bus standard for automotive applications)*
CMOS *Complementary metal-oxide semiconductor*
DALI *Digital addressable lighting Interface (protocol for light control in building automation systems)*
DFG *Deutsche Forschungsgemeinschaft (German Research Foundation)*
DLR *Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Centre)*
EDA *Electronic design automation*
EFRE *Europäischer Fonds für regionale Entwicklung (European Regional Development Fund)*
ERDF *European Regional Development Fund*
FPGA *Field programmable gate array*
FTE *Full-time equivalent*
IC *Integrated circuit*
ICT *Information and communications technology*
IP *Intellectual property*
LIN *Local interconnect network (bus standard for automotive applications)*
MEMS *Micro-electro-mechanical system*
OCIT-C *Open communication interface for road traffic control systems – centre to centre*
OLED *Organic light-emitting diode*
RFID *Radio-frequency identification*
RMS *Root mean square*
SAE *Society of Automotive Engineers*
SENT *Single edge nibble transmission for automotive applications*
TU *Technische Universität (University of Technology)*

Foreword

Prof. Dr. Ralf Sommer (right) and Dipl.-Ing. Hans-Joachim Kelm (left). Photograph: IMMS.

Thank you for your interest in IMMS. Our Institute has been intensely active in 2014, helping our partners by bridging the gap between the first idea and a new application – both for them and with them. In our interdisciplinary projects, we have not only achieved the sort of pure research result that promises well for future technology but also produced ready-to-market solutions and devices. The future-oriented work has paved the way for the approach of Industry 4.0, Smart Mobility, the Digital Society, and Personalised Medicine as they come ever closer over the next few years. In pursuit of these visions, it is our intention to continue strengthening our bonds with joint networks, clusters and commissions, building up our research infrastructure, fostering the talents of young scientists and involving them early in well-chosen tasks.

We are pleased with our 2014 achievements. Reports on our scientific work at two leading conferences were named Best Paper. In addition, our industrial partners are highly appreciative of the eminently usable results we together produce and the constructive and efficient way they are produced. What we have achieved so far spurs us on to stay the course as a competent, reliable research partner enabling new developments to cross the divide between science and industry.

The funding of our Institute by the German 'Land' of Thüringen has given us the means to support all this activity. We express sincere thanks on behalf of the team and the industrial partners who have gained competitive edge from the help. Local SMEs, above all, have in IMMS the only Thüringen research centre for microelectronics and mechatronics. IMMS serves them not only technologically at the regional level but also by linking them together in widely coordinated public schemes which promote industrial progress. In recognition of the responsibility entailed, we have guidance from our Scientific Advisory Board and our Board of Directors on how to realise the policies in which we are agents. We are very grateful to these two bodies for their commitment. Our thanks go, too, to the Ilmenau University of Technology for superb cooperation, which constantly enriches our work, and, more than that, brings such close research collaboration that synergy effects are felt in both establishments right across the boundaries between disciplines. Thank you all – sponsors, business partners, friends and every person bearing us up in our endeavours.

And, within IMMS, thanks go to staff and students for the constructive, reliable way they contribute their knowledge and their efforts to promote our shared future.

This foreword and this report bring you an invitation to join us in our forward thinking and accompany us along our way.

Prof. Dr.-Ing.
Ralf Sommer

Dipl.-Ing.
Hans-Joachim Kelm

Collaborating with Ilmenau University of Technology

One of the inter-establishment teams of 2014, with authors from Ilmenau TU and IMMS. Their work on nanopositioning systems is a field in which the TU and the Institute have been collaborating for more than 10 years. Photograph: IMMS.

Being an affiliated institute of Ilmenau University of Technology (TU), IMMS benefits from networking with the university while the TU benefits from the Institute's close relations with industry. The TU departments with which IMMS co-operated actively in 2014 were 28 in number, from the broad fields of electrical and mechanical engineering, computer science and engineering, automation, mathematics, media and communications, while the academic subjects addressed included high-precision positioning and measuring machines, biomedical technology, sensors for monitoring of high-temperature processes, and RF technology for satellite-aided navigation. In parallel, the Institute operates in a close industrial network, in the form both of industrial clusters and of regional and national innovatory networks. These fields include automotive engineering, microtechnology, microelectronics and optics. Valuable impetus is given by the groupings. They are the chance to pool skills, use partners' technology and develop joint marketing strategies.

Joint research projects

In the context of ThIMo (the Thüringen Mobility Innovation centre) IMMS is co-operating in the PORT research group (PORT stands for Powertrain/radio train), which will be a powerful contributor to "green" manufacturing and resource consumption. The present IMMS report includes an article on energy harvesting which illuminates these research contributions in close detail.

In the DFG (German Research Council) project named MUSIK, IMMS researchers and members of the TU are working in partnership on the amplifying, controlling, oscillating and switching properties of MEMS (micro-electro-mechanical systems) in order to design MEMS in conjunction with the electronics for radio frequency circuits and systems. The results contribute to the MEMS2015 project also reported on in this document.

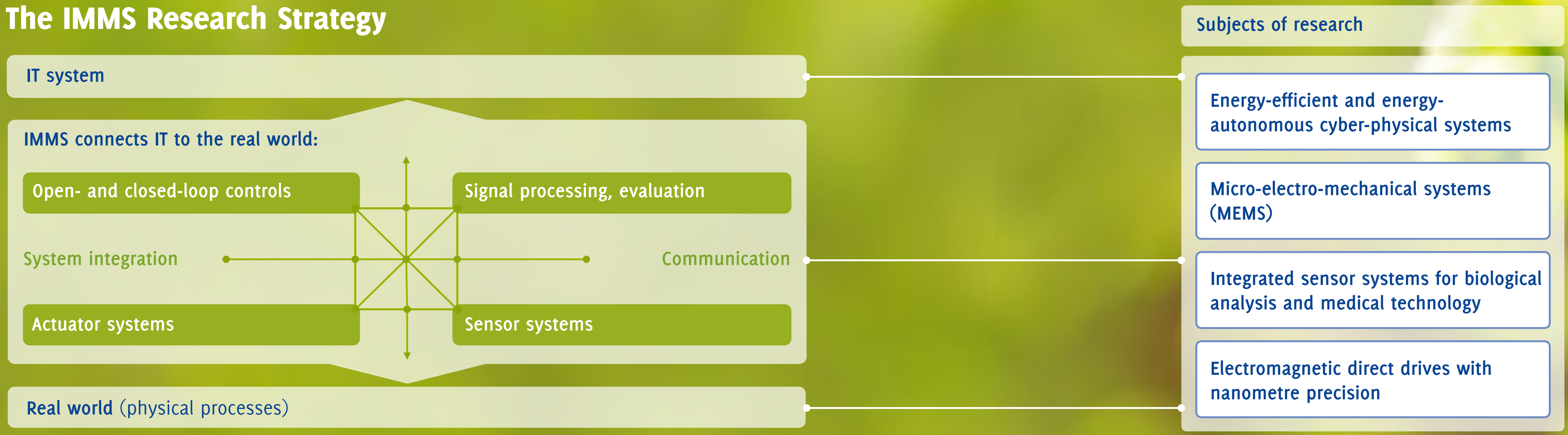
From the start of 2014, the 3-year-long KOSERNA project will see an industrial prototype developed that contains an even more robust and accurate receiver which is based on the results of the KOMPASSION project. For this, the TU has subcontracted the work on the front-end circuit to IMMS, who will also transfer the new designs to a second frequency band.

Joint encouragement of young academics

One way, but not the only way, in which IMMS complements the TU's teaching is the challenging industrial placements it offers. Another way is that various lectures and seminars are given by IMMS staff. Professor Sommer himself is, in his teaching role, involved not only in the AG Lehre (national working party on teaching) but also, together with IMMS, in the Basic Engineering School that TU has established. IMMS is both trainer and motivator, offering not only highly practical and relevant placements but illuminating guided tours.

There is a yet younger generation receiving the attention of IMMS and the University: at Kinderuni (Children's University) the more than 650 students aged between 8 and 12 heard a lecture in which IMMS gave a practical demonstration with many interactive games to show how music and signals can be stored and processed in both analogue and digital form.

The IMMS Research Strategy



"We connect information technology to the real world"

We are commissioned by our customers in science and industry and other partners in regional, national and international joint research ventures to pursue applied research and engineering in the fields of microelectronics, mechatronics and embedded systems. Our activities are driven by the need for technological contributions to help meet societal challenges like the protection of the environment, the efficient use of energy and resources, and the preservation of health and safety in industrial, public and private spheres.

Across this range we apply our skills to designing highly accurate, energy-efficient electronic and mechatronic systems which will measure and control physical processes and are networked into the virtual world of data processing.

In fulfilment of the Institute motto ("**We connect information technology to the real world**"), we research innovative integrated sensor and actuator systems that will capture, process, transmit and control process parameters for a wide range of industrial and scientific applications.

Our particular foci are fields of application and branches of industry which offer scope for the integration of electronics, mechatronics and software into smart solutions with high innovative and growth potential, especially

- automation,
- medical technology and life sciences,
- environmental technology,
- transportation and
- semi-conductor manufacture.

Our services include collaboration on research both pure and applied, research-related development from the feasibility study, creation of hardware and software and systems design and right through to the prototyping and the verification of the functioning prototypes. We join with strategic partners like Ilmenau University of Technology or various research centres and technological services in or beyond our region of Germany to address interdisciplinary research issues.

Subjects of research

Our scientific work helps develop such key areas as information and communications technology, microsystems and nanotechnology and helps all these to be applied in the future-oriented projects of Industry 4.0, Smart Mobility, Digital Society and Personalised Medicine.

There are four main emphases in our research:

- energy-efficient and energy autonomous CPS (cyber-physical systems),
- MEMS (micro-electro-mechanical systems),
- integrated sensor systems for biological analysis and medical technology, and
- electromagnetic direct drives with nanometre precision.

We pursue the engineering and methodology needed for development, integration and testing of application-specific sensor-actuator systems. The research projects in which we have been involved in 2014 and the relation they bear to our various research categories are presented in detail for you to read about in this annual report.

We connect science and industry

This vital bridging task cannot be undertaken in the context of the pure research conducted at universities, and yet, if an idea is to be taken from the drawing board through to the market launch of a product, it is sine qua non. Rarely can SMEs, with their few R&D resources, find the means within their own organisation of spanning the gap between research and product, a costly, labour-intensive task.

As a research institute serving the German "Land" of Thüringen we, therefore, make a very special contribution. We help increase the competitiveness of the small and medium-sized technological companies in the region with our product-related R&D input. It is our role to provide a technical infrastructure and collaboration schemes which enable electronic and mechatronic systems to be developed in specific response to the research needs of these SMEs.

IMMS not only builds but also strengthens this bridge between science and industry, firstly by collaborating closely in research and training that is shared with both the industrial partners and Ilmenau University of Technology, secondly by committing itself to research networks and clusters and thirdly by consistent encouragement of talented new engineers.

Research infrastructure

To support our customers long-term with electronic systems that are always up-to-date, one of our techniques is constantly to explore new methodology of manufacture and new R&D partnerships. Another is regularly to augment our range of technical laboratory equipment so as to remain competitive in the international scientific arena with all its challenges.

IMMS is engaging ever more intensively in research collaboration schemes concerning electronic micro and nano systems, working with leading national and European industrial and/or research enterprises. So as to gain entry into highly innovative projects, the Institute extended its semiconductor testing equipment at the end of 2014 by the addition of a semi-automatic analytic 300-mm wafer probing station as part of the SensorLab infrastructure project funded by the German 'Land' of Thüringen. The new equipment will enable IMMS to build up more international research cooperation in the coming years for the development and testing of microelectronic analog/mixed-signal/RF and smart-power circuits, so that the opportunities of state-of-the-art semiconductors are opened up to its partners in Thüringen.

Contact person:
Dr. Eckhard Hennig, Scientific Strategy Manager,
Eckhard.Hennig@imms.de

Voices from industry and academia

René Heidl,
Head of Indu-Sol GmbH.
Photograph: Indu-Sol.

René Heidl, Indu-Sol

"The devices and software solutions made by our company are the means of improving EMC quality around field buses in industrial plant. We were in search of a solution for our customers which would enable the parasitics on communication wires to be registered and evaluated while keeping the plant working. The aim was to create a small, mobile device which would be capable of much more than any previous analytic instruments or procedures because it enabled users themselves to identify sources of interference on site, to determine the level of interference and to store the data for analysis later.

IMMS with its many years of experience in energy-autonomous systems and in developing integrated hardware and software complemented our own work perfectly. The staff partnering us defined the exact specifications for the target system and developed for us a battery-operated current clamp which will take, process and store measurements in the kHz range over a period of 14 days. In addition, IMMS carried out a range of tests on magnetic circuits (and more), applied efficiency criteria so that the right hardware, analogue adaptive circuits and software elements could be selected, then developed the software and optimised the energy consumption of the entire system. We are more than happy with the product, which is now being mass-produced and is a valuable addition to our range. We estimate that we will sell about 200 of these current clamps a year, with prospects of an increase.

The collaboration was, besides, a smooth one, marked always by a problem-solving attitude with high self-motivation. It went without saying that the IMMS colleagues would find a solution when we asked for a modification; not only that, but they made various suggestions of their own, like the implementation of the menu structure, the conservation of the insulation and the positioning of the SD card. Thanks to the housing designed and made by IMMS as well, we have been able to go into the early stages of mass production with a complete, ready-made solution. For these early stages IMMS is still our supportive and competent partner.

We shall certainly come to IMMS again for help on combined hardware and software development so that we can launch further attractive products on the market, again with the benefit of their know-how in funded research projects."

www.indu-sol.com

Reinhard Jurisch, Graduate Physicist, Head of microsensys GmbH, Erfurt. Photograph: microsensys.

Reinhard Jurisch, microsensys

"In my role as a member of the industrial advisory council to the GreenSense research group, I have actively accompanied the research work done by IMMS over the last three years on the subject of smart energy-efficient sensor systems. The project scientists' aims were to develop microelectronic multi-sensors with an RFID interface and also to develop new ways of creating micromechatronic energy harvesters. My team members and I gave support to the working party in the form of detailed advisory sessions sharing technical know-how on RFID sensors and how they may be applied industrially. Very promising technology has emerged from the research work. In order to build on the results, IMMS has already become involved in new joint R&D projects which will, in collaboration with ourselves and other sensor companies, advance the field of networked industrial sensors. IMMS, being the sole research institute in Thüringen for microelectronic applications, has a central role for enterprises like ours in the region, acting as technology partner and coordinator for joint industrial research with public funding."

www.microsensys.de

Dr. Gisbert Hölzer,
MEMS Process Development,
X-FAB MEMS Foundry GmbH.
Photograph: X-FAB.

Dr. Gisbert Hölzer, X-FAB

"MEMS are an engineering product in great demand worldwide, and for that reason we are currently expanding our manufacturing capacity for this highly innovative corner of the technology market. In pursuit of the goal, we are also improving our design support products in the MEMS development field as an assistance to our customers. As well as our previous standard products, we shall be able in future to offer process design kits (PDK) for MEMS technologies. Along this route, our path has been smoothed by the close cooperation and company of IMMS in the MEMS2015 research project.

Firstly, IMMS designed test structures enabling material parameters to be analysed so that MEMS structures could be more accurately simulated. Secondly, IMMS developed a specific design flow strategy for accelerometers which can be used in the design and simulation of sensors that have a variety of purposes and features. The design flow makes use even at this stage of the first elements of a MEMS PDK. The sensors have already been manufactured using X-FAB foundry technology and their features measured at IMMS. The verification measurements are now being incorporated into X-FAB's MEMS technology development. In our shared discussions around the project, IMMS has frequently been a source of new ideas, for instance concerning MEMS layout verification.

For many years as we followed our 'More-than-Moore' roadmap, IMMS has been a support to us, acting as our most important research partner. The Institute melded together in sovereign fashion its skills in ASIC design and in micromechanics during the MEMS2015 project. And in the future, too, we look forward not only to making use of the expert, confident and collaborative skills of IMMS but also to benefitting from the Institute's high competence in organising publicly funded projects. We are already counting on continuing our successful cooperation with IMMS in the sphere of MEMS development and have applied for a successor project."

www.xfab.com

Dipl.-Ing. Eric Markweg, Mechatronics Development, TETRA Gesellschaft für Sensorik, Robotik und Automation mbH (experts for sensors, robots and automated systems). Photograph: Norman Petzold, TETRA.

Eric Markweg, TETRA

"We have developed a micromechanical system for measuring forces on a tiny scale in quality control for surface finishing in industry. The sensor head is suitable for rapid insertion into manufacturing equipment during production. An important element of this flexible, quick-change system is the integrated circuit designed by IMMS to register data on force and temperature very precisely and de-noise it for signal transmission.

With its high level of competence and experience in capturing and pre-treating sensor signals, IMMS has progressed the product considerably and, besides, contributed new design methodology to our development processes. Our partners at IMMS provided not only the ASIC but also looked at our MEMS system as a whole, making a decisive contribution to our new-found ability to offer a tailor-made solution for the intended use which has not so far been available on the market and even includes such features as smart error recognition.

We have for many years been appreciative of our cooperation with IMMS. In this project, we have once more benefited from their focused attitude to the work, their close checking of each point and their clear graphic representations. IMMS is for us a strengh and partner at every stage of a project, from the drawing board to the prototype, which was true in MEMS2015 and will be so in future."

www.tetra-ilmenau.de

Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. mult. Peter Scharff, Rector, Technische Universität Ilmenau (Ilmenau University of Technology, Germany). Photograph: Ilmenau TU.

Prof. Dr. Peter Scharff, TU Ilmenau

"As Rector of Technische Universität Ilmenau (Ilmenau University of Technology / TU) it gives me great pleasure that the year 2014 has been a successful one for our partner, IMMS. As an affiliated Institute of the University IMMS is particularly close to us in all senses, with its role of transferring results from shared research to the benefit of industry. The transfer of research and development is a task we un-dertake hand in hand in order to provide industrial partners who are of economic importance to Thür-ingen with the means of meeting global challenges in the shifting world economy. Our work focuses on e-mobility, micro- and nano-sytem integration and the needs of Industry 4.0.

We know from our long experience of IMMS that the Institute is a fast and highly flexible operator when it comes to converting research outcomes into solutions for industry. Indeed, no fewer than 28 of our University departments are currently in collaboration with IMMS. Our many years of working together have seen us progress many projects, bringing them to highly successful conclusions. The MUSIK project (Multiphysical Synthesis and Integration of Complex high-frequency circuits) is cur-rently in receipt of high praise from the German Research Council (DFG), so that we shall be able to continue the research together into the future at greater depth. The KOSERNA project (Compact Sat-ellite Receiver Systems for Robust Navigation Applications) has already brought us success. In this project, IMMS was commissioned by the TU to develop vital ASICs. Here, too, the joint work was rat-ed as excellent, by the DLR (German Aerospace Centre).

I am, personally, particularly pleased that we take the same view of our commitment in all our collaborative projects, which is that IMMS and the Ilmenau TU carry out their applied research for the bene-fit of society. And in the same way we both feel a sense of responsibility for encouraging the devel-opment of our region, especially that of the local cluster known as the "Technologieregion Ilmenau und Arnstadt". For this technology region it is our intention to achieve yet more in future.

In this context we are particularly concerned to encourage the next generation. The central emphasis is, of course, on the training of young scientists who possess not only knowledge and skills but also a sense of social responsibility. IMMS is firmly integrated into the University's teaching and training system. By supervising highly practical placements and students' work and dissertations for their BSc or MSc, the Institute is making a valuable contribution to the education and motivation of our students, enabling them to see and prepare themselves for practically relevant professional opportunities at an early stage."
www.tu-ilmenau.de

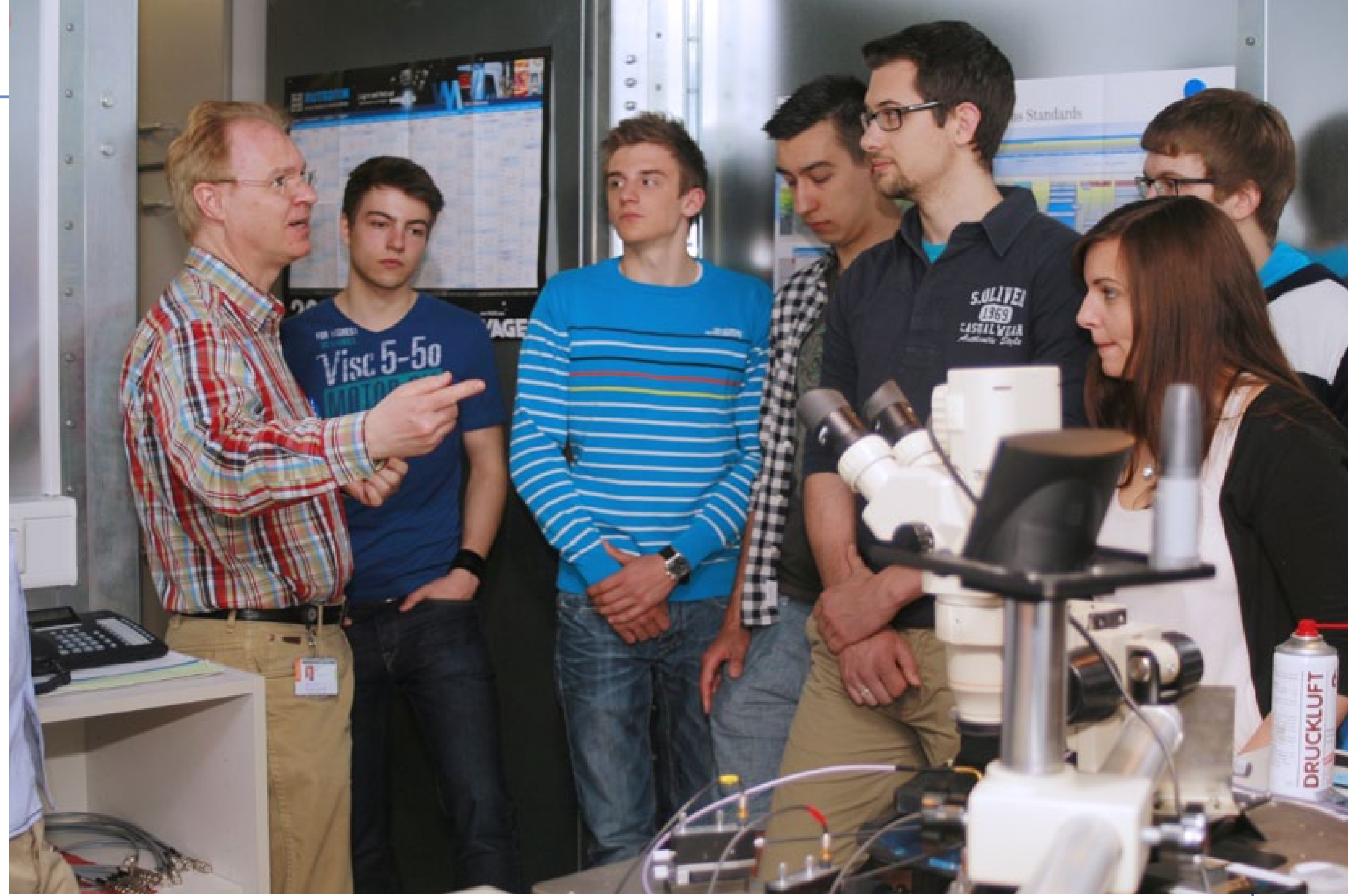
Lutz Wohlleben, ARS

"In our work, we test for leaks in pipelines using pigs while the pipeline is in full flow. The pig devices are inserted into the pipe and carried with the current for up to 30 days. They can locate leaks at an accuracy of a metre over a distance of up to 1000 km by registering their own distance travelled, the pressure, the temperature and the noise level in the pipeline and evaluating all this detail.

Inserting an ARS pig device into a pipeline. Photograph: Kathrin Butter, ARS Betriebsservice GmbH.

For our system, IMMS created the entire electronics. They made embedded electronic components, developed programs for the microcontrollers and for the application and carried out a huge range of tests and analyses. They were an outstanding support as we worked on the development and improvement of our technology. IMMS is for us a highly reliable partner to whom we shall gladly return in the future."

Lutz Wohlleben, Project engineer, ARS Betriebsservice GmbH.
www.ars-bs.com



Prof. Dr. Ralf Sommer giving a guided tour of the IMMS labs to Basic Engineering School visitors. Photograph: IMMS.

IMMS and the encouragement of young academics

It is one of IMMS' highest priorities to bring on the new blood in science. Again in 2014, the research staff at IMMS has been active in pursuit of this goal, inspiring and supporting undergraduate and Master's students in particular. School pupils, too, have been given insight into the work of IMMS by means of events and internships or by having their coursework supervised by IMMS professionals. It is, above all, the students at Ilmenau TU who come to the Institute, but they are joined by students from other universities at home and abroad in receiving a knowledge of methodology soundly based in theory and in linking this to its practical use. Young engineers from a variety of disciplines – biomedical, electrical or automotive, computer or mechanical engineering, mathematics, mechatronics and physics – are able to work on exciting scientific problems at IMMS and all receive individual supervision. The Institute also offers training courses and guided tours of the establishment. In all, the year 2014 saw 53 students working at IMMS either as interns or student research assistants or in association with the dissertations they were preparing for their BSc, MSc or German "Diplom". The fact that the Institute networks so closely with industry provides the new generation of scientists with the opportunity to work on subjects of practical relevance where the results really matter.

IMMS has its own internationally competitive infrastructure, fully meeting industrial norms, supporting the design of and experimentation on electronic and mechatronic systems, and underpinning its research work and the preliminary systems qualification processes. The fact that we have so high a proportion of students from our own TU is an indication that our intensive pure research efforts are in the habit of bearing fruit. We think this is why highly motivated, high-flying students find their way to IMMS, to our great delight. There are other ways in which IMMS supports and stimulates new academic blood: one is the Scientific Seminar, at which undergraduate and doctoral students present their work for discussion. The intense and lively academic exchanges initiated in this way cross the subject borders, encouraging new connections to be made and new ideas to be considered.

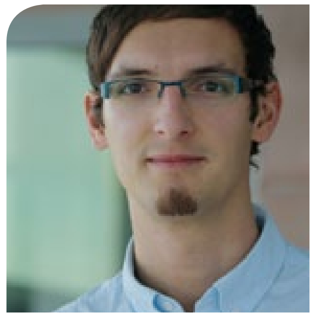
The GreenSense project had students involved on many tasks. Here measurements are being taken in the (cleanroom) laboratory of the Erfurt section of IMMS for a student dissertation on the design and construction of a readout system for a passive RFID microsensor array, supervised by the Institute. Photograph: IMMS.

Student work in the GreenSense research project

IMMS makes a practice of inviting students of engineering subjects to take aspects of the Institute's current research projects as challenging, useful academic material on which to base practical placements or dissertations for Bachelor's and Master's degrees. Our student colleagues thus make a significant contribution to the success of our research by, for instance, addressing some of the important preliminary issues or assisting the project teams on the development side.

In the case of the GreenSense joint research project, during the planning phase and then during the three years over which it ran, we had more than 20 student colleagues involved. Between them they worked on more than 30 individual tasks related to the Institute's research on energy-efficient and energy-autonomous electronic sensor systems. The range of tasks extended from researching the prior art in energy harvesting to technically demanding and time-consuming design work like the development of an RFID base station equipped with field coils in a very particular geometrical shape and the microelectronic interface circuit for RFID sensors.

"The time periods of two to six months normally available for completing a Bachelor's or Master's dissertation are usually much too short to enable students to work on complex engineering tasks like developing a microelectronic circuit from schematic design through to production and measurement," explains Dr. Eckhard Hennig, the GreenSense coordinator. "Therefore, our students frequently take up our invitation to get involved early in their degree course by taking a student research assistant or internship position with us. In these they learn the practical skills they will need in addressing real engineering problems in microelectronics, electronic system design and mechatronics they will face when doing their BSc and MSc at IMMS. This means that our students get a particularly comprehensive and realistic insight into both technical content and management of engineering projects over time. On occasion, the long-term relationships the students make with us lead to a full-scale research job at IMMS later."



Alexander Hofmann, M.Sc., Analog IC Design Engineer of the Bioanalytical and Biomedical Sensors Group at IMMS. Photograph: IMMS.

Alexander Hofmann, M.Sc.

"When I was thinking what degree to read for and then what to work on at IMMS, the crucial factor was that I wanted results from my creativity and, most of all, to be of immediate help to people. The creation of interfaces between biology and technology which could help the blind to see, the paraplegic to walk again and such illnesses (such as Alzheimer's and Parkinson's diseases, MS, cancer, AIDS and many others) to be diagnosed faster so that treatment could be more efficient or there might be better understanding of how the brain works, this was important to me. Important not only because of the challenging, highly complex research questions but above all as the means of my fulfilling my potential in very varied ways.

While studying Biomedical Technology at Ilmenau TU, I worked on a project of the Fraunhofer IBMT (Institute for Biomedical Engineering), Sankt Ingbert, in which we were developing the biomedical instrumentation to monitor wirelessly the effort of breathing. In the Department of Biosignal Processing at my Technical University, I got involved in the development of a macroscopic piezoelectric energy harvesting system to enable biomedical implants to be energy-autonomous. In each case, the work reinforced my wish to continue researching analogue interfaces. They also revealed to me that there are many biological processes and everything that goes with them taking place in the tiny micro- and nano-cosmic worlds but that in the macrocosm of medicine their measurement is "blind", for otherwise the daily life of the patients will be too much restricted. There is a dearth of commercially available microsystems with technical applications specific to the comprehensive solution of medical problems at this microscopic level.

As soon as I had finished my degree in 2012, IMMS gave me insight in the 3DNeuroN[1] project into that microcosm and I was able to gain valuable experience in the development of microsystems and the design of analogue integrated circuits. In 3DNeuroN, we developed an ASIC for low-noise amplification of the signals from neuronal activity and for the stimulation of neurons. One of my tasks was to execute a complete analogue signal amplifier chain in the relevant microsystem. In another project, 4TPixel[2], I have been able to extend my knowledge of designing ASICs and microsystems that can be included in radiographic applications as CMOS image sensors, and in yet another, the IMMS work on biochips[3], I have helped design an ASIC for the recognition of pathogens at molecular level to support veterinary diagnostics on site. Currently I am evaluating the systems developed in the biochip project. What I appreciate at IMMS above all is the warm and constructive cooperation with colleagues, for it really encourages focused creativity, and complex problems are solved in an atmosphere of friendship. I feel lucky to have found my fulfilment in this working environment."

Vojtech Dvorák

"During my first year as a PhD student at Brno University of Technology (Czech Republic) I was looking for an opportunity to visit a research institute in Europe. After some searching my choice was IMMS in Germany. The first contact was mediated by Prof. Háze, head of Department of Microelectronics at Brno University of Technology. I was very glad that I received a positive answer and an invitation from Georg Gläser to take up a three-month internship. Georg offered me a chance to learn SystemC and he came up with an interesting topic for the internship: high-level modelling and synthesis of floating point arithmetics to target mixed signal FPGA-based prototyping – which was also very well suited to my research at Brno University of Technology. The floating point datatype and its arithmetic operations were successfully implemented during my internship and a library for modelling of analog circuits was created. The advantage of this sc_float datatype and FPGA based simulation over a built-in C++ float type of data is that a smaller size of sc_float object can be set, improving computation performance on the FPGA.

Since the arithmetic operations worked very well in simulations, the next step was to create a model of a real analogue circuit. The first analogue circuit modelled was an RC oscillator as proof-of-concept. The oscillator was synthesized at various degrees of accuracy, simulated in an FPGA and found on testing in the laboratory to show very good results. The feasibility now proven, I helped create a second model, that of a phase-locked loop (PLL) circuit which is meanwhile being put to use in a current project."

1 see the 2013 annual report, p. 26, for the 3DNeuroN article.
2 see this annual report, p. 48, for the 4TPixel article.
3 see this annual report, p. 50.

RESEARCH SUBJECT

ENERGY-EFFICIENT AND ENERGY-AUTONOMOUS SYSTEMS

As part of GreenSense, IMMS developed a digital CMOS temperature sensor for use in energy-autonomous integrated sensor systems and got the Best Paper Award for this work at the IEEE Conference APCCAS 2014. The set-up shown here, which is in the IMMS laboratory, depicts a subsequent version of this sensor undergoing characterisation. One of its features is that it will combine with RFID. Photograph: IMMS.

Energy-efficient and energy-autonomous systems

Objectives

In sectors with high energy demand, such as traffic, manufacturing industry, and facility operation, there is a high potential for energy savings. All these sectors are striving to find solutions for cutting down on the consumption and waste of energy. Energy-efficient electronic systems help to reduce energy demand and meet EU or German government targets on carbon emission. They also constitute the enabling factor for the current megatrend in mobile electronic devices, which could never have penetrated into our daily life without low-power microelectronic chips and displays. This trend is mainly driven by consumer applications, but there is a growing demand for mobile equipment in industry as well. In this setting, however, the demands on lifetime, robustness and performance of electronic systems are considerably higher. A further megatrend on the road to "**Industry 4.0**" is the "Internet of Things", in which data exchange is no longer centered around humans but on sensors and actuators connected to the Internet. Embedded computer systems already control the functions of vehicles, machines and facilities of every kind.

Cyber-physical systems represent the new generation of such systems. They form the basis of the future **Internet of Things and Services**, in which everything will communicate with everything else to integrate real-world services into the virtual world of the Internet. For this purpose, new dimensions must be opened up, in which environmental data is acquired and made available on the Internet to autonomously interacting systems which have increasing cognitive ability. It will be vital to use smart control mechanisms to cope with the increasing speed and complexity of the processes.

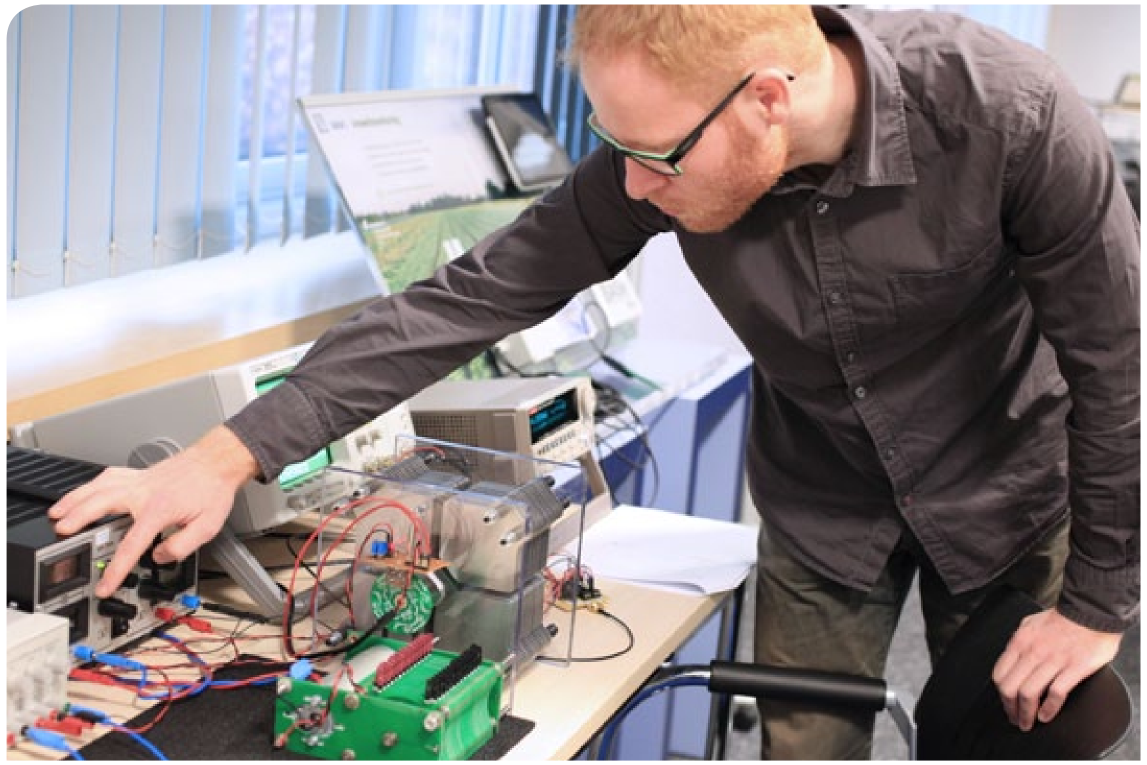
CPSs (**cyber-physical systems**) will thus contain a huge number of sensors and chips, will be networked throughout and will have a vastly extended range of performance. They will not only acquire raw data, but will also monitor, analyse, control and optimize industrial processes independently. Specific technical challenges associated with this vision include making CPSs more reliable, reducing maintenance efforts and – above all – ensuring low energy consumption. The ability of CPSs to run on energy harvested from ambient sources would pave the way for their universal use.

Experience

In this context, IMMS has been active in the fields of sensor systems, communications, signal processing and systems integration for many years. The focus of the work lies in the design of **energy-efficient** ASICs and embedded systems as well as in solutions that make them energy-autonomous. As early as 2005, IMMS began to develop platforms for wireless sensor networks with a battery life of several years for process monitoring in plants, buildings and the environment. For this purpose, one core growth area on which the Institute has done much work at the basic research level is CBS (which stands for Customer Bautronic System). This work involves fundamental concepts for battery management and energy-efficient processing at the software level. IMMS has applied these concepts in projects such as the CoolSilicon initiative "CoolConSens". For smart control of homes, the Institute has been researching and developing new approaches in projects such as "SHS: Facility" since 2009. The results include a smart home gateway with a power consumption of less than 2 Watts, a value which is still best in class in comparison with the performance of current commercial solutions. IMMS has applied these principles to model efficient sensor nodes that enable people and machinery to be located on airport aprons and has taken this research right through to marketable form (as described in the IMMS annual report of 2013).

Autonomous systems can be supplied with electricity using batteries or by harvesting energy from their environment. IMMS staff analyse the actual current consumption of a device in great detail and with high accuracy to design energy storage systems optimally for a given application. This includes the analysis of peak currents the energy storage medium has to supply, as these have an effect on the total available energy capacity.

Energy harvesting systems present a particular challenge because they obtain their energy entirely from the environment. The systems have to be designed in such a way that there is always enough energy available for their operation even when the harvestable energy has been reduced by external conditions. In addition, mechanisms for resuming operation after a power loss have to be implemented. These issues have been the subject of research at the Institute since 2007. As a result, a vibration harvester has been developed in which the energy harvesting principle is applied to operate a wireless monitoring system for construction machines. Current research activities focus on electrostatic and electromagnetic harvester modules capable of supplying autonomous sensor nodes with electrical power in the range from 10 µW to 10 mW. The Institute develops the electromechanical components as well as integrated harvester front-end circuits and energy management functions.



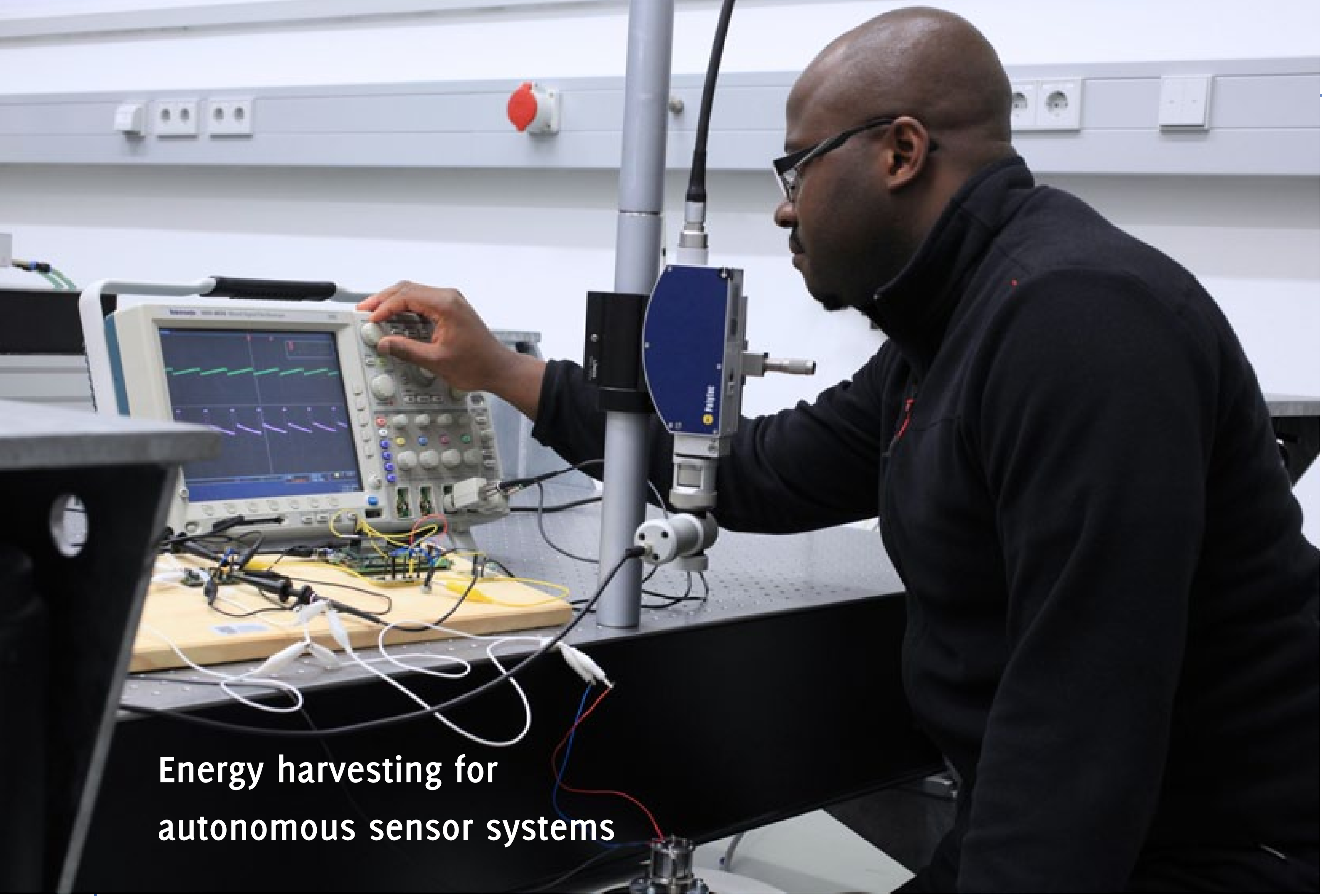
One of the many research outcomes presented at the GreenSense closing workshop late in 2014. The rotary variable capacitor shown was used to characterise the MEMS* energy harvesting frontend IC developed as part of the project. The capacitor serves as macroscopic equivalent of the electrostatic MEMS harvester structures. Photograph: IMMS.

Current Status

Using this technical know-how and special laboratory equipment, IMMS develops not only individual components but also complete systems tailored optimally to specific application requirements. IMMS' capabilities in the field of energy autonomous systems were significantly enhanced by the work in the research group "GreenSense" (2012 – 2014). The researchers developed new integrated sensor ASICs for recording pH and temperature values, which will be used in future life-science applications as described in the section on bioelectronics in this report. New communication solutions have been developed to read out large arrays of sensor ASICs wirelessly using RFID techniques. In the field of systems integration, another of the IMMS' areas of competence, a method for modelling the energy consumption of smart sensor networks in specific application scenarios has been designed. The modelling technique starts from the application requirements, maps these onto hardware and software and optimizes total energy demand.

IMMS combines its experience in the design of low-power sensor ASICs with its systems design and IT know-how to develop application-specific energy-efficient and autonomous sensor systems. This knowledge is being enhanced systematically for life-science and Industry 4.0 applications in various research activities and projects described in this report, including GreenSense, sMobility, EroLEDT, and Current Clamp.

* **MEMS** *Micro-electro-mechanical system, see the MEMS section.*



Energy harvesting for autonomous sensor systems

For purposes of combining an electromagnetic generator with their wireless sensor nodes, IMMS scientists made and investigated various harvester circuits, one of which is shown here being tested on a shaker in the in-house mechatronics lab. Photograph: IMMS.

Objectives

Among the building blocks for Industry 4.0 will be cyber-physical systems, as they are called, which contain finely distributed, networked sensors. All over the world, for about fifteen years, research has been carried out into the ecologically sustainable supply of energy for these and other systems. Batteries have been used up to now in many cases. However, batteries not only contain chemicals which can be damaging to health and the environment but they also occupy huge amounts of space and, for large networks of sensors, are uneconomical to maintain. Another problem is that it is impossible to replace or recharge them if they are inaccessibly sited.

Solutions

Energy harvesting is a means whereby systems are supplied with energy from their environment. The current state of the art includes approaches whereby electrical energy is formed from converted light, heat, movement or electromagnetic fields. IMMS is focusing mainly on energy harvesting from kinetic excitation and from electromagnetic fields, attempting to improve the output power density in these cases. Possible solutions are MEMS harvesters for microsensors or precision mechanical energy convertors for higher-performance radio sensor nodes: the choice depends on the output power needed in the application. Inspired by these concepts, IMMS has not only developed an innovative design strategy for MEMS harvesters (and applied for a patent) but also in 2014 progressed its work on a modular energy-efficient radio sensor platform which can be used for a variety of sensors and provided with electricity by energy harvesting.

In addition, IMMS is developing energy-efficient sensor systems. Only with these is it possible to create complete energy-autonomous systems that will fit into an acceptable size of product. In contrast to batteries, which call for dimensions reflecting the total amount of energy to be supplied over their lifetime, energy harvesters can be dimensioned simply to reflect the mean power supply required. This means that the tiniest of systems, sourcing their energy autonomously, can be created for long-term applications.

* **MEMS** *Micro-electro-mechanical system, see the MEMS section.*

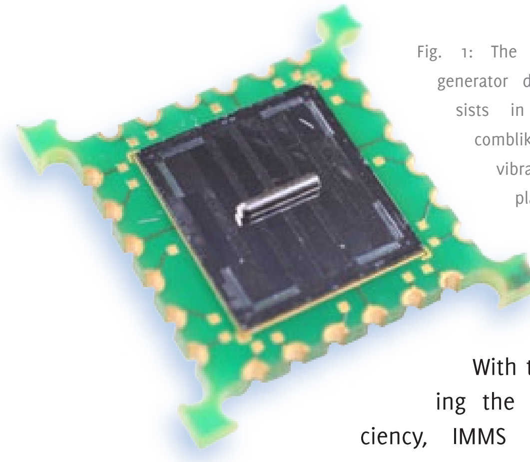


Fig. 1: The micromechanical energy generator developed by IMMS consists in moveable electrostatic comblike structures which vibrate outside the wafer plane and produce a contінous electrical output of approx. 10 µW. Photograph: IMMS.

With the focus on improving the overall system efficiency, IMMS always views the autonomous energy supply as a whole. There must be a physical mechanism to convert the energy from different energy types into electrical power plus an electronic frontend which will enable the consumer to make use of that power. Among the mechanical elements necessary are a converter for the voltage level, a rectifier and an interim energy store for periods of high demand.

A MEMS harvester made by IMMS for microsensors

In the GreenSense project, IMMS has developed micromechancial energy convertors that produce continuous output power at around 10 µW. Such a wattage is enough to supply, for instance, an integrated low-power CMOS* temperature sensor which is energy-efficient and provides the signal data for RFID** readout. The aim is to convert energy from very low-frequency vibrations such as are created by human movement.

The basic principle in the system is that of moveable electrostatic comb structures. The main challenge was to achieve low eigenfrequency, capacitance at the highest level possible and a marked change in capacitance when the structures vibrate, all on a tiny chip area. To meet the challenge, IMMS has put into practice a new idea for MEMS harvesters and applied for a patent on the design and electronics, which rely on an out-of-plane oscillator. This name refers to the fact that the central proof mass is in oscillation outside the wafer plane. The low-frequency spring elements were thinned down to keep the construction compact. In the development of the technology and the creation of the MEMS structures, IMMS has worked closely with MacroNano®, the Institute for Micro- and Nanotechnology at the Ilmenau University of Technology.

In 2014, the IMMS approaches to the temperature sensor and system architecture for the MEMS energy harvesting module were presented at conferences, APCCAS and Analog2014. At each of these they received the Best Paper award. The scientific details are both to be found in this report: in the present section and that on MEMS.

Precision-engineered energy converters for radio sensor nodes

The systems described above, which have a power output of a few microwatts, cannot be used for the acquisition and transmission of rapidly changing data and cannot be used to transmit over great distances. A sensor platform in such situations may well require power up to 10 mW. A mean power of 0.4 mW is necessary, for example, in the case of a digital pressure sensor subject to readout every second and wireless data-transfer at a power level of +3 dBm.

With this in mind, IMMS has, in the GreenSense project, taken **radio sensor nodes** and **optimised** their **energy properties** so that they can be fully supplied from the environment. The work involved a comparison of various design approaches for radio sensors, measurement of their energy demands for particular applications, and the creation of design methodology for autonomous sensor nodes. An energy simulator was created. Energy simulators have so far been marketed by certain manufacturers for individual microcontrollers. They support the investigation of the energy aspects of operational cycles and various scenarios for data readout, processing and transmission. However, the IMMS energy simulator functions independently of any manufacturer. It is a solution that constitutes an innovation in the service of circuit design for PCBs, permitting estimation of the electrical consumption of complex microcontroller-based systems before they are combined into the hardware. It also enables the designer to evaluate the energy aspects if peripherals are replaced and the interfaces change. Such details are essential to optimum design of energy-autonomous radio sensor nodes. The modular radio sensor platform which has been created on this basis can be used for a range of sensors and energy can be harvested from the environment.

It was in cooperation with the PORT research group at Ilmenau TU that IMMS brought the **energy-autonomous radio sensor system** to completion. The Department of Advanced Electromagnetics was responsible for the energy generator that is associated with the

***CMOS** *Complementary metal-oxide semiconductor*
****RFID** *Radio-frequency identification*

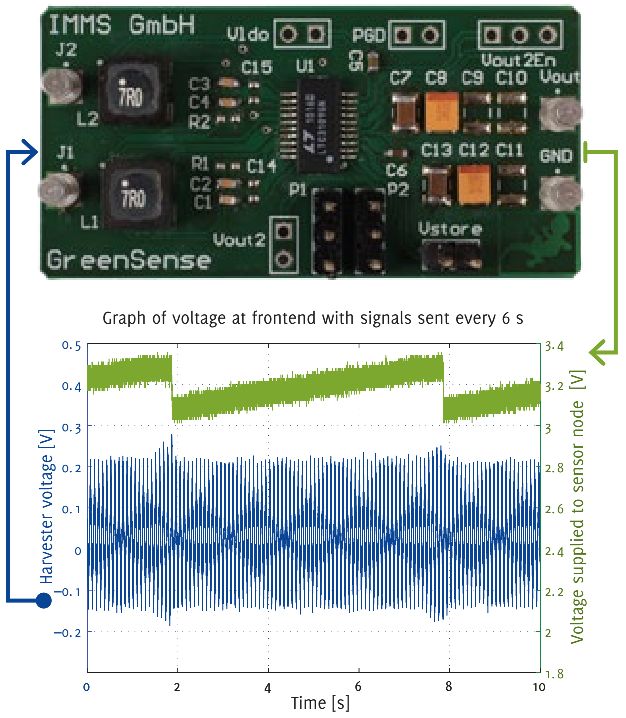


Fig. 2: Circuit developed by IMMS for the harvesting of energy from micromechanical energy generators. The tiny AC voltage generated by the harvester is stored and provides a relatively constant DC voltage of 3.3 V. Photograph and graph: IMMS.

IMMS system. This generator operates on a similar principle to bicycle dynamos or shake-to-charge torches. In the housing, there is a suspended and moveable magnetic circuit and a fixed coil. Excitation leads to movement of the magnetic circuit relative to the coil and thus to induction of voltage. To supply sensors which are close to a rotating wheel with energy, the system was developed with eigenfrequency around 10 Hz.

So that this electromagnetic generator can be connected up in the context of GreenSense, IMMS explored and constructed a variety of **circuits for harvesters**, comparing their energy use and their suitability for the generator in question. The circuits were given the appropriate dimensions and optimised so as to obtain from the harvester the maximum energy possible. So that the energy could be stored as long as possible for the system, suitable condensors were selected not only for their type and optimum capacitance but also for their very low self-discharge. Serial tests were conducted to establish the best configurations for a variety of application situations. The harvester circuits optimised in this way will function with alternating voltage at the relatively low effective figure of less than 100 mV.

Construction of the testing instruments for energy generators

For the excitation of the generator just described, and others, IMMS has installed a measuring station to enable generators relying on the vibration principle to be characterised. Among the instruments are two different shakers which can be easily adapted for testing either MEMS structures or micromechanical generators. To create the measuring station, IMMS not only linked together the individual components mechanically but also developed the software so that they all function in a coordinated fashion. The type of excitation is set at the computer, with the staff characterising the actual use case for the harvester and imitating it in the shaker. The force of excitation is adjusted using a dSpace system and feedback coupling of an acceleration sensor. The movement of the oscillating mass is registered by a vibrometer and the data recorded simultaneously with the relevant excitation. These measurements enable IMMS to give figures for the resonance frequency and damping behaviour of the energy generators. With the knowledge gained, the Institute can refine its modelling and thus its development of both harvesters and complete systems.

Future prospects

IMMS plans to build on these results in the field of energy harvesting and combine them with many energy-efficient systems which have been created in house in such projects serving such fields as bioanalysis, medical technology, automation and environmental monitoring. The procedure that IMMS has developed for autonomous sensor nodes, together with the energy simulator, are to be transferred in the near future to an overall design methodology for autonomous mechatronic systems.

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EUROPÄISCHE UNION
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Smart current clamp registers parasitic currents in industry

Energy measurements for the smart current clamp. Photograph: IMMS.

Objectives

Expensive downtime in complex industrial plant is often attributable to malfunctioning of the closed- and open-loop control technology. These malfunctions are, in turn, often caused by unwanted interaction between the electricity supply and the control system. The effect is that communication between components is impaired. If the interference level is outside the error tolerance margin, the controls will no longer compensate and will thus cause machinery to stop, so that production is interrupted.

It is not always possible to apply the classic error analysis methods in the search for the causes of such interference. To observe signals as they pass through the communication wires it would be necessary to pause the ongoing operation of the plant. It is often not feasible to evaluate a number of appropriate measuring points simultaneously as the plant will usually be a very complex combination of machines and sometimes there is no detailed documentation of these available on site. Another reason is that the components of the plant which function in combination may well be at a considerable distance from each other and not susceptible of observation from one single point in the plant. Yet another is that the breakdowns seem to happen sporadically, tending only to happen at intervals of perhaps several hours or even days. If expert staff apply themselves and complex measurement equipment to ongoing analysis over such long periods, the costs will be high.

Development

For all these reasons, IMMS has developed a compact, smart current clamp for Indu-Sol to manufacture. It is a mobile device, energy autonomous, which will register automatically and continuously the true RMS level of parasitic current in a wire of the communication bus system in industrial plant for a period of 14 days, recording this on an SD card for later detailed analysis.

The energy for its operation is stored in six LR6 mignon batteries supplying a total of approximately 20 Wh. This is about three times the capacity of a normal smartphone battery. The clamp recognises the parasitic currents from threshold values and is able to register values across a wide range, between 10 mA

The smart current clamp (EmCheck® ISMZ I) developed by IMMS in cooperation with its industrial partner Indu-Sol can be ordered from Indu-Sol (item no. 122010020). Photograph: IMMS.

and 30A, at up to 40 kSa/s, digitising them at 16-bit resolution. It will display the root mean square value (RMS) of the current parasitics in either numerical, graphic or spectral form and can be easily and intuitively operated. If the owners of industrial plant use several clamps at once they can establish the site of the parasitics, thus greatly reducing the effort required for analysis. The evaluation of the data is carried out with dedicated software on the PC. Thanks to its special provisions to ensure electrical safety, the device can also be clamped around wires under current which have a high electrical touch voltage as in overvoltage category III. This means that it is possible also to carry out measurements, for instance, in plant control cabinets which have fixed wiring.

Remedy

IMMS' development work relied on the detailed information relating to analysis of the problems caused by conducted interference currents which was supplied by its industrial partner, Indu-Sol, an expert company in the field, which had analysed its numerous call-outs to such plant. The company had established that on interrupted communication wires there was often a high level of unwanted balancing currents flowing mainly along the conductive shield of the cable. The cause of the currents is usually an unfavourable grounding condition associated with components that switch on and off. Alternatively, depending on component function, a high level of transient or high frequency leakage current may be the cause in, for instance, variable-frequency drives. As the data stream is normally transmitted differentially, it cannot be detected outside the wiring. However, the analysis of the unwanted balancing currents can be enough to conclude that there is a possible risk of interference, so that it is not necessary to investigate the data stream for the purpose. An example is shown in Figure 1 where the current passage measured by a current clamp encircling such a communication wire is depicted. Experience would suggest that the low current level and unremarkable envelope mean that little interference is to be expected on this communication wire. Figure 2, on the other hand, has an envelope indicating a distinctive flow of current which may be a sign of a high level of parasitics.

Various patterns had been identified to assist in the definition of a particular interference current. They include temporary or permanent high peak current levels, high slew rates for the current, and certain frequency sections of the current flow.

The challenge to IMMS in designing the current clamp was the fact that it would have to run for 14 days on commercially obtainable LR6 batteries as they would enable it to be used all over the world. The precondition dictates low energy consumption by all components and energy-efficient algorithms within the software. At the same time the wide dynamic range required, stretching from 10mA to 30A, was a considerable challenge to the magnetic detection coil, the electronics and the analogue-digital-converter combined in the system. In the selection of components, IMMS investigated the accuracy of various **magnetic detection coils** in the intended frequency range of between 40Hz and 10kHz and on that basis determined the analogue circuit elements necessary.

The Institute took many serial measurements for energy consumption by a variety of **microcontrollers** and for the time they took to go through certain algorithms. The times measured are shown in summary form for four selected microcontrollers in Figure 3. For purposes of comparison, it was assumed that the values would be registered at 200kHz. For this to be

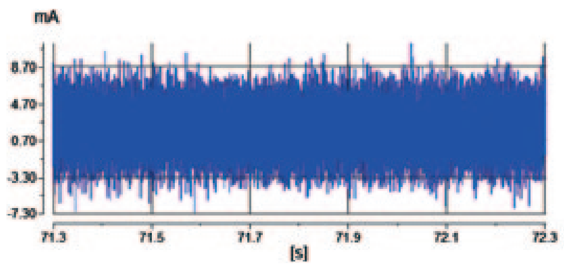

Fig. 1: Unremarkable current flow in the conductive shield of a communication cable. Source: Indu-Sol.

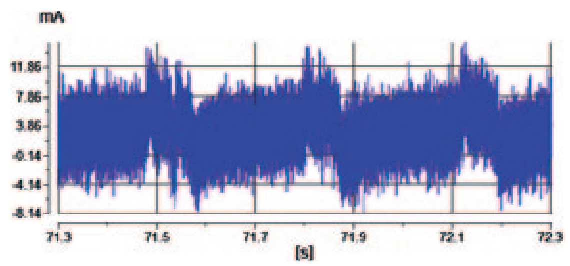

Fig. 2: Current flow with distinctive envelope in the conductive shield of a communication cable. Source: Indu-Sol.

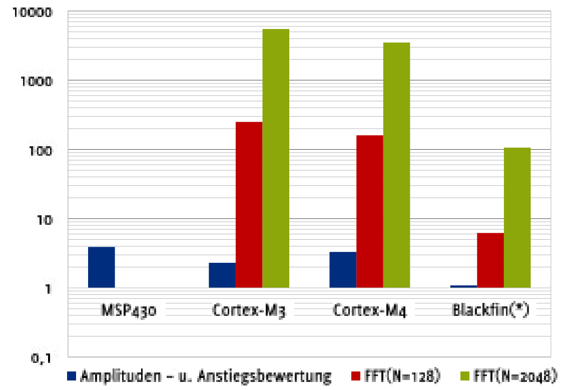

Fig. 3: Computation times compared. Blue: computation of signal amplitude and gain at cyclical frequency of 12MHz; red and green: computation of different rapid FFTs at the maximum possible frequency in each case. Diagram: IMMS.

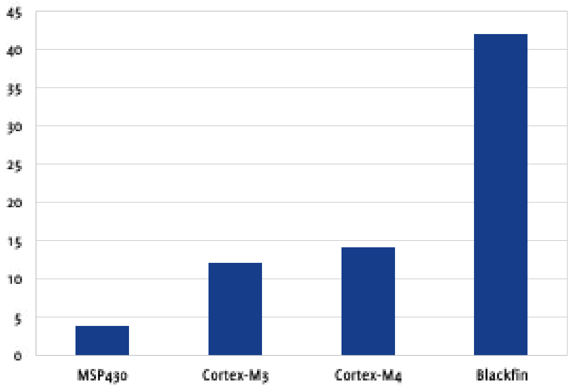

Fig. 4: Energy needs compared for a 14-day period at cyclical frequency of 12 MHz. Diagram: IMMS.

the case, a new value must enter into the computation procedure every five microseconds. The diagram shows that all four microcontrollers achieve evaluation of amplitude and gain of the signal faster than in the maximum permitted time of 5 µs. A comparison was also made using the same computation at a lower cyclical rate of 12MHz with the consequent reduced energy consumption. The energy consumption for the four microcontrollers over a period of 14 days appears in Figure 4.

After evaluating all these measurements, IMMS decided on a microcontroller suitable for the task which possesses the periphery embracing the necessary measurements together with appropriate low power modes.

To set optimum dimensions for the **batteries** with the **necessary capacity**, the Institute identified the current consumed by the system in each operational cycle. The capacity was derived not only on these measurements but also on experience from other projects. The amount of energy available from a battery is, however, dependent also on the peak load arising during the process with which the system is dealing. The peak values were thus also identified for the supply current during the measurement procedures and the order in which the process was carried out was optimised in the software to avoid too much stress on the batteries during operation. For example, it is energy intensive to write a large number of small data sets onto an SD card. Therefore, specific cycles were defined for the writing onto the card. Another tactic was to adapt the data sets to the cluster size of the file system, again reducing electricity consumption. By writing several clusters in one writing operation it was also possible to bring the energy use down by 50 % as compared with the initial requirement. Even more current-saving measures were applied, too: for example, in certain operational modes the microcontroller cyclical frequency was reduced. Any controller components not currently required were also switched off.

Commercially available batteries were subjected to comprehensive testing and measurement to demonstrate how batteries will behave under given discharging conditions. This made it possible to establish more accurately what **battery capacity** would be **available** to actual use scenarios for the current clamp and to improve the dimensioning even further.

IMMS first made an experimental prototype of the system, tested it and optimised it again. The final design of the hardware was based on the casing design which was also an IMMS development. The system was commissioned, tested and then integrated into the casing. The software to carry out the initial evaluation of the data in the current clamp was likewise made at IMMS and then implemented.

Future prospects

The current clamp was presented by Indu-Sol to a large specialist audience at the "sps ipc drives" trade fair in November 2014. As yet there is no comparable product available on the market. Mass production is to begin in the summer of 2015.

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sMobiliTy

An energy-optimised wireless sensor solution for traffic applications

Making prototype weatherproof, reliable sensors with wireless signalling that can be installed in the "tactile road" and will contribute to mobility with electric vehicles. Photograph: IMMS.

Objectives

Electric vehicles (EVs) have a shorter range and longer "electrical filling up" times than do conventional vehicles. For optimum navigation as regards trip time and distance travelled, it is important to have up-to-date local information: details of traffic jams, battery charging prices and destination accessibility. Ten sMobiliTy project partners are working on solutions to bring the information together so that electromobility is significantly improved. IMMS' role is the R&D on a sensor system to register such data as the number, type and speed of the vehicles on a "tactile" road. The Institute is also establishing safe transmission of data to a traffic monitoring and management system, is providing the traffic information to the interface of this traffic monitoring system and is developing a wireless environmental sensor system.

IMMS development

To support acquisition of data on road-users, IMMS is working on wireless sensor solutions that can be installed very easily at lower cost than the cable systems presently in use for traffic detection. The magnetic field sensors relied on by the Institute serve to measure traffic flow on the "tactile road". Passively, the system registers local changes to the earth's magnetic field caused by passing vehicles. From what is detected, the vehicle type can be classified and its speed determined.

The particular system solution which IMMS has developed registers this data wirelessly, collects it in a gateway near to grouped detectors and then sends it to a data concentrator in the traffic control centre of the model town, Erfurt, in central Germany. There, the new wireless sensor network complements the data capture methods already in place, allowing traffic data to be registered in finer detail than before. Only on this foundation is it possible to create more comprehensive and accurate traffic models with which to control traffic actively in real time.

Approach

In order for the "tactile road" sensors to be brought into use, IMMS has addressed many of the associated challenges. Any devices must be weatherproof, capable of installation and maintenance in the road surface, competent in permitting reliable wireless communication, reliant on batteries with as long a life as possible – and all this in limited space with fluctuating ambient temperatures. Furthermore, the system itself has to be flexible, allowing detectors to be moved or removed at any stage. It must also be capable of extension by sensors that go beyond mere traffic data capture, so as to offer an alternative to insular solutions, which are more costly from a financial and administrative point of view.

Fig. 1: The electronic detector module (A) developed by IMMS for insertion into the sensor pod (B) installed in the "tactile road" (C). Photographs: IMMS.

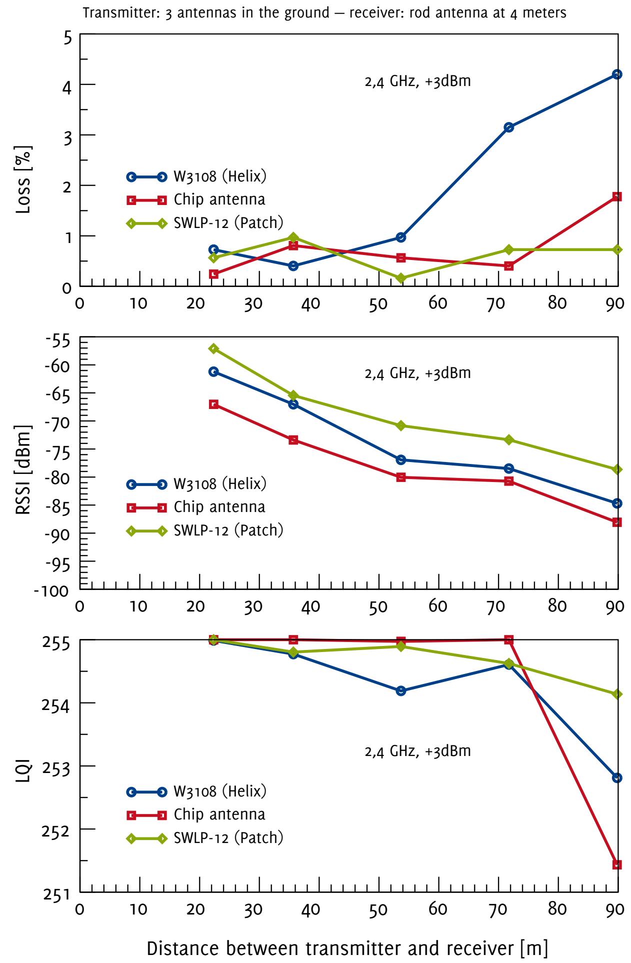

Fig. 2: Range and signal quality measurements compared for various antennae structures (helix, chip, planar) (LQI, RSSI). Diagram: IMMS.

As wireless communication is central to these challenges, the Institute has carried out very many **measurements**, taking into account a variety of frequency bands, antennae structures, antennae directions, protocol parameters and so on (see Fig. 2). The data for the energy consumption (see Fig. 3) of both detectors and gateways have also been analysed in relation to various practical expressions of the proposed scenarios.

The analysis included not only the individual consumption by building blocks and components but also overall consumption by the systems in various operational phases. In addition, a variety of battery types has been simulated so that their life could be

Fig. 3: Measurement of energy consumption, laboratory setup for a traffic detector (high consumption: detection message transmission). Diagram: IMMS.

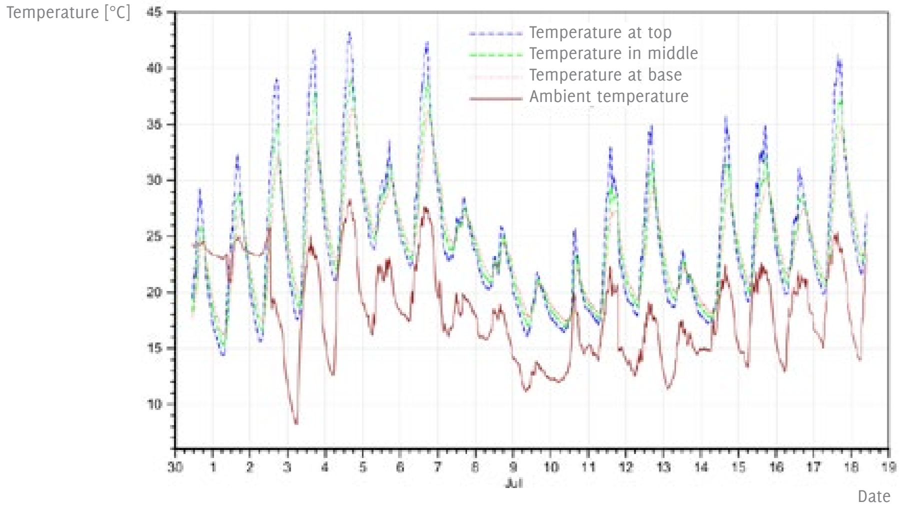

Fig. 4:

Sample measurement of temperature differences in the sensor housing, summer 2014. Diagram: IMMS.

assessed empirically. Design decisions for the system components have taken account of all these results.

Further, IMMS has investigated whether the inclusion of **energy harvesting** modules in the traffic detector will extend the life of the system. The approaches taken by the Institute have been both mechanical and thermal, analysing the variations in vibration and temperature beneath the road surface. However, the quantities of energy to be harvested from vibrations proved to be too small. The frequency bands are too broad for this purpose. It was also found that the carriageway materials and the type of substrate at the installation points vary too much to allow a universally applicable harvesting concept. On the temperature front, the differences measured by IMMS were at first very promising: up to 9 K. However, these high variations appeared only in summer and then only for the short period as day changed to night and vice versa. The limited space available, the insulation provided by the housing, the waterproofing considerations and the limited effectivity of thermal energy harvesters were all factors in the decision to reject this approach as lacking cost benefit.

After these lengthy preliminary investigations, IMMS developed a system solution and created an experimental version. The Institute here applied the knowhow that it has obtained over the years on design of energy-efficient embedded systems with wireless communication and on integrating sensors. The system will in future provide communal traffic computers with flexible traffic detection in a detector-to-gateway-to-data-concentrator chain that has a standard interface (OCIT-C*) and is extendable with additional sensors. An example is the sensor system with its own gateway that IMMS has developed and integrated for pollution measurement.

Future prospects

The present task is the optimisation of the system. Currently, the limits are set by the fact that the readout from the pairs of detectors must be simultaneous and, together with that from the magnetic field sensor, take place at as constant a rate as possible. Both these challenges demand highly accurate timers, which do prevent the system switching back to particularly energy-efficient modes of suspended operation. As things stand at present in the development work, the indications are that a lifetime of between one and two years without a change of battery will be achieved, which is considered practicable in actual use. Currently, 250 detector prototypes and 30 gateway prototypes are being prepared by IMMS so that they can be field-tested at sites in Erfurt between April 2015 and September 2015, when the project ends. The knowledge gained in the project has significantly enhanced the breadth and depth of the Institute's capabilities in the fields of energy efficiency and wireless communication.

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*OCIT-C *Open communication interface for road traffic control systems – centre to centre*

Instruments used in the IMMS laboratory for the characterisation of the OLED driver developed at the Institute. The ASIC, laid out specifically for the OLED panel, enables it to run efficiently and compensates for the effects of OLED ageing. Photograph: IMMS.

Objectives

"Organic LEDs", or OLEDs*, have been used for some years already in smartphones and television screens. At the moment, they are not in common use for general lighting purposes. An OLED is, however, highly efficient in its use of energy and about 60% more economical than halogen lighting. By virtue of its physics, an OLED also provides more naturally coloured light. Where an LED is a point beam source, an OLED radiates diffuse surface light with less dazzle and no need of additional optical elements to distribute the light. In coming years, the falling costs of producing OLED panels and their ever-increasing efficiency are bound to cause this technology to be used more and more in lighting applications. OLEDs will thus be the building blocks of efficient solutions which enable energy-intensive sectors such as building automation to avoid wasting energy.

A necessary precondition is that electronics will have to be available that are suitable to the open- and closed-loop control of the OLEDs. A semi-conductor circuit is being developed in the EROLEDT research project at IMMS which is laid out to match the characteristics of OLED panels and which will enable them to run efficiently in energy terms. The driving concept selected has been optimised to the long life enjoyed by OLEDs. Sensors integrated into the circuit will compensate for the effects of OLED ageing, achieving constant perceived brightness and colour. There is a digital addressable lighting interface, or DALI, which enables the OLED panel to be integrated into a building's automation system and the circuit to be controlled there.

The integrated solutions that currently exist for LED lighting cannot be used for OLEDs. They can be the cause of significant loss in efficiency or even of damage to the OLED. This is because the specific characteristics of the OLED have not been taken into account and the appropriate control options have either been inadequately implemented or left out altogether, so that, among other effects, the lifetime of the luminaire will be reduced. There should be no current peaks while the OLED is being operated; these can

*OLED *Organic light-emitting diode*

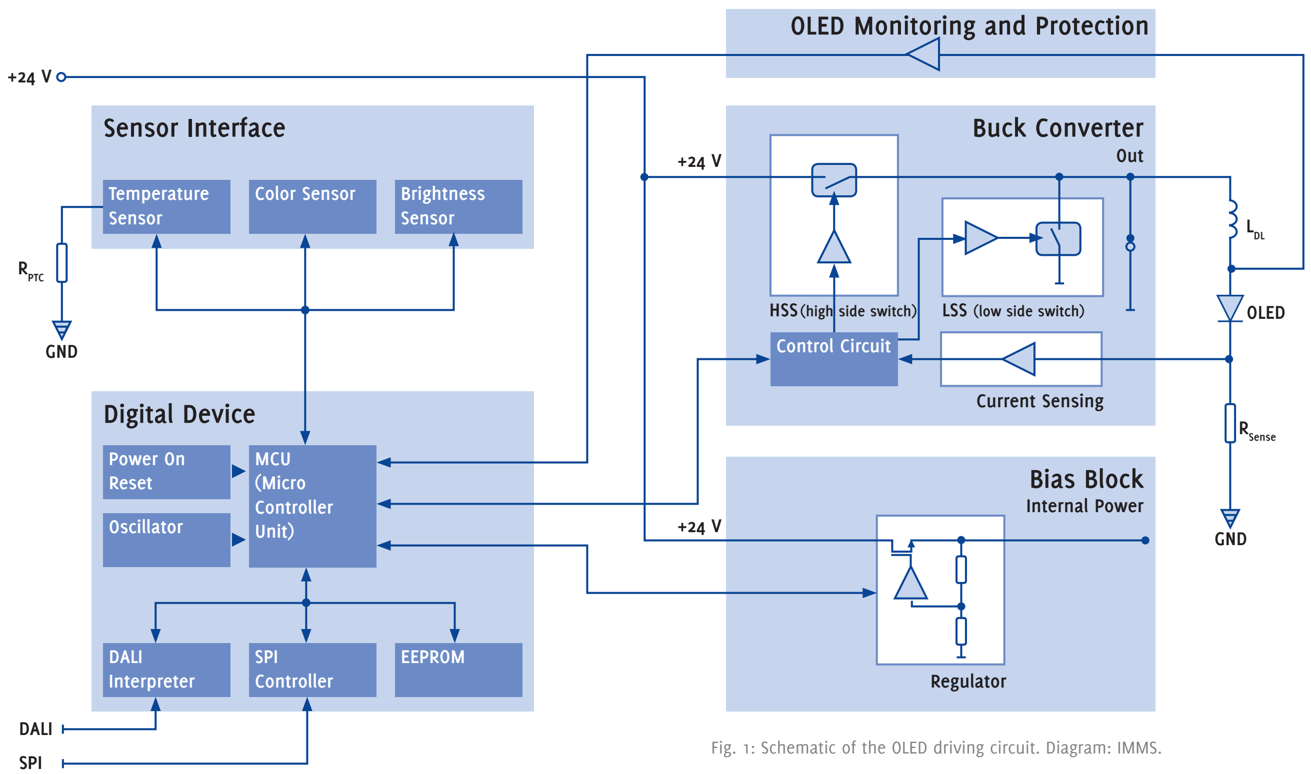


Fig. 1: Schematic of the OLED driving circuit. Diagram: IMMS.

arise in the case of pulse-width modulated voltage signals, accelerating the OLED ageing process. The cause of high current peaks is the large parasitic capacitance of the OLED, which is a result of the large area of the OLED and will mean that during voltage jumps there is a higher current flowing. While an LED reacts to a malfunction with highly resistive behaviour, an OLED will short-circuit. This means that the supply to the OLED must be switched off immediately so as to avoid further damage from the increased current flow in the OLED's surroundings.

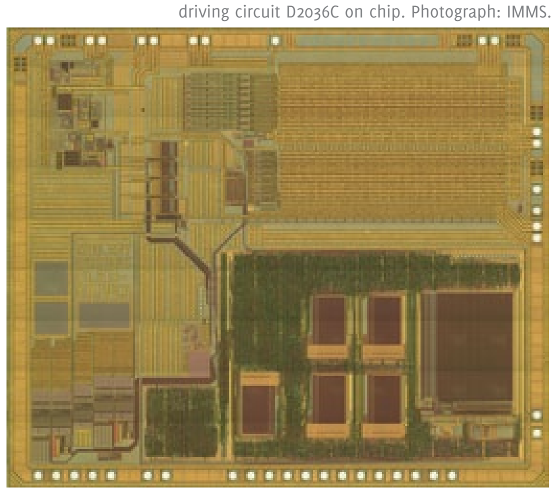
Development of an OLED driving circuit

The early stages in development where spent in considering how to achieve a system which is both highly efficient and long-lived, what type of control and interface would be necessary, and which of the OLED data would require to be continuously captured. Since OLEDs are not yet an established form of room lighting and sources of information are thus rare, IMMS first undertook long-term investigations, developing a variety of system concepts to be weighed against each other. For the purpose, the Institute characterised the OLED parameters. Among these characteristics are the optical, thermal and, above all, electrical features determining the behaviour of the OLED during operation and influencing its lifetime. They have either not been taken into account at all, or only inadequately, in previous approaches.

It was thus primarily a question of measuring the heat distribution, brightness, spectral distribution, capacitance, and current-voltage characteristic. The next stage was to specify on this basis the requirements for the driving circuit. The circuit schematic shows the system concept which was selected. It is made up of five functional blocks, all controlled by the microprocessor.

In the course of the project, the blocks were individually characterised in order to verify their function. Proceeding in this manner provided exact understanding of the features of each block and led to optimum interaction across the driving circuit.

Fig. 2: Photograph of the OLED driving circuit D2036C on chip. Photograph: IMMS.



Working principle

The integrated circuit developed at IMMS controls an OLED panel at voltage up to 34 V and current up to 500 mA. At the core of the circuit is a microcontroller unit (MCU) which can modify the control parameters. The control program in the MCU is capable of modification from a serial peripheral interface (SPI). The course followed by the program can be thus freely configured and adapted to the relevant OLED panel. A digital addressable lighting interface (DALI) is the means of controlling the OLED during operation.

The item responsible for the internal electricity supply in the circuit is the bias block. The buck converter is in direct control of the OLED panel. It switches on the OLED current, operating on the principle of a current-controlled step-down converter. The top limit of the OLED current is set by the figure for the resistance RSense . The OLED monitoring and protection block serves to monitor the voltage at the OLED and recognises any panel failure, immediately switching off the supply of current.

The sensor interface has integrated thermal and optical sensors for temperature, colour changes and brightness in the OLED panel. The optical sensors rely on the spectral characteristic curve appropriate to the human eye to evaluate the brightness. The appropriate point for the electrical operation of the OLED panel is found by comparing the actual measured brightness with the set value in the DALI. This method enables the brightness of the panel to be kept constant whatever its age or temperature, which, in turn, enables the OLED to work with uniform properties through to the end of its life.

Future prospects

The ASIC has already been manufactured and is in its test phase. It is to be part of a prototype under current development by IMMS and its research partners, LUCAS GmbH, LUST Hybrid-Technik GmbH and X-FAB AG. The prototype is a module made up of various components, among them the OLED driving circuit

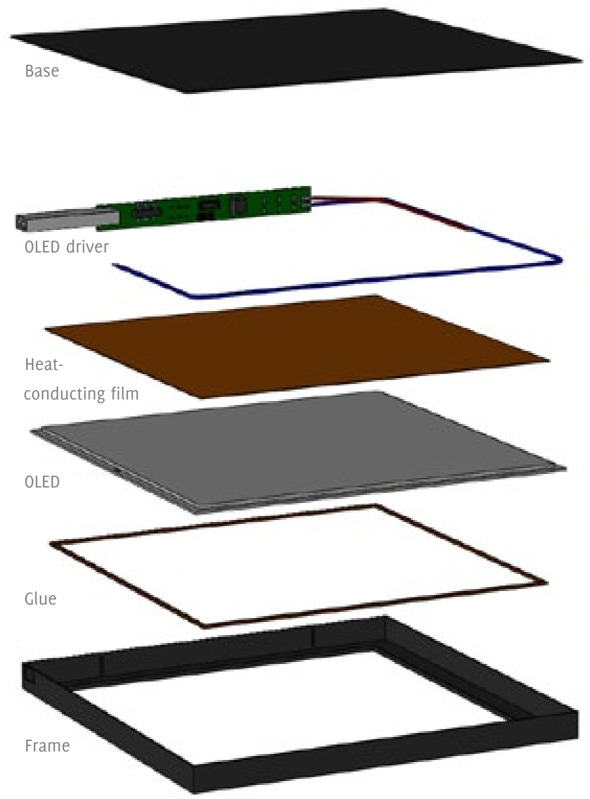


Fig. 3: Components of the OLED module. Diagram: Lust Hybrid-Technik GmbH.

which is on a PCB integrated into the module. The prototype can be plugged in directly to the mains power and regulated from a DALI controller. In the first quarter of 2015, samples will be available.

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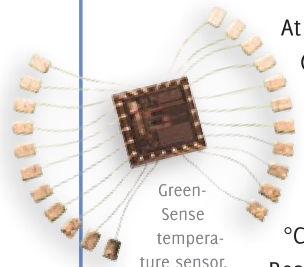
Highlights of 2014 in our energy-efficient and autonomous systems research

GreenSense project culminates with Best Paper Award for work on energy-efficient sensors

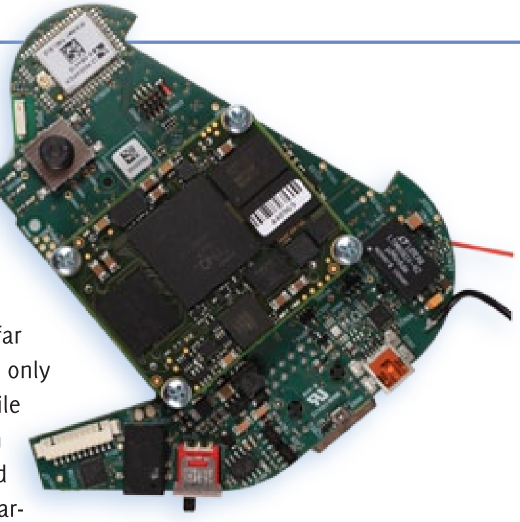


Green-Sense temperature sensor. Photograph: IMMS.

At the IEEE Asia Pacific Conference on Circuits and Systems (APCCAS 2014) in Okinawa, Japan, the IMMS contribution entitled "A Low-Voltage Low-Power CMOS[1] Time-Domain Temperature Sensor Accurate to within [–0.1; +0.5] °C from –40 °C to 125 °C" was named Best Paper. The authors were presenting a new digital CMOS temperature sensor developed in the GreenSense research project for application in energy-autonomous integrated sensor systems. In this project, IMMS developed integrated microelectronic sensor components, manufactured cheaply with CMOS technology and optimal energy saving features, which will measure and provide electronic evaluation of various physical dimensions. The intention is that a single parameter, temperature in this instance, should be measured and digitised using well below 10 µW of electric power, which would facilitate the use of a sensor operable without interruption for at least a 10-year period from a mignon battery with a typical capacity of 1000 mAh. At the conference, IMMS presented systems enabling the new digital CMOS temperature sensor to cope across a wide temperature range with high energy efficiency. The accuracy of the sensor is absolute and systematic between -0.1 °C and +0.5 °C in the range from –40 °C to 125 °C, or, in the range from 0 °C to 125 °C, between –0.1 °C and +0.1 °C. It has been manufactured in 0.35-µm CMOS technology and requires a current of 2.5 µA from a 1.4 V voltage source for its operation, which equates to an electrical power requirement of only 3.5 µW.

Conclusion of MARS project

Working with eight other partners, IMMS played a role in the two-year long national German BMBF project, helping develop MARS, Mobile Authentification by Retina Scanning. In the eye, the pattern of blood vessels is, like a fingerprint, highly individual. Retina scanning, being non-invasive and incapable of manipulation, is an identification method not easily compromised and certainly safe. Any retina scanners so far available have been suitable only for stationary use. The mobile retina scanner developed in the MARS project can be used as authentification in many areas of daily life. Examples are e-banking, e-commerce, access to high-security areas, use of sensitive information and sensitive infrastructures, and protection of privacy, among many others. Evaluation of optical signals in retina scanners of the mobile type requires energy efficiency in the components. To meet the need, IMMS developed a system concept and selected a processor platform which will later enable the software to be integrated into a smartphone. Another contribution made by the Institute was to create the interface to the processor as an FPGA, implement it and test it, then integrate it into the operating system and drivers and establish a coupling point for visualisation and integration into an app. The research consortium was led by the Fraunhofer IPMS, which presented the battery-driven mobile retina scanner at trade fairs including Optatec. The acceptibility of the scanner is being explored by means of user surveys in many contexts. One partner in the project, Securitas, is evaluating its use in an airport setting to control access to sensitive areas.



Electronics developed by IMMS in the MARS project for the mobile retina scanner. Photograph: IMMS.

Successful conclusion of EFSUES project

In February 2014, IMMS and its project partner, SMI GmbH, presented their partners at Erfurt-Weimar airport with the result of two years' joint development. This was the prototype of a new monitoring system enabling small and medium-sized airports to keep their aprons safer and operate them more efficiently. The monitoring system will detect the presence and position of aircraft, vehicles and people with such certainty that take-off and landing can continue efficiently whatever the weather or visibility. As a result of the development work, special service vehicles will be operated safely and smoothly, waiting time for aircraft reduced to a minimum and traffic safety on the airport apron greatly improved. For the low-energy transmitters installed in the location system for objects and staff, IMMS drew on its skills in and knowledge of wireless sensor networks.

Presentation of Rapid Prototyping platform for embedded systems at embedded world 2014

At the "embedded world 2014" conference, IMMS was able to present a newly-developed rapid prototyping solution which is based on the BASe-Box platform presented the previous year. This energy-efficient platform is a means of integrating modules from commercially available development platforms into new work. It uses Linux in the making and cheap, rapid testing of customised applications. The new platform is targeted at the business of prototyping, small series production and the manufacture of scientific instruments. It takes account of features of these settings not usually taken into account by development platforms, such as the robustness for industrial use or the type of housing design.

IMMS SENT transmitter IP for the next generation of automotive smart sensors

SENT is a digital point-to-point communication scheme for transmission of high-resolution sensor data from a smart sensor to a control unit. It is employed in the automotive field as a low-cost alternative to the LIN and CAN bus standard. An example of its application is the transmission of the exhaust gas temperature to the electronic control unit. The newest version of the SENT transmitter IP, the D2026C, now supports transfer of up to 16-bit data from two independent sensors. The soft IP is a SENT transmitter implementation which fulfils the SAE standard J2716 JAN2010 entitled SENT – single edge nibble transmission for automotive applications. Being implemented in Verilog and independent of the technology, it can be used in all FPGAs[2] and ASICs[3].

IMMS makes an investment in a wafer tester for 300-mm semiconductor technologies to support its Thüringen partners

Thanks to the infrastructure project funded in 2014 by the German 'Land' of Thüringen with the title SensorLab – a Laboratory for Multisensors in Micro- and Nanotechnologies, IMMS has been able to add to the equipment at its disposal a wafer tester for 300-mm semiconductor technologies. This is vital infrastructure for future joint or shared research projects involving the characterisation and testing of micro and nanoelectronic technologies and circuits for smart, energy-efficient sensor-actuator systems. Such systems are essential items for developments in the Internet of Things and Industry 4.0. The 300-mm engineering is a key factor which will ensure that IMMS and its partners in Thüringen are able to keep up with current More-than-Moore technologies and semiconductor manufacturers across Europe for the next 10 years. The initial work on installation and commissioning of the equipment is already in progress. It was delivered at the end of 2014.

Start of EDA cluster research project ANCONA

IMMS has been involved in the 3-year long cluster research project known as ANCONA (Analog Coverage in Nanoelectronics). The cluster also includes five universities or research establishments. Computer-aided verification methods are the research subject, with the intention of improving and greatly accelerate the design of analog / mixed signal circuits, which will be the technological basis for the realisation of such visions as the Internet of Things and Industry 4.0. To date, it has largely been impossible to test the interaction between the system components and any of the parasitic currents to which they may be exposed from the mains voltage in any setting but a laboratory. Because of this, the project partners are working on computer-aided procedures which will provide reliable testing of complex systems even at the design stage and prove their functionality. The development task of IMMS is to focus on specialised methods which will enable parasitic coupling instances to be integrated into the system models, and the models efficiently simulated.

Start of KOSERNA project

KOSERNA is a 3-year project. IMMS has been involved since February 2014, developing an industrial prototype which is based on the KOMPASSION project results. In KOMPASSION, the Institute and the University together produced a satellite navigation receiver which is only a quarter of the size of a conventional group antenna but has the same number of individual elements. The receiver frontend circuit for the antenna was designed and created by IMMS. The partners are working on an even more robust and accurate version in KOSERNA, with the desired high marketing potential. To this end, IMMS is extending the front-end circuit and transferring the new designs onto a second frequency band.

1 **CMOS** *Complementary metal-oxide semiconductor*
2 **FPGA** *Field programmable gate array*
3 **ASIC** *Application-specific integrated circuit*

RESEARCH SUBJECT MEMS

Starting the vibrometric testing in the IMMS mechatronics lab of the MEMS energy harvesting solutions developed at the Institute, which will provide energy to a wireless network of energy autonomous micro-sensors. This work, done for the GreenSense project, achieved the Best Paper award at Analog 2014. Photograph: IMMS.

Research into MEMS

Objectives

MEMS (micro-electromechanical systems) are a driving force for the development of future products in a wide range of market segments. Extending only over an area of a few square millimetres, they combine micromechanical sensors and actuators with control electronics in a single device. They are formed directly on silicon wafers by a procedure combining semiconductor manufacturing methods and MEMS processing capabilities enhanced for the purpose. Integrated sensor and actuator systems are being developed with these established MEMS production processes at enormous rates for consumer, automotive and industrial applications; the quantities and revenues go into the billions. The tiny modules control, for example, ink ejection in inkjet printers and act as microphones or position sensors in smartphones. MEMS accelerometers and gyroscopes are used in cars as sensors for electronic stability and airbag control. The pressure sensors which monitor the air-conditioning and tyres are also MEMS components.

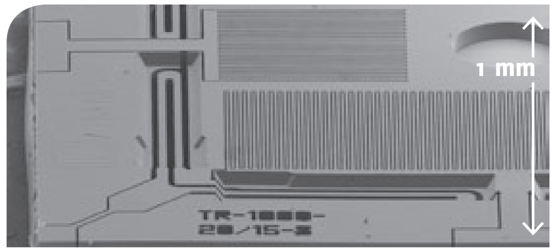
The fields in which IMMS concentrates its R&D activities are MEMS-based electronic systems for innovative applications in industrial communication and control and for special new growth areas such as the life sciences and biomedical technology. The Institute works in close cooperation with MEMS process development and manufacturing partners, itself focusing on the design of new mechatronic systems solutions. These are composed of micromechanical sensors and actuators, microelectronic circuits and embedded hardware and software components. New approaches, such as the MEMS energy harvesting modules developed by IMMS, have made production of a wide range of innovative devices possible, with attractive market opportunities particularly for small and medium enterprises. To open up these markets successfully in cooperation with its customers, IMMS has continuously applied itself to extending its MEMS design capabilities. The efficiency of future MEMS development depends strongly on systematic and tightly coupled processes for the design of micromechanical sensor components and microelectronic readout circuits. The Institute is, therefore, continuing to expand its methods of MEMS/ASIC co-design and setting up specific laboratory equipment for the characterisation and testing of MEMS components and modules.

Experience

The Institute's MEMS measurement laboratory has been extended systematically over several years. With its help the parameters of MEMS devices can now be determined in house and their mechanical and electrical behaviour characterised. Based on these measurement capabilities, the Institute has developed methods for indirect, non-destructive parameter identification. The knowledge and data thus obtained are necessary for modelling MEMS accurately, which is a prerequisite for a systematic, model-based design process. With this modelling approach, the behaviour of MEMS structures has been successfully simulated, so that the Institute has been able to verify and refine its MEMS design methodology. This allows the Institute to design novel MEMS devices, such as energy harvesters (GreenSense), and to implement state-of-the-art methodology for the design of MEMS-based systems with integrated electronic components (MEMS2015).

Proprietary MEMS measurement equipment was developed in the SMARTIEHS project, led by IMMS and concluded in 2011. A scalable parallel measuring system was created which enabled 25 MEMS structures to be tested simultaneously at wafer level.

MEMS structures, which have features in the micrometer range of dimensions, are far too delicate for tests involving mechanical contact, which would destroy them. Therefore, IMMS has spent many years on developing a procedure for indirect, non-destructive identification of the parameters of material properties. The method uses data produced by vibrometric (and thus non-destructive) measurement of the eigenfrequencies of various MEMS test structures. At the core of the method, FE (finite elements) simulation is used to find the functional relationship between the measured eigenfrequencies and the material and design parameters to be determined. The Institute has enhanced and validated the procedure in several research projects since 2005, including PARTEST, PRIMOS and USENEMS. The method facilitates the development of ultrasensitive integrated MEMS and nanosystems which are based on new high-performance materials such as group-III nitrides, nano-laminates or graphene. In addition, the method allows the quality and function of MEMS to be monitored throughout the entire manufacturing process, fulfilling the demand for ever finer parameter tolerances and thus higher measurement accuracy. It is possible, for instance, to monitor the effects of manufacturing processes on the mechanical stress in micromachined



MEMS energy harvester designed and manufactured in the GreenSense project. Photograph: IMMS.

membranes, which is necessary when MEMS devices are being sawn and glued. The comprehensive procedure for indirect parameter identification was first used by the Institute in 2013 to optimise such glueing processes. This has put IMMS into a leading position in the field.

Current Status

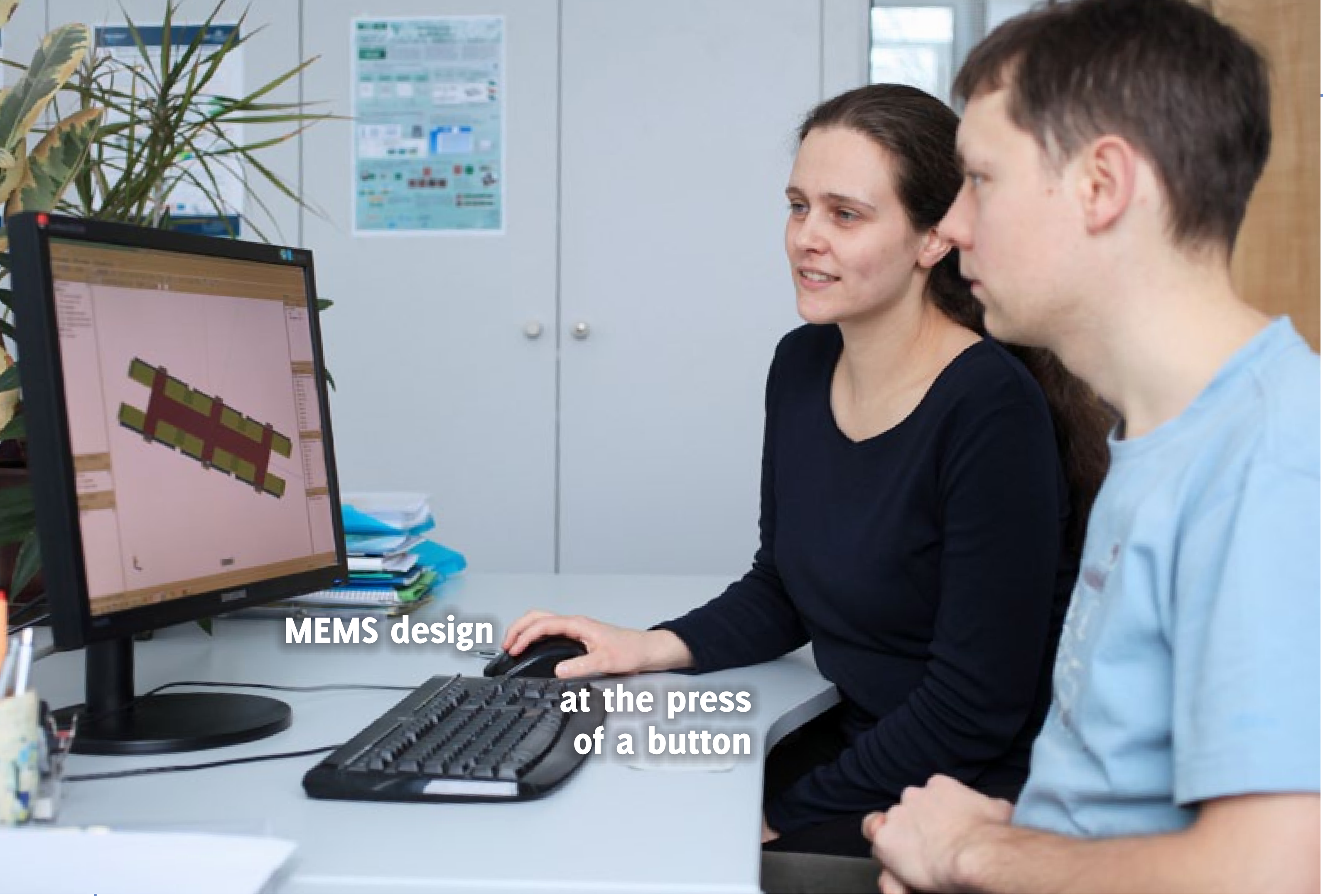
In the project "GreenSense", completed in 2014, IMMS carried out research on the design and manufactoring of miniaturised energy harvesting modules based on micromechanical vibration converters. Such harvester modules can be expected to open up new energy supply options for wireless, networked, energy-autonomous microsensors (see also the section on Energy-Efficient and Energy-Autonomous Sensor System research). In cooperation with the Institute for Micro- and Nanotechnology MacroNano® at Ilmenau University of Technology, IMMS has developed basic structures and a wafer-level manufacturing process for micromechanical combs and springs. These components can be used to design electrostatic out-of-plane MEMS harvester modules. In this type of harvester, a central proof mass oscillates out of the wafer plane, thereby causing periodic variation of the electrical capacitance between the pairs of comb-shaped electrodes, one moving and one fixed. Mechanical energy from ambient vibrations can be converted into electrical energy by electronically controlled charging and discharging of the working capacitances in synchronism with the oscillation.

Research goals that have been demonstrated successfully on several manufactured samples include the production of thin yet mechanically stable spring suspensions, deep etching of comb structures up to 100 µm in height with air gap widths as small as 3 to 5 µm, and the proof that the oscillator can actually vibrate. The complete energy harvesting module is composed of the MEMS vibration harvester described above and a high-voltage/low-power CMOS frontend IC with a lithium microbattery for the extraction and storage of the converted energy. The module works at a maximum voltage between the harvester electrodes of 40 V. It is specified to deliver a DC voltage of 3.8 V with a continuous output power in the double-digit µW range while consuming less than 1 µW internally. The research team has been able to show experimentally that the proposed micromechatronic harvester architecture is generally capable of generating a positive power output in the desired range.

These research results were presented at several scientific conferences, including the 40th European Solid-State Circuits Conference (ESSCIRC 2014) in Venice and the 14th GMM/ITG Conference on Analog Circuits (Analog 2014). The contribution to the latter, entitled "A System Architecture for an Integrated Electrostatic MEMS Energy-Harvesting Module", received the Best Paper Award.

One of the aims being pursued in the current research projects MEMS2015 and MUSIK is the combination and harmonisation of the design process for the mechanical and the electronic components of MEMS. The goal is to reduce design time by 30 % and raise the marketability of MEMS by 50 %. This new type of comprehensive design methodology can be expected to enable SMEs to compose their own individual, tailor-made solutions using a flexible MEMS and electronics construction kit so that they can capture a share of the MEMS boom. First results from this design flow developed at IMMS are described in the article on the new design tool developed in the MEMS2015 project. In the same project, IMMS produced first samples of an application-specific frontend IC for a MEMS cantilever. The ASIC has been designed for future use in AFM probes (atomic force scanning microscopes) which are capable of measuring forces of less than ten nano-newtons. This development work is presented in the second MEMS2015 article.

The characterisation of this cantilever readout ASIC was the first to be carried out in the new test lab for MEMS-based microsystems, installed in the context of the "MEMS-T-Lab" infrastructure development project in 2014. This project contributed significantly to the capacity for innovation both at IMMS and among its research partners. MEMS-T-Lab enables IMMS and its SME partners to model the parameters of MEMS and characterise them. The new instrumentation has extended the Institute's infrastructure of modelling tools, measurement technology and laboratory equipment, facilitating measurements with a very high degree of complexity. A higher degree of automation has now made it possible to carry out MEMS measurements on complete wafers.



The methodology of synthesising MEMS exemplified in an accelerometer

Small and medium-sized enterprises (SMEs) will be able to use the newly developed design tool to generate their own MEMS without possessing much design experience. The image shows an accelerometer as an example. Photograph: IMMS.

Objectives

There is a need for new procedures and tools in the field of MEMS design to enable smart, up-to-date, high-performance sensor-and-actuator systems to be developed. To this end, during its involvement in the MEMS2015 research project funded by the BMBF (the German Ministry of Education and Research), IMMS has developed a new type of methodology. The tried and trusted modular principle from microelectronic design has been adopted by the Institute and transferred to mechanical systems and to MEMS. The two design procedures have been combined into a systematic start-to-finish procedure. As a result, MEMS can now be simulated and verified as an entire system, which means that errors can be recognised and remedied early. The new methodology unites technological expertise with measurement, modelling and design procedures and is supported by high-performance design tools. IMMS itself has as one outcome of its work produced a special design tool that supports XM-SC, the SOI technology of X-FAB AG, by providing a sensor design system for computer-aided design of the electromechanical unidimensional sensors known as accelerometers. This outcome is now the basis of work on the transfer of the methodology to systems of greater complexity, such as 3D or 6D accelerometers and energy-harvesting modules.

In future, it is hoped that small and medium-sized enterprises (SMEs) will be able to use the system to design their own MEMS without possessing much design experience. The tool works by using a mathematical algorithm developed at IMMS to compute the various design possibilties that might match the customer's requirements. The tool is, furthermore, a source of sensor models which the user can integrate into the design tools made by our resarch partners Coventor and Cadence. It will generate the necessary mechanical layouts for the manufacturing stage.

* MEMS *Micro-electro-mechanical system.*

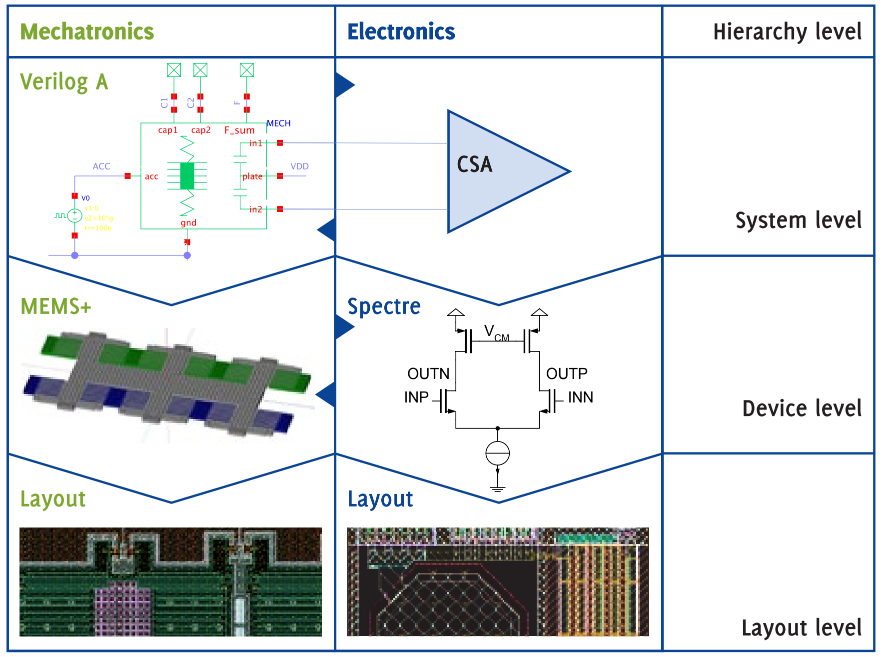


Fig. 1: Hierarchical levels in the overall design process for the mechanics and the readout electronics. CSA: Charge sensitive amplifier. Diagram: IMMS.

The newly-developed MEMS design flow from the user's point of view

For the overall design of a MEMS, it is necessary for a user to carry out a system-level simulation of both the mechanics and the readout electronics on the various levels, which are shown in Figure 1. On both system and component level, the user will need models of both the mechanics and the electronics, with different degrees of abstraction. In addition, he or she will need layouts for the production of the MEMS.

These models of the mechanics, together with the layout for the MEMS, are available "at the press of a button" in the special design tool developed at IMMS. As the schematic in Figure 2 reveals, all the user needs to do is to enter the specifications for the sensor into the tool. The algorithm on which the tool relies then automatically selects suitable basic structures, computes the appropriate geometric parameters and presents the user with a choice of relevant designs. It is possible to use the design tool to produce Verilog-A and Coventor-MEMS+ models automatically for the design computed. These will model the mechanics of the sensor at various degrees of abstraction. De-

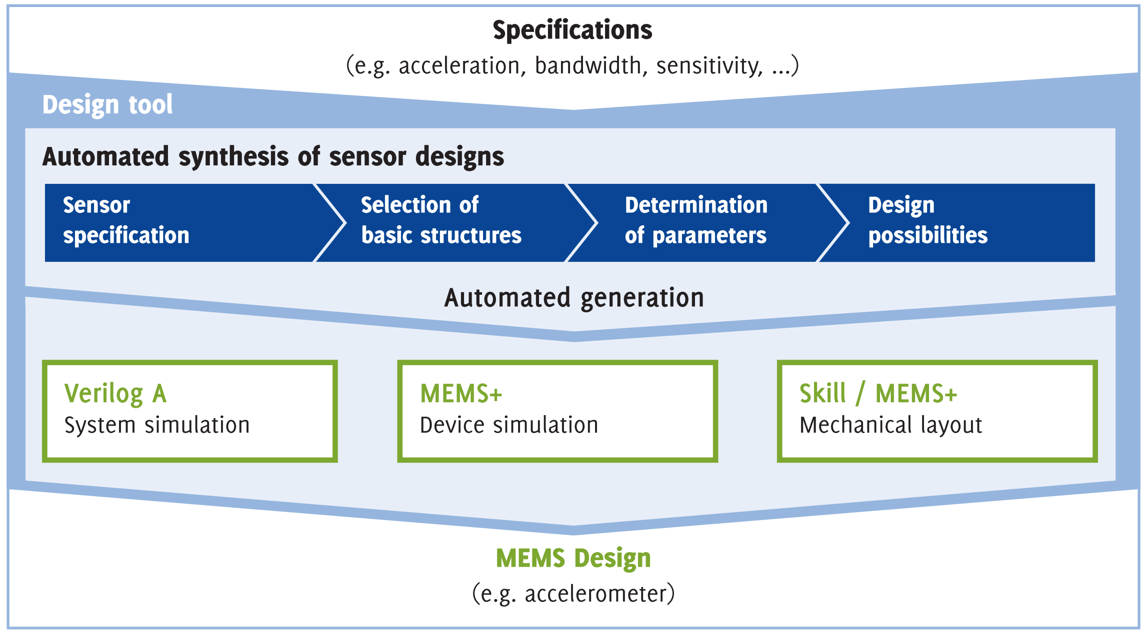


Fig. 2: Schematic of the newly developed design tool. Diagram: IMMS.

* IC *Integrated circuit*

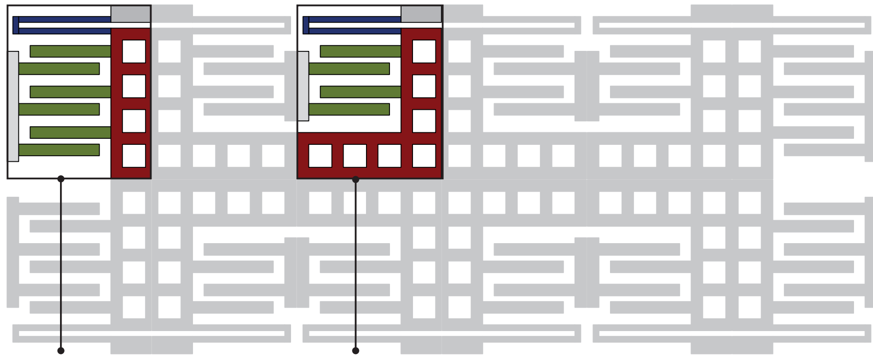


Fig. 3: Example of a basic structure for an accelerometer which is composed of 8 internal and 4 external basic modules with the relevant function units.
Movable electrodes with plates with/without etching holes
Interdigital comb structure with fingers
Spring(s) with
Anchor(s)
Stator electrode.
Diagram: IMMS.

signers can integrate the models into conventional IC design environments, carry out system simulations there for the mechanics and the readout electronics and thus form an opinion of how well the two parts work together. In this way, using the new tool, it is possible to verify a MEMS sensor in its entirety. Any problems can be discovered and any necessary corrections made to the mechanical parameters. For the creation of the MEMS layout, a script which can be run in Cadence is automatically generated. All the layout elements necessary for the specific MEMS will be created, and any X-FAB library elements (such as conductor intersections) which are required will be integrated by the newly developed tool.

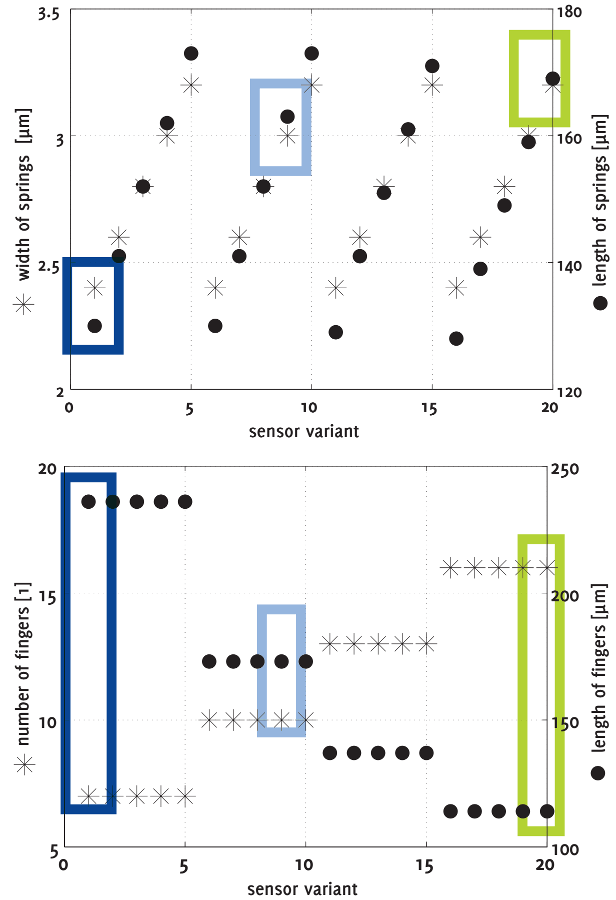
The new MEMS design method in detail

The special design tool has been developed by IMMS in the first instance for an accelerometer. This is a capacitive sensor that will register any acceleration along one spatial axis. On the sensor, this type of stimulus shifts a movable electrode opposite two fixed stator electrodes (cf. Figure 3), thus changing the capacitances. The change is read out in an electronic circuit which has been designed by IMMS. In order to obtain the highest capacitance possible in a small space, the electrodes are usually laid out as interdigital comb structures. The fingers of a movable comb electrode engage with the fingers of the stator electrodes. The properties of the sensor are very much determined by the number of fingers on a comb, their geometric dimensions and their distance from one another. Another determining factor is the characteristics of the suspension of the movable electrode. For the sensor class presently under consideration, this suspension is in the form of folded beams, which are made up of two beams laid parallel to each other.

Any of the accelerometers under consideration can be assigned to a certain basic structure, which will be made up of a certain combination and number of basic modules. Each of these will, in turn, contain the same function units: a stator, which, in combination with a comb forms the fixed electrode, and a movable electrode, composed of a plate, which (depending on the technology) may have etching holes, comb structures with interlocking fingers and one or more springs, which are suspended on anchors (cf. Figure 3). The basic modules and function units have been implemented by IMMS as a modular system in MATLAB software using object-oriented methodology.

When starting to use the design tool, the user enters the following sensor dimensions as desired: the resolution, the maximum detectable acceleration amplitude, the minimum measurable capacitance difference and the base capacitance, i.e., the capacitance between the electrodes when there is no acceleration taking place. These dimensions will be directly related to the sensitivity of the sensor. The resolution and maximum acceleration will be dictated by the field in which the sensor is used; the capacitance demands will, in turn, be dictated by the performance of the readout electronics.

The IMMS **mathematical algorithm** underpinning the design tool works on a set of sensors. The basic structure of these sensors will be determined by the number of basic modules and numbers of springs per module. The module technique permits selection from a variety of basic structures. When selecting from these, the algorithm starts from the simplest form. If it cannot find a design which is appropriate to the requirements, it moves on to the structure next in complexity. The sensors differ from each other



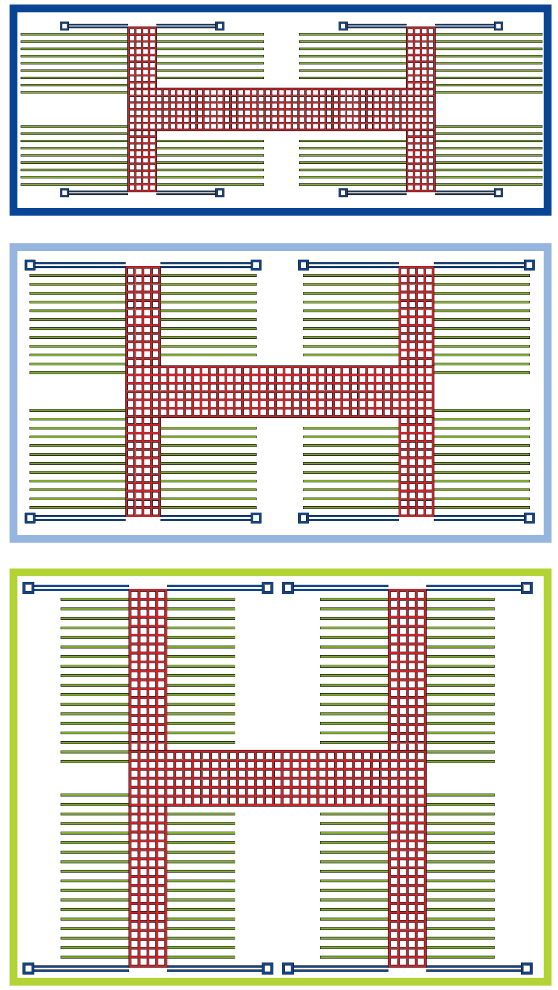


Fig. 4: Customised sensor variants devised by the IMMS design tool: designs V1 (dark blue), V2 (light blue) and V3 (green) show some options. Diagram: IMMS.

in their different number of fingers, length of fingers, width of springs and length of springs. All other geometrical dimensions are the same, particularly the depth of the structures, which is dictated by the X-FAB SOI technology. The algorithm aims to determine the above geometrical dimensions in such a way that the user's specification for the necessary sensor will be fulfilled. Only sensors with certain combinations of number and length of fingers will possess the desired base capacitance. Which these are will be decided in an initial step of the algorithm. The modelling follows a linear approach. For this to work, it must be certain that the sensors will be actuated far below the resonance frequency and that there will only be small displacements. The linearity of the models used enables a direct relationship to be established between the spring parameters and the other three sensor dimensions as described. This means that relevant spring widths can be computed in a second step of the algorithm, together with the appropriate spring lengths for the sensors found in the first step. Examples of sensor versions found in this manner are shown in Figure 4. From these versions, designs can then be selected to reflect further desired features. The moveable sensor parts shown in variants V1, V2 and V3 are each associated with their own particular number and length of fingers and with their own particular width and length of spring.

For each of the relevant sensors, the design tool provides **models** which describe the sensor's electromechanical behaviour. Firstly, the tool automatically generates a Verilog-A model which is suitable for rapid simulations of the system. It is based on simple model equations describing a spring-mass system of the second order with reactive force coupling and attention to Brownian noise. Secondly, the tool generates a model for MEMS+. In MEMS+, Coventor has integrated innovative approaches to the computation of fringe capacitance, with which a very exact de-

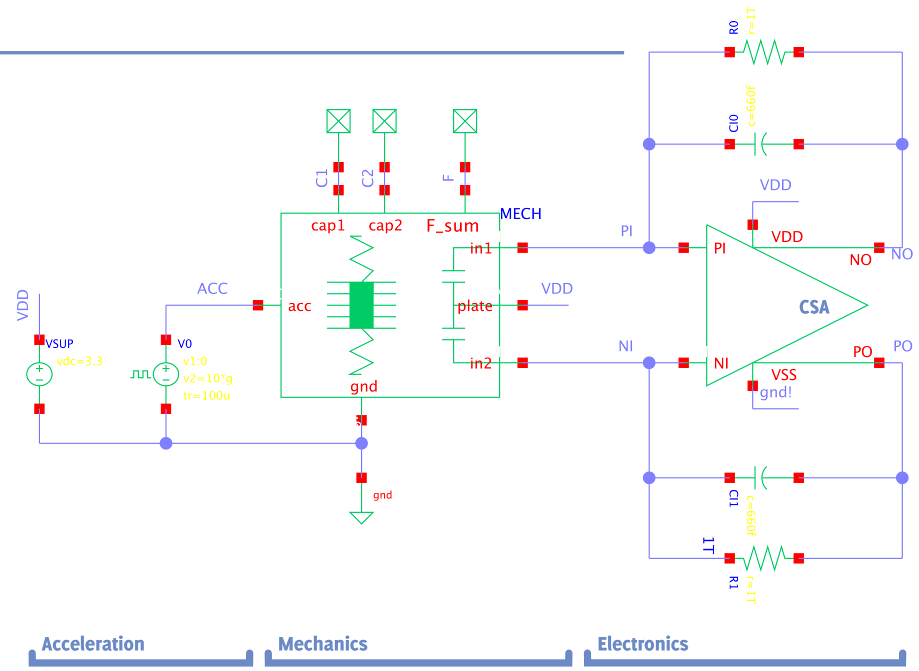


Fig. 5: Simple simulation environment for MEMS. The input voltage in the left-hand section of the illustration corresponds to a figure for the acceleration affecting the sensor. The middle section represents a mechanical model of the MEMS. Here the acceleration input dimension is converted into capacitance change. A charge-sensitive amplifier in the right-hand section forms the electronic circuit that converts the capacitance change into a measurable differential voltage. Diagram: IMMS.

termination of capacitance changes is possible. The MEMS+ model can be integrated into the Cadence IC design environment but does require longer computing times than the Verilog-A implementations. When both models are integrated into simulation environments as shown in Figure 5, they make it possible to observe the interaction of the MEMS and the integrated circuit.

Future prospects

In realising the overall design procedure, IMMS did not only create various sensor designs but also a complex electronic readout system for accelerations of 10 g. The MEMS structures have already been manufactured by X-FAB, a partner of IMMS in the project. In the first quarter of 2015, IMMS is to carry out the measurements for the structures in its MEMS-T-Lab, set up for this project (among others) and commissioned in 2014. The measurements will hopefully verify the methodology and facilitate further improvement of the design flow. The electronics manufactured by X-FAB will also be available in early 2015.

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Partners of IMMS in the project are Bosch, Cadence, Carl Zeiss SMT, Coventor, Munich, TU, TETRA, Bremen University and X-FAB.

The MEMS2015 project is funded by the BMBF (German Ministry of Education and Research) in its IKT 2020 programme, with the reference 16M3093.

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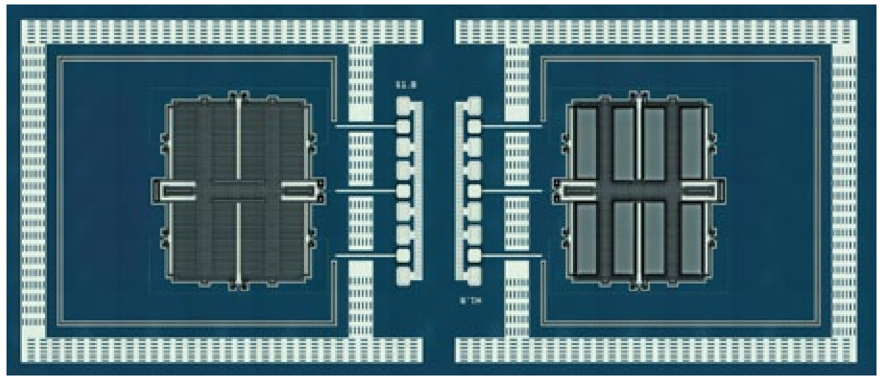

Fig. 6: Microscope image of the finished MEMS structures. Photograph: IMMS.

Readout circuit for a smart force sensor MEMS

The ASIC developed by IMMS is part of a compact sensor head capable of measuring surface quality at a resolution of less than 100 nanometres in the industrial setting. Photograph: IMMS.

Objectives

Because microsystems technology is advancing so fast, particularly in the trend towards ever larger wafer diameters, and ever smaller components, the challenges confronting process monitoring and quality tests for microsystems are ever greater. In the attempt to minimise reject rates for components and even for finished products, it is necessary to subject them to measurements at ever higher accuracy as early in the production process as possible. There is often a requirement to test the surface quality and other properties of microsystems during their manufacture at a resolution in the nanometre range. For the analysis of the mechanical properties, there is a variety of measurement methods and equipment, such as atomic force microscopy (AFM), profilometers and nanoindentation, all of which have proved valuable in the laboratory but are hardly suitable for use on the production line. With none of these is it possible to examine entire wafers non-destructively. It has up to now always been necessary to divide the wafers because the measurement samples have to be so small. This means that only random sampling is possible using the customary technology, rather than 100% inspection.

Development

Together, TETRA and IMMS have come up with solutions in the MEMS2015 project leading to a compact sensor head capable of measuring surface quality at a resolution of less than 100 nanometres in the industrial setting. The product developed unites a sensor and analogue signal processing unit into a tiny space. Being so compact, the sensor head can be installed above the precision direct drive systems developed by IMMS, so that an entire wafer can be subjected to highly accurate measurement. The force sensor which has been developed by TETRA is based on a MEMS cantilever, which is a flexible silicon strip with a tip at one end for measuring, and a piezoresistive bridge circuit at the other end, composed of four integrated strain-dependent resistances. The tip is used to explore surfaces. The forces generated by any unevenness it finds have the effect of altering the resistance in the bridge circuit. The changes generate a signal which is transmitted to the electronic signal processing system. The ASIC (application-specific integrated circuit) developed by IMMS has been adapted both mechanically and electrically to the properties of this cantilever. The task of the ASIC is to convert and amplify the high-resolution signal so that transmission to the readout unit is parasitic-free. The ASIC and the cantilever are assembled on each side of the carrier plate in the sensor head, one on top of the other. This keeps the signal wiring as short as possible so as to prevent any ambient interference with the signals. It was required to develop this ASIC as earlier investigations had shown that the sought-after resolution cannot be achieved with standard components because of the interference on the connecting wires. Another reason for the need was that conventional solutions capable of performing the function were too large for a compact sensor head.

So that a marketable nN level force measuring unit could be developed for application on industrial production lines, IMMS, jointly with TETRA, has worked out the electronic requirements, integrating functions into the circuit which would not be supported by conventional components. The ASIC includes an amplifier operating on a zoom principle developed by IMMS that achieves a measuring range of up to 100 µN at a resolution in the two-digit nano Newton range. To support precise analysis of the surface quality from the measured values, the chip also registers the cantilever temperature. IMMS has also equipped the ASIC with an error detection circuit, which recognises any cantilever defects and provides the basis for verification of the measured values. Communication with the ASIC takes place across a digital interface.

The approach in detail

To achieve the high measurement resolution, the change to the resistance made by the force is processed through a highly sensitive low-noise amplifier in the ASIC. There are four levels of amplification that can be set. The lowest level covers the largest range of measurement, while the highest covers the smallest range, but with the highest resolution. Ideally, the resistance measurement bridge of the cantilever should be in balance, i.e., the signal from the surface should move around zero (Fig. 3a). When used during production, this is, however, not the case. Because of such factors as the tolerance in the measurement resistance and the pressure of the cantilever on the surface, the measurements tend to range outside the area around zero. If there were no additional circuit, the voltage at the amplifier output would be shifted in a similar way and then would be subject to the maximum value feasible in the amplifier. This output voltage would then no longer reflect the measured value (Fig. 3b). For these reasons, IMMS has implemented a zoom principle which enables even the tiny signals that are further from zero to be measured. Via the digital interface the amplification first reduces to a level where the signal lies in the measuring range (Fig. 3c). After that, the shift in the zero point and the amplification of the ASIC are set to bring the signal centrally in the measuring range (Fig. 3d). The zero point setting can be shifted in 64 steps across the whole of the measuring range.

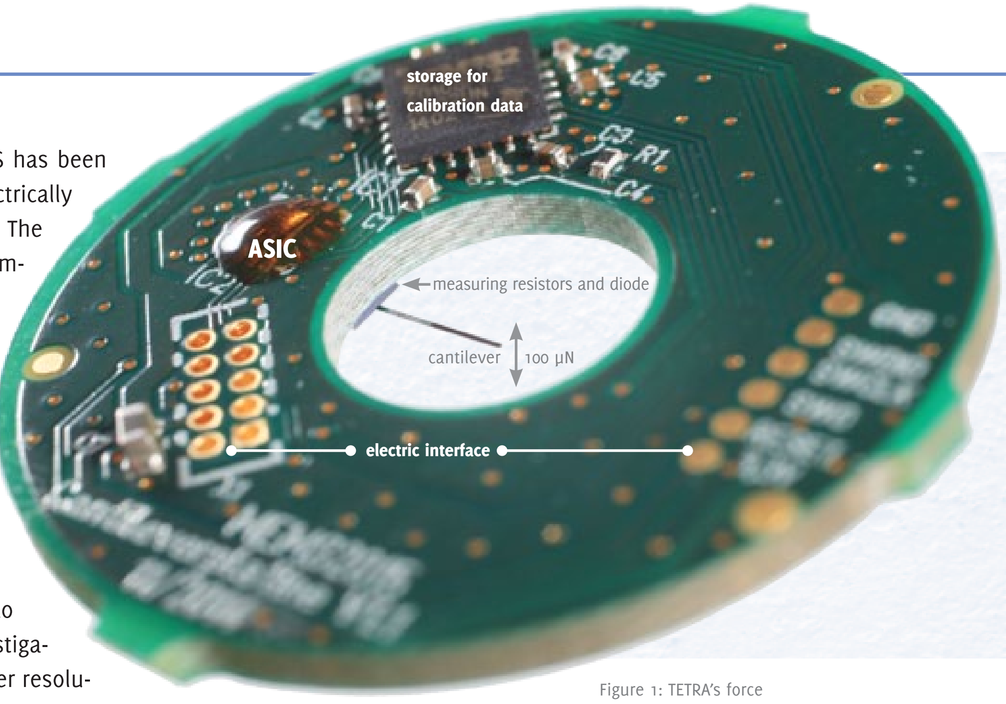

Figure 1: TETRA's force sensor MEMS module with the ASIC developed by IMMS for the examination of surface structures in industrial production. Photograph: IMMS.

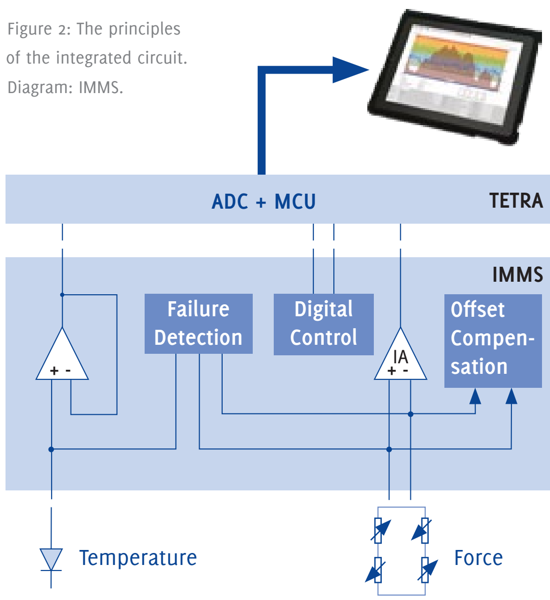

Figure 2: The principles of the integrated circuit. Diagram: IMMS.

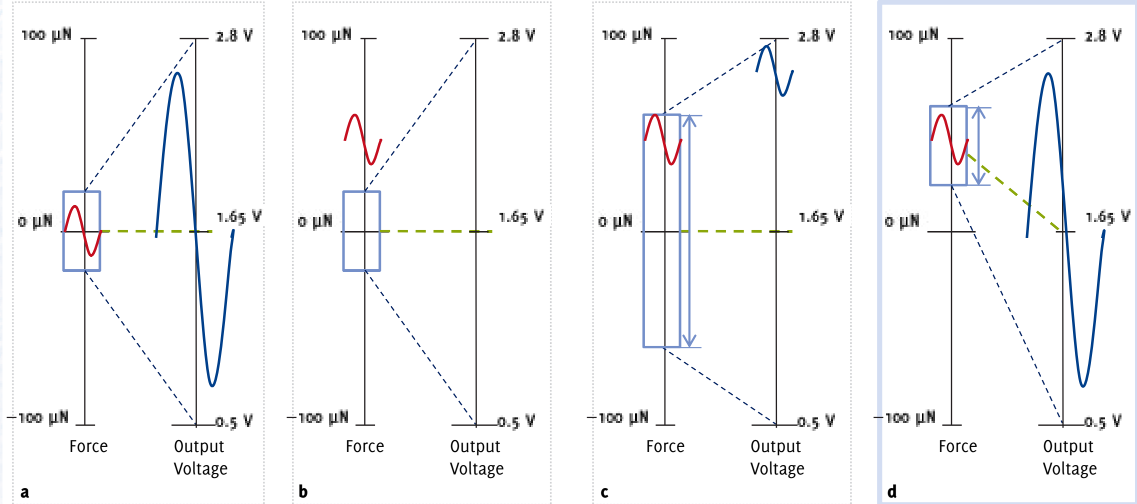

Figure 3: Zoom principle in the ASIC developed by IMMS.
a) Force: Ideal setting. Output Voltage: Best possible modulation.
b) Force: Wrong setting, signal (red) outside measuring range (light blue). Output Voltage: limited by upper modulation limit, no signal visible.
c) Force: Measuring range enlarged (light blue). Output Voltage: Signal visible but modulation (dark blue) not optimal.
d) Force: Zero point shifted (green) and measuring range reduced (light blue). Output Voltage: Optimum modulation (dark blue). Diagram: IMMS.

The cantilever properties change according to its temperature. The readout unit therefore has to determine the cantilever temperature for every measurement and include this in the force calculations, so that the readout circuit must also contain a measurement amplifier for the temperature-dependent forward voltage of a diode which is integrated into the cantilever. Used industrially, the measurement system may well suffer wear and tear and the cantilever even be damaged. For example, pressing too hard can break off the cantilever. Mechanical damage of this kind will be reflected in altered electrical behaviour. The ASIC therefore carries out a full self-test before each measurement. The error recognition system is able to identify any atypical electrical properties of cantilever or temperature diode. The test takes only a few microseconds.

Future prospects

The ASIC as developed by IMMS has been designed in CMOS XH035 technology, manufactured by X-FAB, partner in the project, and verified at the Institute. IMMS has developed testing hardware in house which will minimise disturbances in the measurement module so as to verify the high sensitivity. The measurements obtained do confirm that the ASIC fulfils the specification. The samples of the ASIC for the force sensor module delivered to TETRA at the end of October, 2014, are now being tested there. The intention is that the prototype sensor head will be cleared for use in a demonstration version by the end of the MEMS2015 project in June 2015. The readout circuit designed by IMMS is a core component of the sensor head, enabling it to act as a smart autonomous system in industrial processes. The Institute plans steadily to reinforce its competence in these solutions with their integrated self-testing, self-calibrating and signal-verifying functions so that it can pave the way for other measurement and process technology on the approach to Industry 4.0.

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Partners of IMMS in the project are Bosch, Cadence, Carl Zeiss SMT, Coventor, Munich TU, TETRA, Bremen University and X-FAB.

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RESEARCH SUBJECT

INTEGRATED SENSOR SYSTEMS FOR BIOLOGICAL ANALYSIS AND MEDICAL TECHNOLOGY

Integrated sensor systems for biological analysis and medical technology

IMMS has as one of its goals the advancement of medical engineering, biological analysis and personalised medical care using electronic sensor systems. Such systems will, in particular, help extend diagnostic procedures, help in the targetting of treatment and help reduce risk and discomfort for patients during diagnosis. The new solutions should be cheaper to produce and use, bringing down health service costs, which, according to the German Office of Statistics, amount in Germany to eleven per cent of the GDP and are increasing every year. The rise in costs is due partly to higher life expectancy and the associated rise in the number of cases of serious degenerative illness such as cancer, cardiovascular disease and dementia. In parallel, there is a rise in patient demand for and expectations of higher quality of life. It is therefore a part of the national high-tech policy in Germany to encourage the growth areas of life sciences and biomedical technology. The focus on these megatrends has multiple aims: the development of medical technology to meet patient needs, the suppression of widespread diseases and the improvement of patient care through the concept of personalised medicine. In a number of research projects focussed on these strategically important applications, IMMS has over recent years extended its work on medical technology and biological analysis, and proposes to intensify this.

Medical technology

As early as 2006, IMMS was already contributing its knowledge of sensor systems and systems integration to the development of a personalised miniaturised noise dosimeter. This mobile device was the first of its kind able to measure noise exposure rapidly and accurately near and in the ear by registering momentary or long-term noise levels. The data captured enables health and safety measures to be taken so that noise-related hearing loss can be prevented.

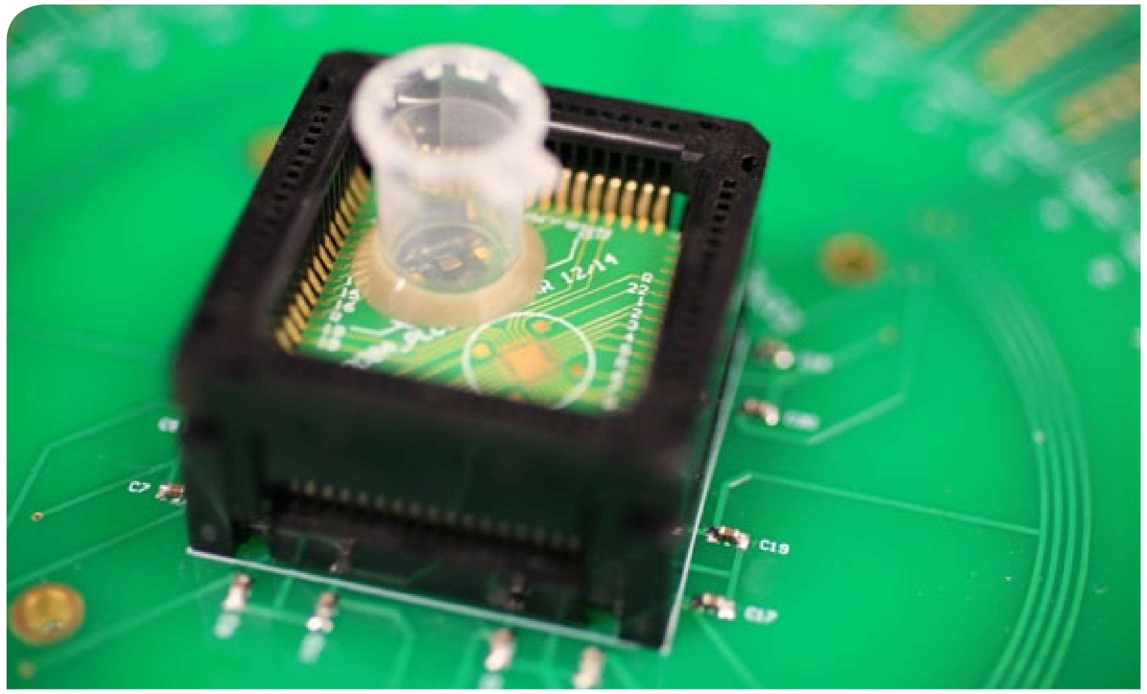
There is a report on page 48 of IMMS' current work on the design of a four-transistor pixel (4TP) array demonstrator, which involves a pixel cell of which the technology has been newly developed by X-FAB Semiconductor Foundries AG. The intention is to combine it with the readout circuit of IMMS and provide high-quality recordings of two-dimensional images with less noise. The 4TP image sensors for use in radiography which are arising from the work will be capable of use in receiver modules for the X-ray images in, for instance, dental diagnostics or mammography.

Moreover IMMS has fields of competence in systems integration, communications and signal processing, and contributed these skills to the successful conclusion of the MARS research project in the autumn of 2014. This project required a mobile retina scanner to be developed. For it, IMMS designed and created the electronics (with the necessary systems design), the interfaces, the Linux software support and data transfer solutions.

Biological analysis

With its innovative electronic sensor systems for biological analysis, IMMS is focusing particularly on swift simple and personalised early recognition of cancer, which will raise the chances of survival for the patients affected. Other research work going on at the Institute is intended to progress the sort of new or improved and lower-cost product that can benefit diagnostics in human and veterinary medicine. In both these fields there is a need for new means to be found of combining microelectronics, mechatronics and systems technology with current procedures in biological analysis. To this end, IMMS applies a variety of sensor principles to the simultaneous detection of different biological measurands so that diagnosis is more conclusive and less prone to error. The work is based on familiar (and thus relatively inexpensive) manufacturing processes for the electronics and for the packaging but in each case the processing and packaging are adapted to the specific application. IMMS wants to establish new, hybrid solutions on the bio-compatible sensor packaging front which are suitable for mass production, so that it will become possible to carry out on-site testing which is reliable, cheap and largely automated.

Among other skills, IMMS brings into its work on these innovative products its knowhow in the fields of opto-electronics and analogue/mixed signal circuit design, knowhow to which it has been adding ever since it was founded. The aim is to create systems integrating bio-compatible electronics with sensors



Test setup for the RFID multisensor ASIC developed in the GreenSense project for the analysis of aqueous solutions. Photograph: IMMS.

which will recognise optically detectable bio-signals. One example is an optoelectronic biocompatible circuit for a retina implant, designed and realised as early as 2011. This implant partially restores the sight of patients with retinal degeneration. The low-power infrared receiver chip developed by IMMS transmits image data from an external camera into a tiny electrical stimulation unit which has been implanted into the patient's retina.

IMMS has also built on its skills in biosignal processing so that it can as an Institute systematically extend the knowhow it can contribute to the field. Developments have already been completed which are bringing microelectronics closer to the central concerns of diagnostics and medical care.

In this context, IMMS was closely involved with the 3DNeuroN project completed in 2013, contributing the research and development for a new 3-dimensional, low-power, low-noise sensor/actor electrode array to measure and stimulate neuronal activity. In the future, it is hoped that this approach will assist healing processes when there is damage to the tissue of the central nervous system. A 3D array containing 800 electrodes will stimulate neurons and will record in three dimensions the resulting reactions and behaviour. IMMS created the sensor-and-actuator electronics for the array. In this project, the connection was made for the first time by capacitance rather than galvanically between such a three-dimensional sensor and the biological tissue. The method precludes unwanted electrical currents and ensures that the array is biocompatible.

The work of the IMMS GreenSense group came to a successful conclusion in 2014. It brought substances requiring analysis closer to our microelectronic chips. DNA-based analysis procedures not only for the diagnosis and treatment of disease but also for analyses at the molecular level using a micro-array became possible. For both purposes, the sensor and the medium containing the subject substances are together on the CMOS chip, coming into direct contact with it. The project involved the first-ever production of a chip with which detection is possible of the hybridisation of DNA molecules after they are marked with metallic nano-particles, using a number of sensor principles simultaneously. The latest results from this project are reported in detail on page 50. Another contribution made by IMMS to GreenSense is a modular technology platform for the construction of self-powered multimodal smart sensor networks which are energy- and resource-efficient. For the platform, IMMS designed and created a passive 13.56-MHz RFID multisensor ASIC, which registers, wirelessly, any changes in the temperature and pH of aqueous solutions and can be used for biological analysis.

4TPixel

ASIC development for radiography

IMMS developed a readout circuit for a novel pixel cell and provides low-noise high-quality recordings for X-ray photographs. Photograph: IMMS.

Objectives

To improve both diagnostics and treatment options for patients, further development has been taking place for many decades in such imaging methods as radiography, computer tomography (CT) and magnetic resonance imaging (MRI). CMOS image sensors (CIS) have long been established in medical technology. They are semi-conductor structures which combine photo diodes and the electronics for signal processing onto one cheap and energy-efficient microelectronic device. Though at first CIS tended to suffer from limited photo sensitivity and high noise, they now facilitate low-noise and rapid image recording in professional applications. Research is continuing in order to reduce yet further the radiation exposure for patients being X-rayed: research into ever more sensitive sensors and ever more precise and speedy image processing in reliance on more powerful evaluation electronics.

Here the ASIC design of IMMS has contributed to a four transistor pixel (4TP) array demonstrator: in combination with a new pixel cell which has been developed from scratch by X-FAB Semiconductor Foundries AG, the Institute's readout circuit is to be used in the service of radiography, providing high-quality recordings of two-dimensional X-ray photographs with less noise. The 4TP image sensors developed in this way will, for instance, be capable of use in receiver modules for X-ray images for dental diagnostics or mammography.

The 4TP cell, sensitive to green light, contains a large area with high photodiode-sensitivity and four transistors for the low-noise readout. The integrated circuit components that have been developed by IMMS for these conditions will, together with the readout procedures implemented, make high-precision evaluation possible. They will, in addition, contribute to a wide dynamic range for the demonstrator because not only very weak photo signals but also any very strong ones which are registered will be capable of being processed.

The IMMS ASIC design in detail

IMMS developed models for the 4TP cells and included them in such a way in the simulation environment that the signal behaviour of the 4TP cells was as exactly represented as possible for the circuit design. Fig. 1 shows the schematic for one such cell.

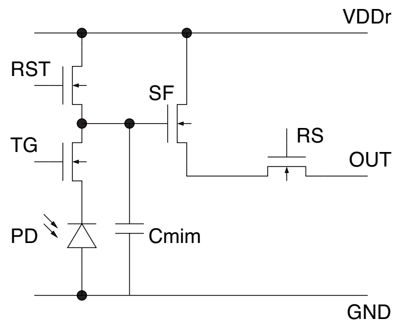


Fig. 1: Schematic of the 4T-P cell:
. Transistors (RST, TG, SF, RS) *for exact timing and low-noise readout*
. Photodiode (PD) as photosensitive area and a storage capacitance (C_{mim}) in parallel to this: *for conversion of the light signal into an electrical signal and to store the generated charge carriers (electrons).* Diagram: IMMS.

On the basis of the models, IMMS configured the circuit design for the demonstrator in such a way (cf. Fig. 2) that the properties of the pixel cell could be thoroughly tested both in the array and in its interaction with the readout circuit. For this purpose, the Institute implemented a digitally controlled readout and control logic system which is freely configurable via SPI. The logic system enables the user freely to define the timing and duration of cycles of operation to investigate any time-dependent effects on the quality of the array readout process. An additional advantage of the solution is that various control signal voltage levels and pixel array supply voltages can be set so as to influence and test the performance of the pixel.

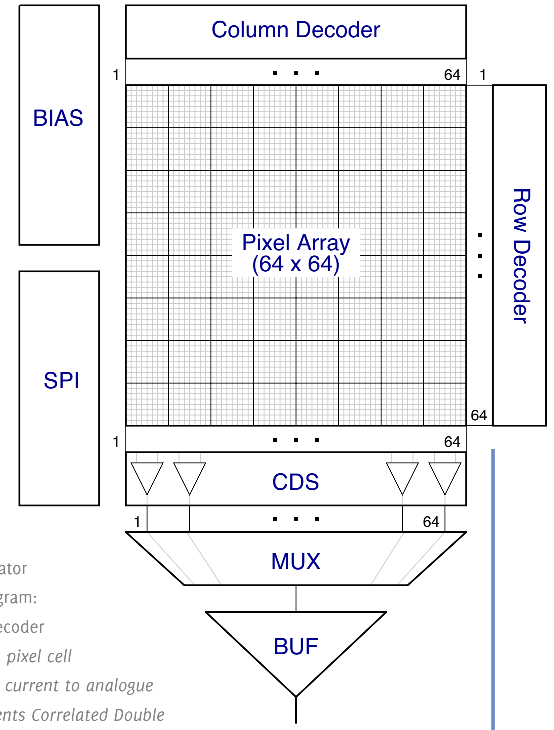


Fig. 2: Demonstrator block circuit diagram:
. Row/column decoder *to address each pixel cell*
. BIAS: *to supply current to analogue circuit components Correlated Double Samplings (CDS) stage and Output buffer (BUF)*
. Multiplexer (MUX) *to forward processed analogue pixel values from the CDS to the BUF sequentially.* Diagram: IMMS.

The rolling shutter principle implemented means that the signal values from the pixel matrix are readout row by row, captured as appropriate to the switching operation, and then processed. At the end of the last row the two dimensional signal acquisition closes and the next imaging process begins.

The CDS (correlated double sampling) is the central principle of the IMMS circuit, adapted by the Institute to the pixel signal behaviour modelled. The CDS stage catches the dark voltage of the pixel in its first switching state: without pixel illumination. In a second switching cycle, after pixel illumination, the light signal is captured, subtracted from the dark signal and related to the system's own reference voltage. The circuit can fully exploit the dynamic range of the pixel. Also, this CDS technique effectively 'de-noises' the pixel cell. The whole analogue signal path as simulated achieves a dynamic range of 91 dB for input referred noise of 71 μV_{RMS} and an absolute signal error of less than 0.5%. The demonstrator can thus ensure the necessary image quality because of its excellent signal to noise ratio and the precise readout process. The ASIC as simulated consumes less than 70 mW in all, which makes it highly energy-efficient.

IMMS has developed the ASIC in such a way that it is possible to test individual circuit components in the analogue signal path and the digital part. The effect is that the influences exerted on the readout behaviour by the pixel itself and by the circuit can be distinguished from each other. In order also to minimise parasitics from and interferences conducted by the digitally induced switching operations, and to ensure that the CDS stage performs well, IMMS has done some further precision engineering on the layout of the ASIC.

Future prospects

The ASIC goes into production in the first quarter of 2015. While it is being characterised and tested, IMMS will be concentrating on the evaluation of the marginal conditions for timing and supply voltage, optimising these and investigating the sensitivity of various 4TP cell topologies. It will be possible to use the investigations in future research to undertake redesign and extend both functionality and complexity. It would be possible to employ the global shutter principle and to integrate analogue to digital signal conversion into the chip. That would provide a basis for further development of even higher-quality and even more reasonably priced CMOS image sensors with integrated processing electronics for radiographic purposes.

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Semiconductor-based biochips for on-site veterinary diagnosis

Test card equipped with an ASIC capable of analysing aqueous solutions applied directly to the chip. Photograph: IMMS.

Objectives

Regular health testing of farm animals is a necessity for high-standard food supplies. Up to now, veterinary diagnosis has been possible only after several days or even weeks because it has been necessary to send off samples to a laboratory where they are prepared for and subjected to microbiological analysis. In cases where a potentially dangerous disease is found to be present, viruses or bacteria may have proliferated meanwhile. Depending on the severity of the infection, a farmer's entire stock may be quarantined or even destroyed to prevent the spread of the disease.

IMMS has therefore joined forces with the Leibniz Institute of Photonic Technology in Jena (IPHT) to develop the means whereby epizootic disease can be readily diagnosed. The idea is that a portable electronic device should enable samples from farm stock to be examined for pathogens automatically and rapidly. The affected animals can then be isolated and treated at an early stage, eliminating any risk to consumers, protecting the healthy animals and limiting financial loss.

The IMMS contribution follows the principles of a diagnostic procedure developed by Jenaer BioChip Initiative (JBCI, IPHT Jena) which has enabled foot and mouth disease (FMD) and other diseases to be detected from samples on glass chips.[1] As the procedure relies on a simple and fast evaluation of the electrical conductivity and optical properties of samples, it can be incorporated into a compact on-site diagnostic system. IMMS and JBCI have worked together for the purpose of a highly accurate diagnosis with automated readout. In the GreenSense project, the measurement principles have been implemented on new microelectronic platforms. Bonding technology and system assembly solutions have also been developed. IMMS has, furthermore added to the measurement methodology and laid out the electronic system for an impedance-based procedure. The microelectronic approach offers additional measurement options as an alternative to the original glass plate-based platform. The aim is to use the new devices to keep track on the reactions taking place during diagnosis and to unify the three types of measurement on a single semiconductor biochip.

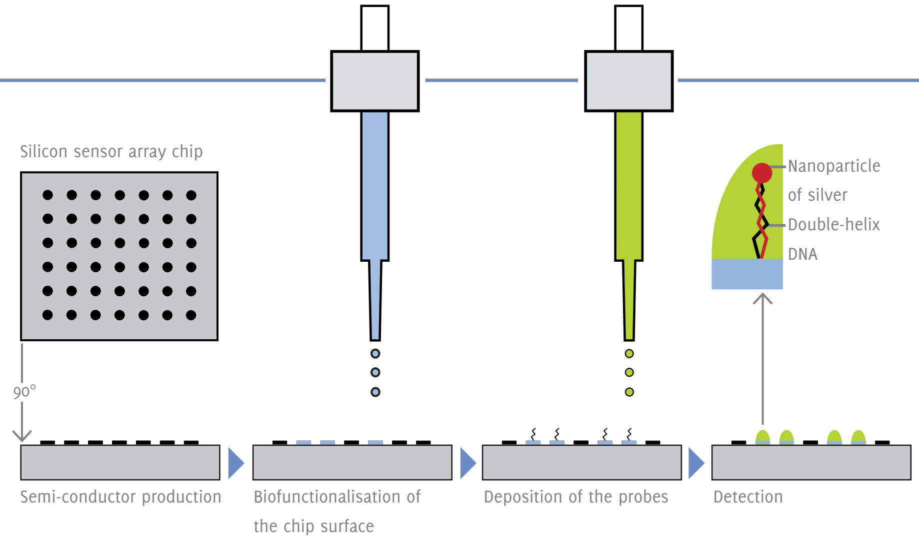


Figure 1:

The JBCI-IPHT diagnostic procedure is the basis for the three ASIC designs developed at IMMS. The three silicon chips each have a different detection method by which the presence of silver nanoparticles is shown. Diagram: IMMS.

Three new ASICs developed by IMMS

The diagnostic procedure researched and developed in Jena is the starting point of the IMMS contribution by which a planar surface made of glass or other substrate material with pairs of gold electrodes sputtered onto it is first functionalised. Here, the glass chip is first pretreated chemically and then coated between the electrodes with biomolecules specific to the relevant viruses. The molecules will detect the viruses on the lock-and-key principle. The sample for analysis is replicated and conducted through the electrode gap on the glass chip in a system of microfluidic channels. If the DNA sought for is present in the sample, it will react with the 'catcher' molecules. Thereupon, nanoparticles of silver will be deposited, forming a conducting layer, which will bridge the electrode gap and cause a short-circuit. A simple direct current measurement will reveal this as a change in the resistance between the electrodes. There is also the possibility of using optical data capture by determining the level of greyness due to any silver deposit. IMMS has developed three different sensor systems based on CMOS semiconductor technology which allow measurement of new silver nanoparticles directly without the use of the glass plate. The three microelectronic systems will not only register that the particles have been deposited but will also by virtue of their design establish details of the nanoparticle concentration and quality of detection.

In order that the IPHT can subject the samples and controls to the biotechnological tests in parallel, comparing results and using these for further research, IMMS has at this stage implemented the three measurement principles in three separate system versions. As a result, there are two sensor ASICs on which sensors are arrayed as a 6 x 7 matrix comparably to the JBCI chip system. For the third ASIC design there is a set of test structures. The integrated sensors have been so arranged in the electronics that the distances between them allow sample solutions to be added separately, electrode by electrode. The functions of the microelectronic chips are set up at the IPHT in a similar way to that described above and the samples are prepared as appropriate to the method. In all three of the IMMS systems, the analysis results are dependent on the number of silver nanoparticles deposited on the surface of the ASIC. The concentration of target DNA present is then computed from the nanoparticle result; calibrated measurements serve as a reference.

For the first version, IMMS transferred the IPHT's principle for measuring conductivity onto a microelectronic chip and further extended it. The **resistance** present between two electrodes is measured and evaluated. The design of the ASIC takes into account the maximum amps and voltage to which it is known that the DNA can be exposed, knowledge obtained in prior investigations by JBCI. The ASIC also has four possible amplification settings, as the intention is that there should be digital processing not only of the initial stage of the detection but also of the complete procedure.

In the second chip design, the nanoparticle presence is established by **optical** readout. The sample in this case is exposed to a light source providing homogeneous illumination. With an array of photodetectors which are highly sensitive to light including the visible spectrum, the ASIC registers how the strength of the light is changed by the non-transparent silver nanoparticles in the course of the detection procedure.

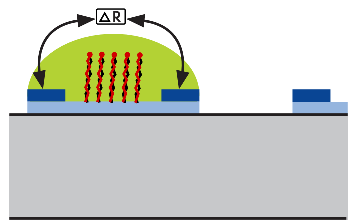
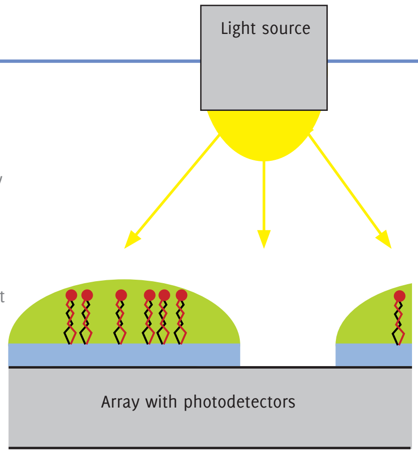


Figure 2: The principle of the ASIC developed by IMMS to detect the presence of nanoparticles of silver by means of resistance measurements. Diagram: IMMS.

Figure 3:

Light source array of photosensors principle of the ASIC developed by IMMS to detect the presence of nanoparticles of silver by optical means. Diagram: IMMS.



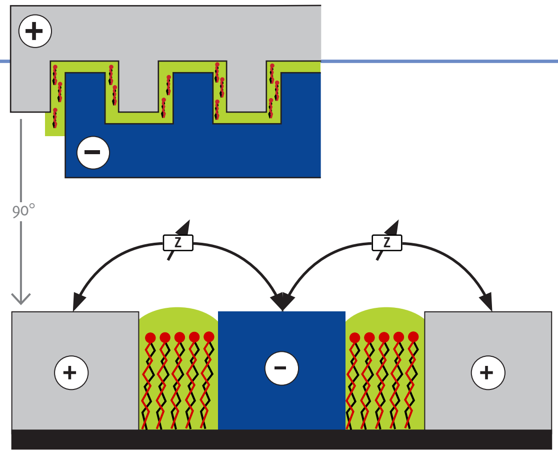


Figure 4: Principle of the ASIC developed by IMMS to register silver nanoparticles from impedance measurement. Diagram: IMMS.

With the aim of achieving the highest possible resolution during readout and also of successfully adapting the amplification chain in the circuit to the variable current output of the photodiodes in real time, IMMS defined 72 settings for the signal amplification system, in three steps. This wide choice of settings is intended to ensure complete optical characterisation for the minimum number of nanoparticles still capable of detection.

A third version is to be constructed in which silver nanoparticles are found from the **impedance** measurements. The Institute has already developed six interdigitated impedance analysis structures. Like the teeth of a comb, the structures have been designed at this preliminary stage with different spacing and width to find the structure with the highest sensitivity so that it can be included in the third ASIC design. The total impedance between the electrodes changes in relation to the settling of the silver between the teeth of the comb. The changes can be registered by means of an AC metering bridge between two combs. The interdigital sensor structure being so precise, the measurements should be even more sensitive. The impedance measuring sensors have the additional advantage of taking more than one type of measurement at once in rapid succession. Their use in the present instance would enable not only the resistance but also, crucially, the change in capacitance

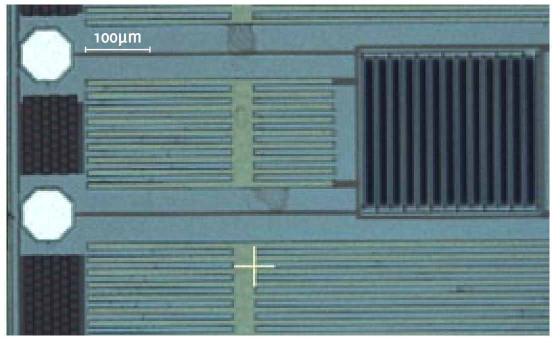


Figure 5: Magnified view of the comb-shaped structures used in the impedance measurement method. Photograph: IMMS.

and phase of the signal to be registered: these are important physical values which could be registered simultaneously to assist in bioanalysis if this procedure were followed.

Summary and future prospects

The applicability of the three different sensor ASIC systems has been under test in joint work with the IPHT since the first quarter of 2015. The biological tests are being run in three stages. On the one hand, this enables the biocompatibility of the materials used in the microelectronics to be tested. On the other hand the effects of the separate procedure steps can only be characterised with respect to the sensor sensitivity by successive measurements. The electronic test and characterisation commenced at IMMS at the beginning of January 2015 has facilitated the start of the first validation measurements for the sensor systems being currently under packaging. It is intended to adapt the work in further veterinary research and to continue the investigation of the reliability of the sensors in succeeding projects. In order to promote active industrial exploitation of the diagnostic system in future, the involvement of customers and small and medium-sized enterprises is envisaged.

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1 Seise, B. et al., Engineering in Life Sciences (2011) doi: 10.1002/elsc.201000046

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IMMS

ESF EUROPA FÜR THÜRINGEN EUROPÄISCHER SOZIALFONDS

EUROPÄISCHE UNION
Europäischer Sozialfonds

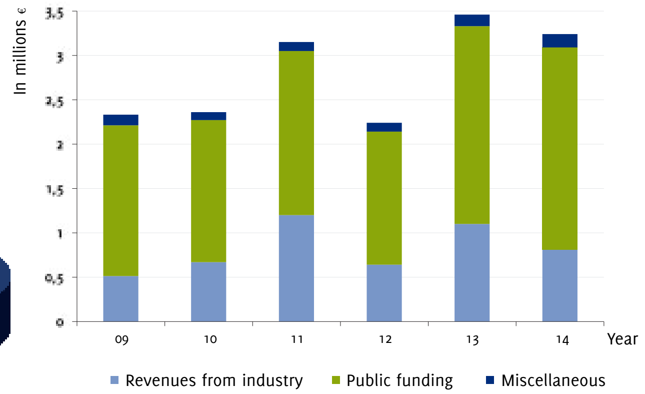
EVIDENCE IN FACTS AND FIGURES

Staff at the IMMS headquartes in Ilmenau. Photograph: IMMS.

Facts and Figures

Staff

Project income



2014 saw 85 members of staff working at IMMS. There were 57 employed as scientists and 9 (FTE*) students, i. e. 85 % of the entire staff, who were directly involved in research and development.

As in all recent years, the number of students (53) availing themselves of the opportunities at IMMS to pursue research of relevance to real life was high. 27 of them came on internships and the Institute's staff supervised seven BSc and MSc dissertations. There are five IMMS researchers currently pursuing doctoral studies at various universities.

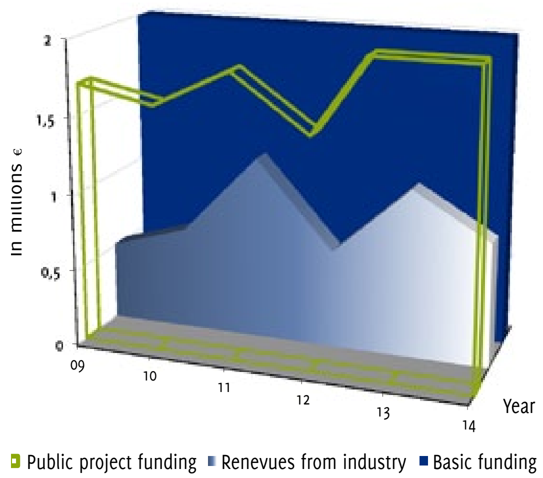
IMMS makes a point of engaging in undergraduate teaching in order to be able to attract enough of the highest quality graduates.

The proceeds from industrial research commissions were about 8% more than that of the previous year and the level of public funding about 5% higher. The actual income fails to reflect this relationship exactly. Delayed payment of project funding that had been claimed occasioned a reduction in income as against the previous year. The market for R&D services developed over the year in a variety of ways. Industry showed a more or less unchanged willingness to finance external R&D from its own funds, but in 2014 there was marked interest in state funding of R&D.

The figures for 2014 clearly suggest that project funding will continue this positive trend. Almost all the IMMS projects are carried out jointly with industrial partners, which is evidence of how well IMMS is accepted in the research partner role. The Institute has succeeded in achieving increased project activity by getting involved in research networks. The aim is to convert the good research results as quickly as possible into industrial applications. This will benefit SMEs most of all. The conversion process can be stabilised if the SMEs are combined into regional, product-oriented value-added supply chains. Access to innovation-driven markets is coming more and more to require systems competence in the design and manufacture of products, using micro- and nanotechnologies. IMMS is excellently placed in this respect.

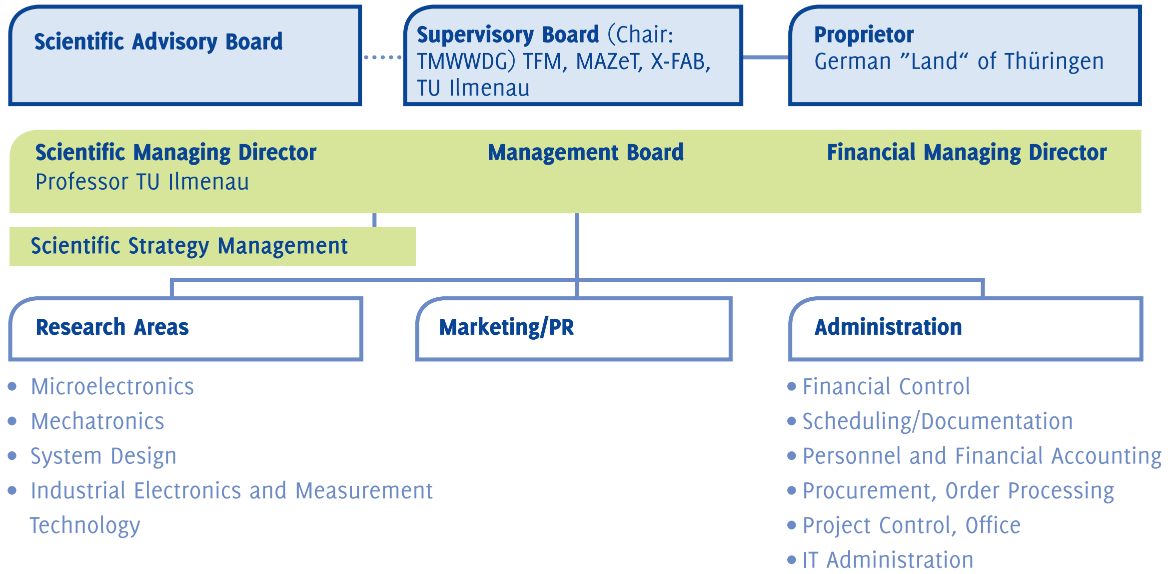
Thüringen as federal "Land" maintained its level of support in 2014 to keep the Institute on an even keel. The work IMMS could do in conjunction with regional SMEs benefited above all from this, but there is no longer any compensation for pay rises and inflation.

Pillars of financial support



* FTE *Full time equivalent.*

Organisation



Scientific Advisory Board

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- Dr. Jens KOSCH, Chief Technical Officer, X-FAB-Semiconductor Foundries AG
- Thomas WEISSENBORN, Ministry of Finance, Thüringen

Lectures, lecture series

Prof. Dr. Ralf Sommer at Ilmenau University of Technology, Department Electronic Circuits and Systems:

- "Grundlagen der analogen Schaltungstechnik", lecture and tutorial, bachelor students 3rd semester,
- "Rechnergestützte Schaltungssimulation und deren Algorithmen (EDA)", lecture and tutorial, bachelor and master students
- "Modellierung und Simulation analoger Systeme", lecture and tutorial, bachelor students

Prof. Dr. Hannes Töpfer at Ilmenau University of Technology, Department of Advanced Electromagnetics:

- "Theoretische Elektrotechnik I", lecture and tutorial, bachelor students 4th/5th semester
- "Modellierung und Simulation", lecture, bachelor students 5th semester
- "Optimierung und inverse Felder in der Elektrotechnik", lecture, master students 2nd semester
- "Schaltungen und Quanteninformationsverarbeitung", lecture, master students 2nd semester
- "Elektromagnetische Sensorik", lecture, master students 2nd semester
- "Technische Elektrodynamik", lecture, master students 2nd semester
- "Grundlagen der Modellierung und Simulation", lecture, bachelor students 6th semester
- "Supraleitung in der Informationstechnik", lecture, master students 1st semester
- "Projektseminar ATET", seminar, master students 1st semester

Dipl.-Ing. Sven Engelhardt for the "Berufsakademie Eisenach" (University of Co-operative Education) "Automatisierungssysteme", lecture and tutorial, field of study Construction, bachelor students

Workshop Embedded Linux "Chancen, praktische Lösungsansätze und rechtliche Aspekte von Open Source", joint organisation with OSADL eG, Ilmenau, 13.05.2014 (host, organisation und presentation)

Seminar Sensor Networks "Durch energieeffiziente eingebettete Systeme zu vernetzten smarten Sensoren", 15.05.2014 (Organiser AMA e.V., scientific management: IMMS)

Trade Fairs

embedded world 2014 Major embedded event for the whole value chain of embedded system technology, 25.-27.02.2014, Nürnberg, Germany (co-exhibitor, OSADL joint booth)

Hannover Messe 7.-11.4.2014, Germany (presentation on BMBF joint booth)

new mobility Trade Fair for Mobility, 27.-29.10.2014, Leipzig, Germany (presentation with sMobiliTy-Projektkonsortium on BMWi joint booth)

MSV Brno, Internationale Maschinenbaumesse, one of Europe's leading industrial Fairs, 29.9.-3.10.2014. Brno, Czech Republic (co-exhibitor BMBF joint booth)

iENA International Trade Fair "Ideen-Erfindungen-Neuheiten", 28.10.-02.11.2014, Nürnberg, Germany (presentation on PATON joint booth)

Medica International Medical Fair, 12.-15.11.2014, Düsseldorf, Germany (co-exhibitor on DiagnostikNet-BB joint booth)

Other Events at IMMS

Girls' Day 2014 aims to introduce young girls to "atypical" occupations in Technology, IT, craft and natural sciences, Ilmenau, Germany, 27.03.2014 (Presentation and laboratory visit)

Sense. Enable. SPITSE. SPITSE-Symposium, 07.-18.07.2014, Ilmenau, Germany (laboratory visit)

Publications 2014

Conferences with contributions by IMMS – an overview

SSD 11th International Multi-Conference on Systems, Signals & Devices, 11.-14.02.2014, Barcelona, Spain (presentation)

EAS 2014 7. GMM-Workshop Energieautarke Sensorik, 24.-25.02.2014, Magdeburg, Germany (presentation)

DATE 2014 Conference & Exhibition on Design, Automation and Test in Europe, Dresden, Germany, 24.-28.03.2014 (poster presentation)

eda WS2014 eda-Workshop, "Ansätze zur Entwicklung durchgängiger Entwurfsstrategien für MEMS", 13.-14.05.2014, Hannover, Germany (presentation)

CDNLive2014 19.-21.05.2014, Munich, Germany (presentation)

IRPS2014 IEEE International Reliability Physics Symposium, 01.-05.06.2014, Hawai, USA (presentation)

LED- und OLED Praxisforum, 02.-03.06.2014, Würzburg, Germany (presentation)

Silicon Saxony Day Fachforum "Smart City" 8th Silicon Saxony Day, Dresden, Germany 03.07.2014 (presentation)

elmug4future Technoloy conference, Friedrichroda, Germany, 15.07.2014 (presentation)

Sense. Enable. SPITSE. SPITSE-Symposium, 07.-18.07.2014, Ilmenau, Germany (3 presentations)

ISMB14 14th International Symposium on Magnetic Bearings, 11.-14.08.2014, Linz, Austria (presentation)

UFFC2014 IEEE International Ultrasonics Symposium, Chicago, USA (presentation), 03.-06.09.2014

EUROSENSORS 07.-10.09.2014, Brescia, Italy, (2 presentations)

IWK 08.-12.09.2014 58th Ilmenau Scientific Colloquium, Germany (presentation)

Analog 2014 ITG/GMM-Fachtagung: Development with CAE-Methods, Hannover, Germany, 17.-19.09.2014 (poster and presentation)

ESSCIRC 2014 40th European Solid-State Circuits Conference, Venice, Italy, 22.-26.09.2014 (presentation)

IWK Mittweida, Germany, 06.11.2014 (presentation)

APCCAS 2014 12th IEEE Asia Pacific Conference on Circuits and Systems, Okinawa, Japan, 17.-20.11.2014 (presentation)

NAVITEC 7th ESA Workshop on Satellite Navigation Technologies & European Workshop on GNSS Signals and Signal Processing, 03.-05.12.2014, Noordwijk, Netherlands (presentation)

Reviewed Publications

Jun TAN, Alexander ROLAPP, Eckhard HENNIG, "A Low-Voltage Low-Power CMOS Time-Domain Temperature Sensor Accurate To Within [-0.1,+0.5]°C From -40°C To 125°C," *12th IEEE Asia Pacific Conference on Circuits and Systems (APCCAS 2014)*, Session Sensor Systems and Emerging Memory Technology, pp. 463 – 466, IEEE Catalog Number: CFP14APC-USB, ISBN: 978-1-4799-5229-8, Ishigaki Iceland, Okinawa, Japan.

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S. HESSE[1], C. SCHAEFFEL[1], S. ZSCHAECK[2], C. AMENT[2], A. MUELLER[3], E. MANSKE[3], "Scan performance of nanopositioning systems with large travel range," *58th IWK Ilmenau Scientific Colloquium, 8.09.2014 - 12.09.2014*, Ilmenau, URN: urn:nbn:de:gbv:ilm1-2014iwk-069:6, [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ilmenau, [2]Institute of Automation ans Systems Engineering, Technische Universität Ilmenau, 3Institute of Process Measurement and Sensor Technology, Technische Universität Ilmenau.

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Stephan ZSCHÄCK[1], Steffen HESSE[2], Avid AMTHOR[1], Michael KATZSCHMANN[2], Christoph SCHÄFFEL[2], Christoph AMENT[1], "Vergleich der Scan-Perfomance bei Nanopositioniersystemen mit großem Bewegungsbereich," *tm – Technisches Messen, Oldenbourg Verlag*, Band 81, Heft 6, Seiten 335 – 342, ISSN (Online) 2196-7113, ISSN (Print) 0171-8096, DOI: http://dx.doi.org/10.1515/teme-2014-0358,May 2014, [1]Technische Universität Ilmenau, Fakultät für Informatik und Automatisierung, Germany, Ilmenau, [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ilmenau.

Gerrit KROPP, Michael MEISTER, "Neuentwicklung und Optimierung eines Treiber-ASIC für Energie- und ressourceneffiziente Ansteuerung von OLED-Modulen," *in Elektronik Praxis*, September 2014, Seite 30 – 32.

Presentations and Posters

Wolfram KATTANEK[1], Sebastian UZIEL[1], Thomas ELSTE[1], Stephan GERLACH[2], Danilo HOLLOSI[2], Stefan GOETZE[2], "Energy-efficient High-Performance Acoustic Processing Unit," *Conference & Exhibition on Design, Automation and Test in Europe (DATE), 24.03.2014 - 28.03.2014*, http://www.date-conference.com/date14/files/file/date14/ubooth/1322.pdf, Dresden, Germany [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, D-98693 Ilmenau, Germany, [2]Fraunhofer Institute for Digital Media Technology IDMT, Project Group Hearing, Speech and Audio Technology, D-26129 Oldenburg, Germany.

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