IMMS

ANNUAL REPORT

2018

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Annual reports for other years at www.imms.de.

Frontispiece: Components of a test system implemented in the INSPECT* project for cancer diagnostics. Samples are put directly on the chip in a cartridge which is plugged into a device connected to PCs for further analysis. Photograph and composition: IMMS.

Foreword

Hans-Joachim Kelm, Ralf Sommer and Martin Eberhardt. Photograph: IMMS.

Thank you for reading the IMMs report for 2018!

Keeping one step ahead – that is ideal, but difficult or even impossible for many small and medium-sized companies if they have no R&D section of their own. As a counterbalance, we have for many years been committed to providing services – as transfer institution, as research and training centre and in product development.

Keeping pace with technological progress, we made good use of the year 2018, forming a large strategy team to set the sails right through to 2030 so as to ensure we as core partner in the innovation system of Thüringen fulfil our important and diverse roles, all with the intention that the SMEs of the "Land" of Thüringen continue to advance.

The most important outcome of this strategic planning is that we have already proved that we are on the right course in many research areas. For our diverse research starting points, following the compass course set, we can see our way to 2030 along the routes indicated, always applying the competence we have built up over the years to support the innovations of tomorrow. To take our research into integrated sensor systems as one example of something in which we have long been engaged: We investigate and develop highly energy-efficient microelectronic systems and embedded systems which can be used not only to capture metrological and control data but also process and communicate it. These skills enable us to work in

partnership with regional companies and their know-how so that together we solve new problems in automation and the life sciences and they can lead in their field.

The projects described in this annual report are an indication of how this works in practice. One of our achievements was to conclude the R&D in 2018 on an optoelectronic testing system as part of the ADMONT project. This is a means of providing targetted on-the-spot decisions as to treatment choice in breast cancer through exact quantitative measurements. The prototype system is currently being tested in practice by our project partner in the investigation of biochemical evidence contained in cell samples. Then there is the RoMulus project, in which we have succeeded in producing an energy-efficient UHF RFID transponder chip. This we have connected to standard commercial digital I²C sensors so that they will work inexpensively without battery. In addition, in our Green-ISAS research group we have achieved results enabling sensor systems compliant with Industry 4.0 to work with energy autonomy, being powered by means of electromagnetic energy harvesters and laid out in the most energy-efficient manner as respects every component and function. This sort of sensor solution is the key to new, innovative business models in industry, offering new value chains and networks, together with data-based services and platforms.

For all these and yet more ideas and solutions with their future potential, our thanks go to all our staff: heartfelt thanks for the constructive, reliable way in which they apply their expert knowledge and individual skills to promoting our shared future as the Institute for Microelectronic and Mechatronic Systems.

For keeping us one step ahead and extending the current state of the art, Georg Gläser was awarded the EDA Achievement Award 2018 by the edacentrum in Hanover. We are immensely proud, especially because Mr. Gläser's is the epitome of a career begun at IMMS on a student internship, continued through BSc and MSc under IMMS' supervision, established in a research post on the staff and culminating in a doctorate for these prize-winning new methods of rapid, faultless design of complex integrated circuits. We are full of anticipation for the new IntelligEnt research group which is to carry these subjects forward under his leadership, including artificial intelligence and machine learning in the design of microelectronics.

It was Hans Joachim Kelm who set the Institute off in this direction. He passed the business management role to Martin Eberhardt in February 2019 and bade us fare-

well as he moved on into well-deserved retirement. The two undersigned, together with the whole IMMS team, thank Mr. Kelm for more than 20 years of outstanding commitment and for his manner of collaboration, distinguished not only by the highest level of expertise but also by warmth, openness, trust and total depend ability. Mr. Kelm had joined IMMS in 1998 and become the business manager of the Institute in 2000, so that he was there at the beginning of many developments and has had a huge influence on the path the Institute has taken.

At regional level the foundation of much of or our work is public funding by our German 'Land' of Thüringen. We gratefully acknowledge its support of our opening of competitive opportunities for our business partners, its financing of posts for new young researchers and of our involvement in associations, clusters and committees.

As our raison d'être is to be a transfer institution we have a Scientific Advisory Board and a Board of Directors, to whom and with whom we constantly present our strategy and its fulfilment. We thank you most sincerely for your commitment.

Our thanks go, too, to our research partners, especially 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 all the establishments right across the boundaries between disciplines.

We thank all donors, friends and people in every walk of life who bear us up in our work, not least all our R&D partners who like us have turned to face the future and without whose trust and stimulus many of the solutions could never have been found.

There is a small selection of these solutions to be found in this annual report. We hope you will enjoy reading it and shall be delighted if it is with you that we work on the next instalment of ideas to underpin the future.

Univ.-Prof. Dr.-Ing. Ralf Sommer
Scientific Managing Director

Dipl.-Kfm. Martin Eberhardt
Financial Managing Director

Annual reports for other years at www.imms.de.

New Head of Microelectronics, New Head of Industrial Electronics and Measurement Technology

2018 saw two colleagues stepping into new roles as head of a division at IMMS. At New Year, **Eric Schäfer** took over the Erfurt branch office of IMMS and became Head of the Microelectronics division. He came as a student to IMMS in 2007 and became a full-time research assistant in 2011. Having been Head of Sensor and Actuator Electronics, Mr Schäfer has much experience of collaborating with many of IMMS' partners in the field of microelectronics.

Eric Schäfer's predecessor in leading the Microelectronics division and the Erfurt branch office of IMMS was Holger Pleß, who had already been in charge of the Optoelectronics division. Having been a total of eight years with the Institute, Mr Pleß left us to work again in industry. To his work at IMMS he had brought many years of experience from the microelectronics industry and led projects in this field, setting the Institute's course. IMMS thanks Mr Pleß for his committed, reliable, trustworthy work, wishing him much success in his present activities. The Institute is not losing touch with him.

Contact Eric Schäfer via www.imms.de

Michael Meister took on the leadership of the Industrial Electronics and Measurement division on 1st June 2018 from Dr. Klaus Förster who had taken retirement. Mr Meister had joined IMMS as a student in 2001, becoming a full time research assistant in 2004. From 2014 onwards, Mr Meister had acted as Head of the Optoelectronic Measurement part of the Sensors and Optronics division, leading a variety of successful projects and collaborating with many different partners.

On his departure, Dr. Förster was bidden farewell by numerous colleagues who looked back with him over his 20 years at IMMS and gave him a send-off accompanied by many good wishes for the new stage in his life. The management and entire team of IMMS extend to Dr. Förster their sincere thanks for many years of high commitment and collaborative work stamped with trust and absolute reliability. IMMS finds it both a joy and a duty to follow the trail he has blazed to achieve the goals he set.

Contact Michael Meister via www.imms.de

Working hand in hand with the Technische Universität Ilmenau

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 year 2018 saw IMMS working on shared research projects with 21 of the University's departments across the range – electrical engineering and computer science, mechanical engineering, information technology and automation, media and communications science. In parallel, the Institute has continued to operate in a compact industrial network, with nodes in the semiconductor industry, in life sciences and in automotive, environmental and transport-associated engineering. IMMS plays a part, too, in regional and national innovation networks and industral clusters. Valuable impetus is given by the groupings. They are the chance to pool skills, use partners' technology and develop joint marketing strategies.

Joint projects

MagSens*research group: developing ultra-sensitive MEMS sensors for detecting small magnetic fields

The MagSens research group, led by Ilmenau TU, has, since 2018, been investigating magnetoelectric MEMS as a form of sensor to assist in the measurement of very weak magnetic fields for medical and other purposes. Magnetic field sensors so far available with this sensitivity require serious cooling, down to at –196 °C or more. The basic principle underlying the MagSens research is that of multi-layer systems on magnetostrictive and piezo-electric principles. Its application will mean the measurements can be taken without any cooling. Among IMMS' contributions are the FEM (finite element modelling) and the simulation of the sensor principle.

More detail on MagSens at www.imms.de.

The NanoFab* RTG: high-speed fabrication with nanometre precision

13 PhD students have been working in the NanoFab Research Training Group (RTG) 2182 since 2017 on a project funded for 4.5 years by the DFG (German Research Council). IMMS has one of the researchers; the work is on tip-based and laser-based three-dimensional nanofabrication techniques applied to large (macroscopic) areas. The supervisors of the PhD students are teaching and research staff of Ilmenau TU and IMMS under the leadership of the Institute of Process Measurement and Sensor Technology (in the Mechanical Engineering Faculty), which is concerned with sensors and process measurements in manufacturing. At IMMS, a drive system is being

More detail on NanoFab at www.imms.de.

developed that permits multi-axis manufacturing and processing of objects with nanometre accuracy.

The MUSIK* German Research Council group: MEMS design and system simulation

In MUSIK*, the aim was Multiphysical Synthesis and Integration of Complex RF Circuits, with logical, consistent attention to the functions of amplification, control, oscillation and switching properties of micro-electromechanical systems (MEMS). In close cooperation with the Ilmenau TU, IMMS researched MEMS properties as building blocks of high-frequency systems. IMMS developed concentrated fundamental blocks or library elements that served as the basis for system simulation, including thermal aspects.

More detail on MUSIK at www.imms.de.

Green-ISAS* research group: sensor/actuator systems as autonomous Industry 4.0 components

Together with the Department of Electronic Circuits and Systems, IMMS worked in the Green-ISAS research group from 2016 to 2018 on new methods and technologies to expand sensor-actuator systems for use in autonomous Industry 4.0 components. A range of broadly applicable solutions was explored. The basic modules can be yoked together to achieve highly efficient design, construction, testing and operation of new systems. Systems with characteristics of independent intelligence, networking capacity and energy autonomy were set up and validated in two demonstrators.

More detail on Green-ISAS in this report.

The fast-wireless* research project: new transmission concepts for the 5G mobile communications standard

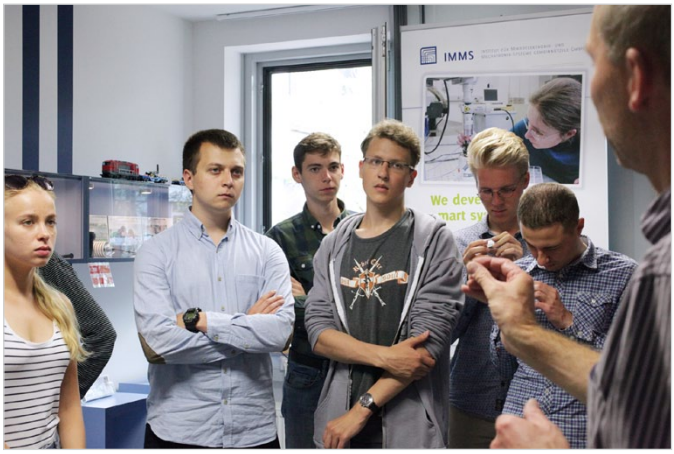
From 2016 to 2018 in the fast-wireless research project, IMMS has been working with the Integrated Communication Systems Group in the University's Faculty of Information Technology and Automation on planning new transmission methods for 5G, the next generation of mobile communication. Mobile devices and control units of the future will, as a result, support the Internet of Things and Industry 4.0 in real time with true reliability.

Specialist article on fast-wireless in this report.

IMMS contributes to the "Mittelstand 4.0"* (SME 4.0) Competence Centre Ilmenau

The IMMS contribution is, as "Migration Model Factory", to give impetus to the introduction of Industry 4.0 technology for the improvement of plant and processes. An example of what this means is retrofitting machinery and equipment with wireless and networked sensors so that data can be obtained and processed to underpin new

More on the SME 4.0 project: www.imms.de.



In 2018 more than 40 student visitors from the Ilmenau TU Summer Course took advantage of the laboratory tours at IMMS to discover suitable internships and support offers.

Photograph: IMMS.

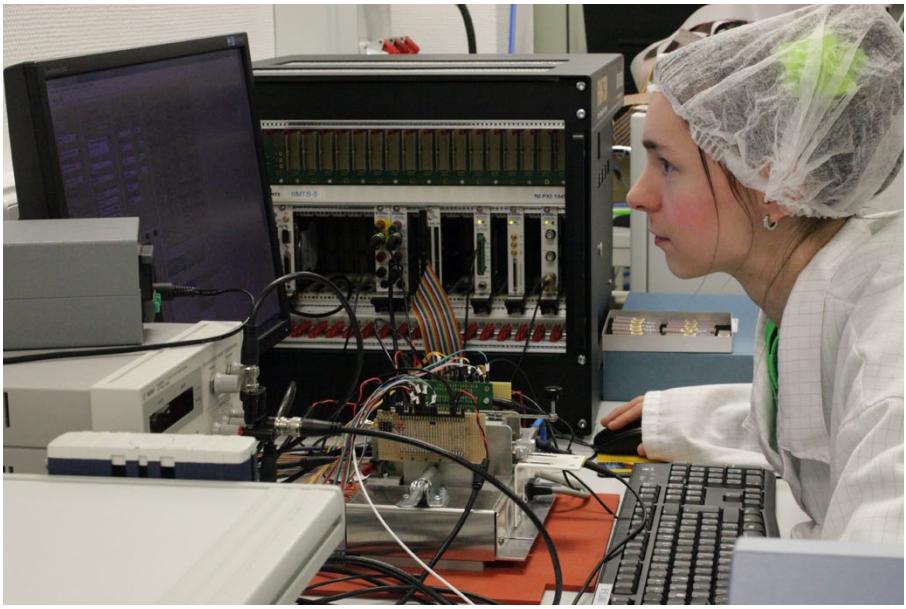
diagnostic, maintenance and service plans. Using universal electronics platforms for components that are Industry 4.0 compatible, together with open-source software, is an effective means of achieving rapid, reasonably priced, real-time innovation.

Joint encouragement of young academics

One way, but not the only way, in which IMMS complements the TU's teaching is the range of industrial placements it offers. Another way is that various lectures and seminars are given by IMMS staff. Professor Sommer himself is involved in teaching in foundation subjects and the MSc courses, IMMS is both trainer and motivator, offering not only highly practical and relevant placements but illuminating guided tours. In 2018, for example, over 40 student visitors from the Ilmenau TU Summer Course took advantage of the laboratory tours at IMMS to discover suitable internships and support offers.

Research subjects for students at www.imms.de.

In the Kinderuni (Children's University), a yet younger generation received the attention of IMMS and the University. Professor Sommer gave a lecture that asked, "What can the computer do with music and your voice?". He demonstrated to more than 1200 children between 8 and 12 years old by means of interactive experiments involving what they saw and heard how sound can become numbers, enabling the computer to "do its sums" and thus recognise and even change both songs and speech.



Graduate in aging investigations for a precision sensor interface in a high-temperature environment for her bachelor thesis supervised at IMMS. Photograph: IMMS.

Encouragement of young academics at IMMS – combination of theory and practice

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. Thus, IMMS researches impart theoretic in-depth knowledge of methods for an early combination with a practical implementation in applications. Moreover, the Institute offers training courses and guided tours of the establishment.

On an average, each year sees up to 40 students working at IMMS either as interns or student research assistants or in association with the dissertations they are preparing for their BSc or MSc. In all, the year 2018 saw 36 students being supervised at IMMS. Furthermore, there are 7 IMMS researchers currently pursuing doctoral studies at various universities.

Research subjects for students at www.imms.de.

The fact that we have so high a proportion of students from Ilmenau TU is an indication that our intensive efforts in fundamental education 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. School pupils, too, are given insight into the work of IMMS by means of events and internships or by having their coursework supervised.

Long-term practical training for challenging research subjects

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.

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.

IMMS events for a younger generation

August microelectronics' day for the engineers of tomorrow, Erfurt

Joining forces in August, 2018 with X-FAB Semiconductor Foundries GmbH and Melexis GmbH, IMMS set up a day when students could be given a multi-facetted programme shedding light on microelectronics. The aim was to enthuse students of Ilmenau TU who had been invited by Professor Ralf Sommer in hopes that they might consider a career in microelectronics. The method was to show in how many fields of research and industry the science is applied and to communicate the many routes Thüringen offers to a microelectronics career in innovative, internationally active en-

Guided tour at X-FAB on the Microelectronics Students' Day in Erfurt in August 2018. IMMS, together with X-FAB and Melexis, had set up a multi-facetted program in the Erfurt part of the institute to inspire students for a career in microelectronics.

Photograph: IMMS.

terprises. The three partners guided the students into the world of semiconductors via lectures and lab tours, explaining the trend towards ever larger wafer diameters, ever tinier components and the challenges arising therefrom for engineers in a range of disciplines.

The day started with a round of discussions and lectures on the specifics from Professor Sommer and the IMMS Erfurt microelectronics team, covering current research and present thinking on such things as how to progress methods for the design of chips or how to characterise optical biomedical sensors which are integrated into in-vitro diagnostic systems. These are areas on which IMMS is offering long-term student jobs or internships to accompany their BSc or MSc studies.

Next, on the premises, came a lecture on semiconductor production, challenges and solutions. It is the business of X-FAB, termed a (modern) foundry, to fabricate analogue-digital integrated circuits on silicon wafers. It does so in six places in Germany, France, Malaysia and the USA, employing more than 3,800 people, a thousand of them in Germany. This was followed by a tour of the manufacturing process to give a glimpse of semiconductor production. As they peered into the clean room, the students were told about the sequence involved and were able to receive answers to their questions.

The next stop was at Melexis. This is another international enterprise, with more than 1,500 employees distributed over 20 sites in 14 countries. The business of Melexis is to provide microelectronic semiconductor systems for a huge variety of uses in the automotive industry. One example is passenger lighting. Lectures were given on the history of developing microchips and the means used and challenges met in verifying chips that have been developed. Having been guided in the laboratories for applications and error analysis through many of the stages described, and had their many questions answered by researchers, the students went home armed with a huge range of information and impressions.

Research subjects for students at www.imms.de.

Guided tours like the one at Melexis (left) and activities including lectures at IMMS (right) during the microelectronics student day, Erfurt, August 2018. Photographs: IMMS.

Visitors to the Ilmenau TU summer courses, August and September

Student visitors of both genders came to visit IMMS from the Russian Federation, Belarus, Hungary, North Macedonia, Moldova, Poland, the Czech Republic, Iran, Mexico, Argentina and Hong Kong in August and September, 2018. They all came from partner universities and represented subjects such as electrical engineering, mechanical engineering and computer science. They were on German courses at Ilmenau TU as their university's partner, preparing for internships or exchange semesters.

The lectures and guided tours of laboratories at IMMS which they were given provided them with examples of options for supervised work at the Institute and of current R&D projects in which there are already students involved. One of the aspects was the possible improvement of manufacturing plant and processes by the digitalisation achieved in retrofitting wireless, networked sensors. By this means, universal electronics platforms may serve different linked elements as needed in Industry 4.0. Also, so that real-time solutions may be underpinned with open-source software. They were also treated in the MEMS laboratory to a demonstration of how a laser Doppler vibrometer assists in investigating the mechanical features of diminutive structures with no contact whatsoever.

Research subjects for students at www.imms.de.

January pupils' visit

Primary school pupils from the Assisi school in Ilmenau came on a voyage of discovery to IMMS in January, 2018. They carried out their first programming experiments and tried out games and equipment as a way of learning about sensor systems: where and how sensors are used, and how they are developed, programmed and networked for their purpose. These pupils were able to look over the shoulder of researchers and developers in their actual daily work at IMMS.

Pupils from the Freie Reformschule "Franz von Assisi", Ilmenau on a guided tour of IMMS, January 2018.

Photograph: IMMS.

Daniel Molina Bravo, M.Sc., Embedded Software Engineer at IMMS.

Photograph: IMMS.

Voices of young scientists at IMMS

Daniel Molina Bravo, M.Sc., Embedded Software Engineer

”In October 2015 I decided to come to Germany from my home in Colombia to take a master’s degree in the Technische Universität Ilmenau. During these studies I had the chance to work on student research projects under the supervision of Dr. Silvia Krug. She gave me the idea of obtaining a part-time job as a student research assistant in IMMS so that I could continue to increase my knowledge and at the same time contribute new ideas in the area of Delay Tolerant Networks (DTNs) and Wireless Sensor Networks (WSNs). Given this opportunity, I didn’t hesitate to take it.

Research subjects for students at www.imms.de.

From July 2017 I started working as a student research assistant at IMMS. My first research goal was to implement the IEEE 802.15.4 standard in Omnet++, a simulation tool which is widely used for WSNs but lacked the 802.15.4 protocol. By implementing this protocol in Omnet++ it was possible to understand better how the tool behaves in different scenarios. As a second research goal I focused on the adaptation of Contiki OS to ATmega256RFR chips.

From the moment I started working at IMMS I felt myself identifying with the research spirit that identifies IMMS. Therefore by the time I was finishing my master studies I had the motivation to keep working with IMMS, not as research assistance but as a full time employee and expressed my interest. In April 2018 I was able to start work in IMMS as a embedded software engineer.

So having started my career officially in April 2018 I am continuing to work at IMMS with motivation to keep learning, and refining my knowledge and skills on Wireless Sensor Networks, building on the inspiration given by getting to know new tools, hardware and new ways to carry out programming processes. I must say that last year was a very interesting year for me, and IMMS was the biggest reason for this. Since I started working I have always felt backed up by my colleagues. They welcomed me in the best way, became my mentors and showed me new ways of doing things, and encouraged my curiosity. I have had the taste of two projects, a cable tester solution and a wireless sensor network implementation on Nordic, early work that has made me challenge myself and rise to levels that I didn't know I could reach.

Thank you IMMS for the support you have given to me and for widening my panorama, my mind and my ideas."

Maximilian Wiener, M.Sc., Analogue IC Design Engineer at IMMS

"I had my first contact with IMMS in my fifth semester in Ilmenau TU. It was Professor Sommer who gave me an insight into the widely varied fields of activity of the Institute. My interest awakened, I applied for a post as a paid part-time student so that I could reinforce the theory I was learning on my degree course by regular practical activity in the Industrial Electronics and Measurement division of IMMS. In my seventh semester, I had my compulsory internship and wrote my BSc thesis at the Erfurt part of the Institute in the Microelectronics division on designing an ultra-low-power ring oscillator for use in time-to-digital converters. In parallel with my MSc course,

Research subjects for students at www.imms.de.

Maximilian Wiener, M.Sc., Analogue IC Design Engineer at IMMS.

Photograph: IMMS.

I continued my part-time student job at IMMS so that I could transfer the results of my BSc dissertation into complete circuit design. Doing so, I contributed to the design of a sensor chip which was a product of the RoMulus project. RoMulus has as its aim the development of robust sensors of potential usefulness in monitoring Industry 4.0 applications. Then I wrote my MSc dissertation on system design for a capacitive low-power humidity sensor with adaptive resolution to be used in self-powered wireless sensors. Finding my subject for myself, receiving professional support and using the skills I had obtained so far were an excellent career start. There were major challenges which gave me the chance to extend my horizons because I had to solve new, more complex circuit problems.

As soon as I had defended my MSc I leapt at the opportunity of continuing my activity at IMMS and have been working since December 2018 as circuit designer for analogue integrated circuits. The experience I gained over several years as a student has provided me with a seamless transfer into the role of full employee – as good a launch into a scientific career as I could wish.

My work at the Institute in parallel with my studies and my tackling of various subjects in several of the IMMS divisions familiarised me rapidly with the structure and staff of the Institute. The flexible hours of work and interdisciplinary activities nurtured my development on all fronts, academic and personal. Working in an international team and with colleagues from different subjects enables me continuously to extend my own skills and to digest the new knowledge I am constantly acquiring.

And so I would say: IMMS offers excellent opportunities to both students and staff to extend their skills in deeply interesting subjects that are closely related to practice.“

Voices of colleagues at www.imms.de.

Voices from project partners

At IMMS, representatives of the industrial advisory council to the the Green-ISAS research group were presented demonstrators on industry 4.0 basic technologies. Photograph: IMMS.

Dr. Katja Nicolai, IL Metronic

”At IL Metronic, we develop, manufacture and distribute glass-to-metal feedthroughs for specific customer needs; also, sensors, sensor modules and electronic equipment for fields where sensors are combined with UV or wet locations. Additionally, we are in constant cooperation with universities and scientific institutes on various R&D matters. In my role as head of the industrial advisory council to the Green-ISAS research group in Thüringen, I have accompanied IMMS in developing basic technologies to underpin sensor-actuator systems which can be applied autonomously in Industry 4.0 settings. This work is of great interest not only to us at IL Metronic but also to many other companies around us.

Dr. Katja Nicolai, Head of R&D, IL Metronic Sensortechnik GmbH, Ilmenau. Photograph: IL Metronic.

More on Green-ISAS in this report.

Companies need production to be networked, automated and flexible in order to provide high quality in an efficient way. To achieve this, there are many points at which measurements and control data need to be captured, processed and transmitted. Machinery in these companies is rarely laid out in ways that suit such data capture and neither is it easy to equip with the necessary sensors. A universal upgrade of the sensor systems is not a simple matter. In many cases, sensors will have to work independently on a single machine. On that machine the sensor(s) are increasingly being required to carry out complex tasks, yet consume a minimum of energy. This balancing act is still no easy, automatic task. The technology is often at its limits and there remains a need for considerable research, which is, however, beyond the scope of SMEs as individual companies.

The IMMS scientists have been open from the first in presenting us, the advisory council, with their work and concepts. In early conversations and then regular workshops they have updated us on how they are approaching the demands in this area. In a mere two years, they have researched and developed a variety of solutions which, by means of new ideas on system architecture and smart energy management, result in more energy-efficient sensors, provide the sensor systems with a better energy supply and optimise the use of resources. Developments include two chips with minimum energy consumption together with their dedicated measurement technology, smart self-powering and energy-managing sensor systems and a design tool for application-specific energy harvesters. These harvesters exploit fine vibrations to supply the energy for independent smart sensors capable of monitoring machinery and plant.

More on sensor systems: www.imms.de

More on chip developments: www.imms.de

From my point of view, the numerous outcomes, many of them already validated by demonstrators, speak for themselves. These wireless solutions with their energy self-sufficiency are blazing the trail for quick, cheap and easy retrofitting. I envisage their use not only in manufacturing processes but in other areas such as transport and logistics.

More on system integration: www.imms.de

We are looking forward to addressing more questions with IMMS and carrying out the joint project for which a funding application has already been made.“

More on Green-ISAS in this report.

www.il-metronic.com

Prof. Dr. Thomas Arnold,
Leibniz Institute of Surface Engineering (IOM)

Professor Thomas Arnold, Head of Department Ultra-precision Figuring and Patterning of Surfaces, Leibniz Institute of Surface Engineering, Leipzig. Photograph: © Arnold.

”Among the things we investigate at the IOM are the mechanisms of interaction involving chemically reactive atmospheric pressure plasma jets. From this work come deterministic processing technologies for ultra-precision figuring of surfaces, right through to the start of viable manufacturing chains. The main field of application of the technologies is the production of complex surface shapes such as aspheres and free-form surfaces for ultra-precision optics, which have to be produced with manufacturing tolerances of a few nanometres. In order to meet these requirements, beam-based processing tools such as plasma jet sources and their mechanisms of action are being experimentally researched and further developed. One of our projects on new applications, which is funded by the AiF and the FEI (research organisations for SMEs and the food industry, respectively) involves designing and making a demonstrator for a three-axis positioning system enabling a plasma head to be moved along prescribed paths using a particular tool.

IMMS has supported us throughout the design of the device, including work on the mechanical hardware and on the data-processing hard- and software, the development, construction and testing of the prototype. They have brought it into operation on our premises.

The IMMS staff incorporated our requirements into the design by constantly checking with us. They researched, selected and implemented the most cost-efficient approach and the use of common, commercially available components.

We are extremely pleased with the resulting demonstration device. Besides proven competence in drive design and experience of product development in the service of research institutes, IMMS also brought to the task a highly professional, purposeful and constructive approach. We do thank the Institute for this outstanding collaboration and shall definitely return to make further use of the Institute’s expertise in future projects.“

https://www.iom-leipzig.de/forschung/praezisions-oberflaechen/strahlbasierte-formgebung-und-strukturierung-von-oberflaechen/ultrapraezisionsformgebung-mit-plasmen-und-ionen/

More on drive systems: www.imms.de.

Dirk-Hendrik John, Software-Service John GmbH

Dipl.-Ing. Dirk-Hendrik John, Managing Director, Software-Service John GmbH. Image source: Software-Service John GmbH.

"Our business is the interactive 3D visualisation and transfer of CAD (computer-aided design) and GIS (geographic information system) data in the service of (for instance) utilities, land registries and surveyors' offices and in such settings as geodesy, industry, land registration, cartography and infrastructure. In the StadtLärm project (the name translates to CityNoise), we developed a new noise monitoring system in collaboration with IMMS, Fraunhofer IDMT and Bischoff-Elektronik GmbH. The system captures noise data on a permanent basis by means of sensors distributed over a wide area of the city of Jena in Germany, providing the local authority with data on the level and type of noise events that occur and thus helping in official decision making. It was our role to integrate all the data as a model of "noise-in-space" into a new application which permitted online processing and 3D depiction of the noise events in maps and explanatory diagrams.

Input to our application came from the central data turntable developed and created by IMMS as communications architecture for the entire system. It used the standard, open MQTT protocol. IMMS tailored the publish-subscribe principle at the heart of MQTT so as to be an efficient means of communications, with a hierarchical structure that could be extended if any new components were to be added. Furthermore, IMMS' application of MQTT enabled our application to send requests to the data service, for instance with a selected time period so that the data for the period could be shown. The administration component was developed by IMMS in the Spring framework. It is here that all the noise sensors log in and get listed in the directory with their status and other information, with the result that they are a valuable support to our application. Further sensors can also easily be added on by the user. From our point of view, the design IMMS came up with for the architecture was in itself convincing. Further, we were impressed by its support in integrating our application with the MQTT standard. Both during the ongoing joint field test in Jena and during the entire project period, IMMS staff were always readily available with prompt support if questions or problems arose. We could always check out with them and enjoyed exchanging knowledge and ideas in joint workshops on the design and realisation of the system. We wish here to extend our sincere thanks to IMMS for the superb collaboration and we greatly look forward to future joint activities." *www.john-software.de* & *www.vis-all.de*

Details in the specialist article on StadtLärm.

More on communications solutions at www.imms.de.

Wafer test at IMMS. Photograph: IMMS.

Hans-Peter Kraus, COO, Productivity Engineering GmbH / Serma Group

"For 20 years, we have been in the business of designing and producing specific circuits, particularly for automated industrial processes, medical technology and instrumentation. We are a one-stop shop for our customers, who can obtain from us both analogue and mixed-signal ASICs, right through from the drawing board to full supply chain management for their manufacturing.

Our supply chain management system has ISO certification and monitors the process from start-to-finish – from fabrication of the wafer through to despatch of the finished item, including all necessary analysis and testing, whether for the prototype or the mass product. All tests necessary are integrated into the supply chain system.

As early as 2014, we involved IMMS in this production chain system as test providers to our industrial partners. In this context, IMMS develops customised environments for wafer tests and final device tests, carries out the tests and, furthermore, offers professional support on test optimisation and yield. Our customers come to us because we are prompt and reliable suppliers of highest-quality components. They become our regular, longstanding customers because our service is so flexible and our communication so responsive. And our partner, IMMS, has exactly the same appeal. In this partnership, not only are we able to rely on consistently high quality, dependability on delivery dates and flexible responses when customised changes are needed, but we benefit all round because IMMS proactively contributes ideas and suggestions for improvement. We can thus recommend the Institute unreservedly as a provider of testing services to industry."

www.pe-gmbh.com

More on testing services: www.imms.de.

More testimonials at www.imms.de.

NEW INFRASTRUCTURE

This RFID test stand was set up at IMMS in 2018 in order to evaluate the widespread standard RFID in various application scenarios with regard to sensitivity, energy requirements, achievable range and RFID protocols and to be able to record performance dependencies. Photograph: IMMS.

This infrastructure equipment has been purchased in the REMEDIA project (Means of measurement for biomedical applications) which was funded by the "Land" of Thüringen in its Guidelines on support for research under the reference 2018 FGI 0008.

Technical equipment and new infrastructure in 2018

More on infrastrudture: www.imms.de.

In order to provide our partners with long-term support in the form of state-of-the-art electronic systems solutions, we continuously develop new manufacturing technologies and partnerships for our R&D work. In addition, we are constantly expanding our technical laboratory and equipment infrastructure in order to remain competitive in the international scientific competitive environment.

IMMS has extensive equipment for the design, characterisation and testing of systems developed at the institute and for test services. The spectrum covers different system levels – starting from material parameters, transistors and devices up to complex applications.

REMEDIA* — more means of measurement for biomedical applications

In 2018, IMMS invested money granted by the Land of Thüringen, buying devices and materials to support its R&D in the field of sensor systems which support biological analysis and medical diagnosis. The new equipment can detect and control UV radiation used in diagnosis; it can also characterise the associated RFID components as part of a specific test station. It has helped IMMS to make significant progress in its work on new point-of-care test (POCT) systems with which, it is hoped, patients in the doctor's surgery of the future will be able to receive rapid, definite diagnosis from tissue or fluid samples. Slow, expensive diagnostic procedures in central laboratories will be rendered unnecessary. The main role of IMMS in the field is to develop ASICs (application-specific integrated circuits) in the form firstly of sensor ASICs which have among their functions the assessment of sample parameters using UV light and secondly of RFID ASICs to transmit the results wirelessly to an evaluation device. The new equipment means ambient conditions can be created which are specific to the uses to which the sensor and RFID ASICs will be put. The targeting reduces the number of iteration cycles.

Devices and materials to modify and detect UV radiation

It is common to employ UV light in detecting substances indicated by biochemical signal. For the purpose of creating new and innovative POCT systems which provide instant biological analysis, optical parameters require very precise definition and settings. Significant parameters are the radiant power, the distribution of the intensity, beam shaping, and the effect of the angle of incidence so that the UV signal generated as input is exactly right and can be characterised. Examples of

how research projects have benefitted from the new characterisation equipment are ADMONT and INSPECT, where the necessary homogenous intensity of UV irradiation has been achieved for the POCT systems developed.

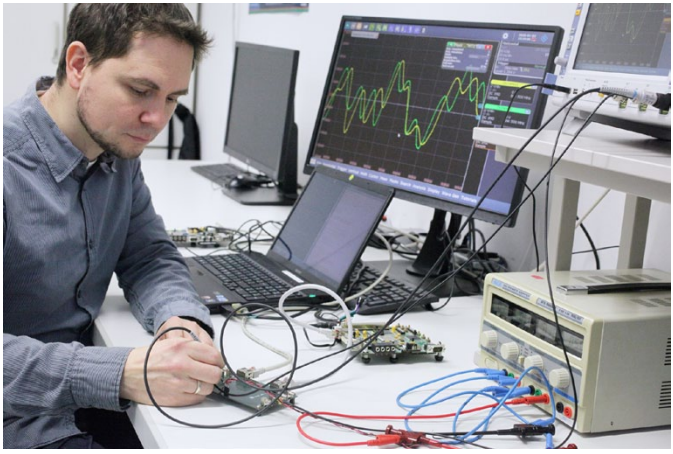
RFID testing station

A data interface is essential if systems are to be used effectively by the doctor at the point of patient care. To support their application in varied scenarios, POCT systems make use of commonly met standards such as RFID. A testing station for RFID has been constructed at IMMS for the verification of POCT data interfaces. Its purpose is to measure and evaluate sensitivity, energy consumption, practicable distances, RFID protocols and the degree of dependence on the power available. The testing station equipment has already been employed in the ADMONT and RoMulus research projects for discovery of errors, characterisation of individual elements of the RFID signal route, and optimisation.

IMMS: the first of Thüringen's testing environments for Industry 4.0, collaboration with SMEs funded by BMBF

Enabling enterprises to put their Industry 4.0 ideas to the test under realistic conditions

In February 2018, IMMS was classified as the first Thüringen testing centre in the Federal German coordination centre for "Industry 4.0 Test Environments – Mobilising SMEs for Industry 4.0" (in brief, I4KMU). I4KMU is funded by the federal Ministry of Education and Research (BMBF) and the idea is to provide a network (there are 50 such test environments across Germany so far) that supports SMEs as they move



Example of I4.0 test environment: preliminary examination of a cheap means of permanently monitoring errors in the data lines of industrial plant while it is being operated.

Photograph: IMMS.

More on infrastrudture: www.imms.de.

into the age of the fourth industrial revolution, also known as Industry 4.0. These centres will enable SMEs before they make a market launch to test under realistic conditions the digitalised processes and products they have developed and any innovative systemic approaches, together with the business models involved. The testing environments are generally to be found at research establishments. They provide not only a breadth of infrastructure technology but also the necessary level of competence to use an I4KMU project to solve any problems arising as companies try to develop their new ideas. IMMS was accepted as an I4.0 test environment because of its expertise in the Industry 4.0 field and the fact that it already had the I4.0 hardware and software, digitalised processes, and readily available facilities for realistic testing. The IMMS' unique selling point in this matter is its test laboratory for TSN (time sensitive networking).

I4.0 test environment at IMMS

Elements of the I4.0 testing environment at IMMS are many: the planning and simulation tools available, the TSN laboratory, the servers and cloud with all their computation and memory capacity, the mobile end devices, the electronic labs, the mechanical workshop and a range of technology permitting cumulative manufacturing processes and the investigation of electromagnetic compatibility, EMC. To focus on the TSN lab – here, the relevant components and products contained in CPPS (cyber physical production systems) can be investigated in real time, in painstaking detail while they are "in use".

More on the TSN test lab at www.imms.de

SMEs profiting from IMMS' expertise in the Industry 4.0 field

IMMS has many years' experience in automation and closed and open-loop control of machines and industrial plant besides all its knowledge of networked data capture, data editing and data communications for both measurement and control purposes. The Institute develops sensor systems which are energy- and resource-saving, mechatronic actuators which are highly accurate, and hardware and software components and systems which are fully embedded. These sensor systems interact with the real world and communicate with each other in real time using a data network. They enable users to develop complex automation solutions and to improve the efficiency of their value chains. The Institute never ceases in its efforts to develop new approaches for such CPPS. These smart solutions involve electronics, mechatronics and the necessary software. They have huge innovative potential for systems, products and the bringing on of new applications.

More on Industry 4.0 at www.imms.de

How SMEs can access I4.0 projects with IMMS and have them funded

If companies have any queries concerning their I4.0 ideas, they can turn direct to IMMS or they can seek information from the national contact point "Industry 4.0 Test Environments – I4KMU". IMMS held various meetings with SMEs on this subject in 2018. They have led to the tackling of a number of joint projects from 2019 onwards.

Contacts to I4KMU at www.imms.de

PraezEm* – Metrological instruments to investigate factors influencing accuracy and electromagnetic sensitivity

With the support of the "Land" of Thüringen, IMMS was fortunate to be able to invest in metrology in 2018. The new instruments enable the sorts of mechanical and electronic components and building blocks which are used in R&D projects to meet the constantly rising demands to be evaluated. Ever higher demands are, indeed, being made on mechanical components, particularly on drive and guide components, because ever-increasing accuracy is required. The challenges are also growing for electronic parts in respect of their energy efficiency, the ever lower operating voltages and the ever more frequent use of wireless communications. These developments have the effect of narrowing the tolerance in respect of electromagnetic compatibility (EMC) and in respect of the actual functioning and usability of the parts.

Metrology with 3D coordinates

To prevent disruption to very finely-tuned total systems it is necessary to inspect and test all the parts delivered by research partners before they are assembled: for dimensional accuracy and the material content. This is particularly true for the smoothness of guide surfaces, the straightness of guidelines and the exact orientation of levels

More on infrastrudture: www.imms.de.

Freistaat Thüringen

This 3D coordinate measuring technology, procured in the PraezEm* project with funds from the Land of Thüringen, allows a measuring accuracy of ± 8 µm within 600 x 300 x 200 mm³.

Photograph: IMMS.

which are stepped or tilted in spatial relation to each other. The 3D instrumentation now obtained permits measurement accuracy to within ± 8 µm in a space 600 x 300 x 200 mm^3.

Magnetoscope for measuring permeability

Certain parts for magnetic actuators – such as the coil housing, the coil core, the coolant housing or the granite plates for the aerostatic guides – require testing for residual magnetism or for permeability, i.e. the degree to which they can be magnetised. If the limit is exceeded, there will be interference with the magnetic drive system. Even small deviations can lead to significant interference and endanger the entire functionality of the system. The magnetoscope that has been acquired will mean that the density of magnetic flux can be determined as an absolute or a differential value and also the relative permeability µr according to IEC 60404-15 and ASTM A342M EMC.

Near-field scanner board with PC and software

The smaller and smaller spaces available for electronic circuits have as their consequence more integration, i.e. more functions per unit of area on the PCB. Together with the reducing signal levels, this results in circuits being more and more susceptible to electromagnetic interference: the parts affect each other and may have an impact on the complete system. The EMC metrology instrumentation now enables a range from 150 kHz to 8 GHz to be tested to discover which structures and positioning will minimise the electromagnetic interference.

More on infrastrudture: www.imms.de.

Use in current research projects

Find more at www.imms.de …

The GraKo Nanofab*, Green-ISAS* and MagSens* projects have all benefited and continue to benefit from the new instruments in respect of their precision drive components and energy harvesting or sensor systems, which all present great challenges concerning accuracy of the components and magnetic properties. In the Ko²SiBus* project, circuits are being investigated that will enable data cables in industrial plant to be monitored. The instrumentation is also being applied where evaluation components are being constructed in which the signal level alters very rapidly under the influence of electromagnetism. The sUSe* project, which investigates and makes ultrasonic sensor systems, is also benefitting. Here the signals must be heavily protected from electromagnetic influence in the stage before digitalisation. Thanks to the new metrology equipment, IMMS is able to undertake tests in-house in parallel with its R&D on its ideas and its components.

… on NanoFab,

… on MagSens,

… on Ko²SiBus,

… on sUSe.

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RESEARCH SUBJECT CPS:

ENERGY-EFFICIENT AND ENERGY-AUTONOMOUS CYBER-PHYSICAL SYSTEMS

In order to use compressed air for industrial processes in an energy-efficient way, IMMS is developing the electronics platform for an automated sensor solution in the sUSe* project. It will enable an integrated monitoring of compressed air systems via distributed ultrasonic and volume flow sensors. The solution will be developed with the partners SONOTEC Ultraschallsensorik Halle GmbH and Postberg+Co. GmbH. Photograph: IMMS.

Research subject ”Energy-efficient and energy-autonomous cyber-physical systems“

Cyber-physical systems (CPS) consist of linked embedded electronic hardware/software components communicating via data networks and interacting with the real world by means of sensors and actuators. CPSs form the basis of the ”Internet of Things and Services“ and for future implementations of complex and distributed control and automation systems to bring forward industrial production (”Industry 4.0“) and energy management (”Smart grid“), amongst others.

As CPSs will thus contain a huge number of components and will be massively distributed, energy- and resource-efficiency of those systems are of great significance. Our research therefore focuses on the development of highly energy-efficient microelectronic and embedded systems for the acquisition, processing and communications of measurement and control data. For this purpose, we investigate and create hardware and software solutions for wired and wireless sensor and actuator networks, particularly regarding aspects such as real-time capability and energy-autonomous operation.

More on Industry 4.0 at www.imms.de

Projects in the CPS field at www.imms.de.

Highlights of 2018 in our energy-efficient and energy-autonomous systems research

Start of sUSe* project for energy-efficient use of compressed air in industrial processes

One of the main causes of wasted energy in industry is leaks of compressed air. Up to 10% of all electricity used for industrial processes is used to generate compressed air, of which, on average, 30% is lost by leakage. This makes it all more important to seek out these leaks, evaluate the losses and set up good maintenance practice.

In the sUSe project, the aim is to develop a systematic monitoring solution for compressed air which can either be permanently installed or retrofitted, greatly assisting decision-making on repairs and maintenance, and thus greatly improving energy efficiency.

sUSe at www.imms.de.

Monitoring compressed air systems using distributed ultrasound and volume flow sensors

The partners in the project are working on a unified monitoring system that will consist of a number of ultrasound and volume flow sensors that are wirelessly con-

nected, can be permanently installed and will keep track of the energy efficiency and quantify it.

On the one hand, the volume flow, i.e. the actual integral quantity of compressed air, is measured by appropriate sensors at particular points in the system and compared to the quantity which is being supplied to the pneumatic system. On the other hand, the ultrasound sensors, which are likewise distributed across the pneumatic system at known relative positions, will detect, locate and evaluate any leaks. When the data of overall volume flow and any leak points found is combined, the proportion of leakage can be allocated to the right point.

IMMS contributes electronics platform, signal processing and communications

IMMS' contribution is to develop and create the means of processing the digital data from the sensors on an electronic platform and achieve a scalable and effective system. This platform will be used at each measuring point in the monitoring system.

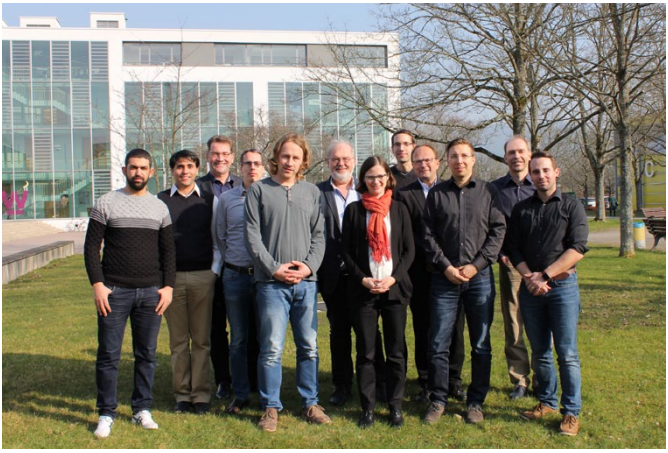
So that the sensors can be adapted to the customer-specific requirements without any need to alter hardware, IMMS is developing the signal processing components with model-based design technology and is configuring the algorithms on this basis for integration into the electronic components (FPGA).

Also, to enable the platform to match up to future requirements and to be integrated into maintenance plans, IMMS is going to realise appropriate interfaces and protocols for communications, making it possible for the wireless sensors to communicate as necessary.

Ko²SiBus research scheme presented to representatives of industry at consortium meeting

A presentation was made in Offenburg on 21st February, 2018 to the committee with representatives from 10 enterprises accompanying the Ko²SiBus project. It gave details of Ko²SiBus (the acronym stands for continuous and cost-effective signal monitoring for industrial bus systems), which is a two-year project started in 2017. Two partners are working with IMMS. They are the ivESK (Institute for reliable embedded systems and communications electronics) of Offenburg University and a team under the Professor for Measurements and Sensor Technology at Chemnitz University of Technology (TU). All are trying to find new ways of reducing the high amount of downtime and time out for maintenance which can be attributed to elusive breakdowns in data cables.

Ko²SiBus at www.imms.de



Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

On 21 Feb 2018 details of the Ko²SiBus research project were presented to industry representatives. Photo: Hochschule Offenburg.

Verdict of the industrial representatives positive

”We have many customers who want predictive error recognition in Ethernet cables”, says Friedrich Becker, head of software and communications at TURCK Electronics GmbH. “Hours are often lost trying to find and remedy the sources of breakdown and halts in manufacturing. The new methods will, it is hoped, recognise the errors as they arise and thus avoid the stoppages. We shall be following very closely the developments we have been able to learn about in detail today.”

The other companies besides TURCK who are involved in the project are Bosch Rexroth AG, GEMAC – Gesellschaft für Mikroelektronikanwendung, Hilscher Gesellschaft für Systemautomation, Indu-Sol GmbH, Pilz GmbH & Co. KG, R. STAHL Schaltgeräte GmbH, Renesas Electronics Europe GmbH, SICK AG and STACKFORCE GmbH.

For networked systems, hitherto no continuous monitoring of communications lines

The conditions and processes in machines and industrial plant are continuously monitored to enable highly automated processes in industry to run smoothly. However, so far, there has been no continuous monitoring of wired Ethernet-based communications lines for fast and secure data exchange and networking of items of industrial plant. The reasons are not only the large number of Ethernet cables, but also that most of these cables are concealed and, so that they will not obstruct production processes, difficult to access. Up to now, investigation of cable breaks and malfunctions has usually had to take place during machine downtime with the aid of additional measuring devices. The cables had to be detached from the system.

Target: trouble-free production through monitoring of wired communications lines

In the Ko²SiBus project, the idea is to achieve a future in which collaborative work has minimised these downtimes and maintenance costs so that the signal quality of wired Ethernet-based installations is continuously and cost-effectively checked during regular plant operation. This should not only make it easier to plan maintenance work. The new concept should also make it possible to pass on the monitoring data via a uniform and open interface so that it can be easily integrated into customer-specific monitoring solutions. The plan is to retrofit the solution into existing systems, for instance as a switch extension, integrating it as a feature directly into network nodes of Industry 4.0 systems.

Chemnitz TU (University of Technology) is supplying the preliminary theoretical work in Ko²SiBus necessary to the development of the embedded cable diagnostics. Offenburg University's main part in the project is to work on the communications interfaces transferring the data from the analyses to upstream systems.

IMMS: planning circuits and building a demonstrator

IMMS is taking the results provided by both partners, designing an embedded system and creating the integrated circuits this will require. Using the know-how gained from developing sensor technology solutions, with the purpose of monitoring industrial plants, for example, Ko²SiBus will bring about a system able to track physical signal parameters using integrated analogue and digital components and report any problematic deviations to a monitoring centre. The functionality will be tested with a demonstrator which is being built by IMMS.

2018 saw IMMS investigating, simulating and modelling three circuit designs for signal analysis. Also, a method of estimating signal quality by evaluating the statistics on signal amplitude was assessed. IMMS created a testing station so that cable faults can be simulated and the signal quality altered during transmission, allowing empirical validation of the ideas in all the cases. It was shown that the newly found method of estimating signal quality by evaluating the statistics on signal amplitude is, indeed, adequate to the task. The method will be incorporated into the cable monitoring scheme in 2019, together with the results from Chemnitz TU.

EDA Achievement Award 2018 for design methods, integrated circuits

The association responsible for the edaWorkshop18 in Hanover (edacentrum e.V.) honoured Georg Gläser at the workshop for his work on new ways of designing complex integrated circuits at speed without error. The EDA Achievement Award 2018 was given for particular R&D achievement in the EDA (automation of electronic design) field and significant extension of the state of the art.

Need for complex chips to be verified automatically and tested for reliability before fabrication

If there are design faults in microelectronics, the effect on safety-relevant systems (for instance, in the automotive field) can be disastrous, with damage that can cost hundreds of millions of euros. This has long motivated scientists to work on the development of microelectronic systems, constantly coming up with improvements and ever more sophisticated design methods. Parallel to the steadily rising requirements which microchips must meet is the exponential rise in complexity and speed of fabrication with simultaneous demand for design costs and risks to be cut. To date, the newest and most complex microchips have not been susceptible to thorough checking before production even with the latest procedures. It has not been possible to analyse completely any potential undesirable interaction between the intended function of the circuit and its layout, i.e. the physical fabrication design.

Georg Gläser of IMMS (3rd from r.) at the EDA Achievement Awards ceremony, 2018 during the edaWorkshop18 in Hanover. He received the prize for his work on new methods of rapid, error-free design of complex integrated circuits to be used in Industry 4.0. Photograph: IMMS.

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Award-winning methods prove circuits will work even at the design stage

A variety of specialised methods has been developed by Georg Gläser at IMMS. On one hand, they enable layout effects as mentioned above to be clarified, to have their actual influence evaluated and an improvement indicated. On the other hand, the methods permit integration of the interaction between complex system components into model systems, with ensuing simulation on an efficient basis. Not only this, but Mr. Gläser has worked out new methods that will enable the fabricator predictively to analyse system behaviour even under operating conditions which are not yet known.

Parasitic impact analysis, symmetry analysis

The design of integrated circuits largely begins at the systems level. It is here that function blocks are combined. Circuits are created within the components that will provide the desired function, amplification for example. After this design stage, the functionality and electrical properties of the blocks are verified by means of simulation. If this step goes well, a layout is designed to serve as template for the chip manufacturer, with such components as transistors and resistances positioned and linked by metallic connections.

However, the relative positions of the building blocks in the layout can lead to new effects such as crosstalk between neighbouring wires caused by parasitics. Such physical effects, quite unrelated to the desired function, mean that the circuit must be verified anew. Usually, the layout has to go through further optimisation stages because of these effects. This is where parasitic impact analysis and symmetry analysis can come in useful: using symmetry analysis, it is possible that optimisation potential will show up even before the layout has taken place. Impact analysis is a way of looking at existing layouts to decide on promising sites where improvements could be brought in. These methods thus considerably shorten layout optimisation time.

Operating conditions taken automatically into account

When correct functionality has been assured, the system can be tested stage by stage in ever larger function groups. If on the large scale there is a need not only for

the functions themselves but also for monitoring of operating conditions, extremely accurate simulation at a low level of abstraction will usually be necessary, and, if so, will take much time and computation. At this point, another method joins the fray, whereby data on permitted operational conditions for individual function blocks is automatically extracted. It is then possible to integrate this data into more abstract models that will speed up simulation and at the same time provide security during subsequent operation.

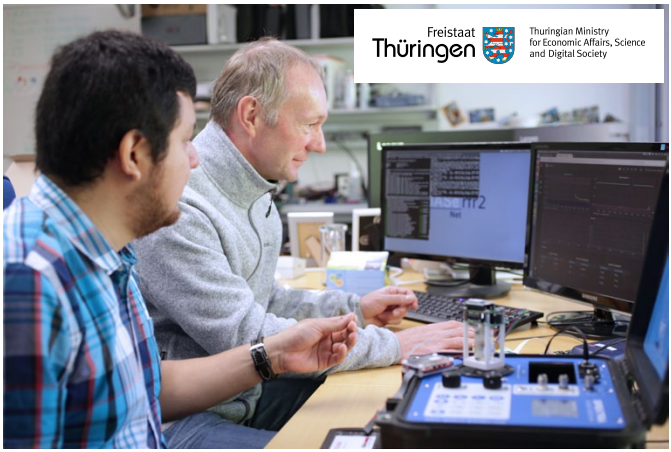
Methods applied successfully in research and industrial developments – to be continued

The methods which were developed in the ANCONA* project which ended in 2017 have already been adopted into the development of circuits at IMMS, in, for instance, the RoMulus* and ADMONT* research projects. 2019 sees the application of these methods to support innovative EDA approaches in the IntelligEnt research group. The work revolves around applicability to practice, which has already been shown with methods from ANCONA in certain industrial projects.

”IMMS has come up with a solution. The institute has developed and implemented a program that automatically finds and evaluates critical parasitics even at the design stage. This has enabled layout optimisation to go much faster,“ says Dr. Dirk Nuernbergk of Melexis GmbH, Erfurt. ”On evaluating this method, we clearly saw its high potential. In a very short time, we were able to identify the problematic points in three circuits. We offer our congratulations on the EDA Achievement Award 2018 and look forward to continuing to apply the new procedure to our future designs.“

More on ANCONA at www.imms.de.

More on IntelligEnt at www.imms.de.



ESF EUROPE FOR THURINGIA EUROPEAN SOCIAL FUND
EUROPEAN UNION European Social Fund

Figure 1:

Measurements being carried out on energy management parts of a wireless sensor for Industry 4.0 which is operated by means of electromagnetic energy harvesters. Photograph: IMMS.

End of the Green-ISAS* project: fundamental technologies for self-powered sensor-actuator systems to serve Industry 4.0

IMMS successfully concluded its participation in the Green-ISAS research group in October 2018 after two years of work on technological approaches and basic issues in design and realisation of self-powered systems which would conform to Industry 4.0 requirements.

Objectives and what is required of Industry 4.0-compatible systems

From the manufacturing systems of the future and the new services that will be based on them comes increasing demand for self-powered sensor and actuator systems. All schemes to meet these needs make particular demands on connectivity and functionality of the hardware components: these must, above all, be equipped to be "smart" – to act and respond with independent intelligence. The following challenges result:

Compatibility with Industry 4.0 To enable sensors and actuators to be installed seemlessly into Industry 4.0 systems, they must match the Industry 4.0 reference architecture model and they must comply with the requirements this makes of all components. For instance, they will have to be individually identifiable in the network, they will have to furnish a description of their features and services and they will have to support the prescribed standard communications protocols.

More on Green-ISAS at www.imms.de.

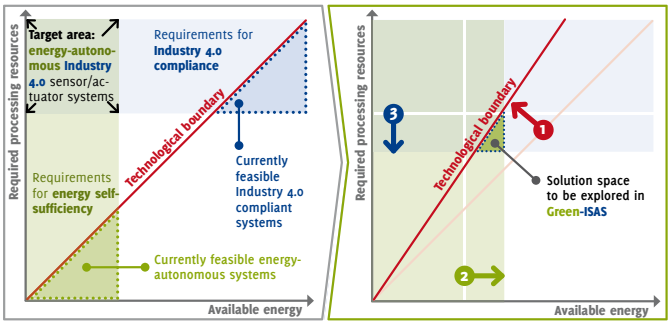


Figure 2:

Primary challenges in design of self-powered Industry 4.0-compatible wireless sensor systems and potential solutions in the Green-ISAS work.

Diagram: IMMS.

More intelligence If they are to have these properties, the components must possess more capability than is needed in classic signal processing and, for example, make validated sensor data available, respond to context details and dynamic quality assurance requirements – and, furthermore, perform self-monitoring and self-correction. The systems will have to be equipped with hardware and software capable of this level of performance.

Energy autonomy Mobile, easy-to-retrofit equipment is of inestimable value in many Industry 4.0 situations. As it is only rarely that such equipment can be supplied with electricity by wire, self-powered operation is indispensable. Energy autonomy dictates the use of either batteries or "energy harvesters", always with maximum energy efficiency in all components and functions.

In these scenarios, it is not enough to ensure that a sensor system is laid out as an independent Industry 4.0 component and is self-powered. It must also be what is known as an intelligent sensor system. The coupling of these two requirements is a huge scientific and technical challenge, involving consideration of all the following three aspects: Industry 4.0 compatibility, minimum lifetime as specified and space available, see Figure 2. The goal the Green-ISAS research group therefore set itself was to investigate basic issues and technological approaches affecting design and realisation of such self-powered, Industry 4.0-compatible systems. The focus was to be on combining both higher energy-harvesting efficiency (resulting from ultra-low-power [ULP] circuits, see Figure 2(1)) with efficient energy-harvesting (2) and the provision of much higher functionality (3) relying on optimal use of resources.

More on Green-ISAS at www.imms.de.

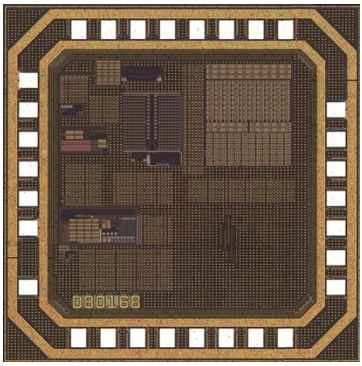


Figure 3: Working on the layout (l.) of the D8016B research ASIC (r.) which contains ULP circuits developed in Green-ISAS. Photographs: IMMS.

Results obtained in Green-ISAS

More on energy efficiency at www.imms.de.

Energy-efficient processing of time-coded sensor signals

With the aim of increasing the energy efficiency of sensor systems, the Green-ISAS workers investigated new concepts of time-coded sensor signal processing, in certain instances expressing the concept in the form of an ultra-low-power (ULP) circuit. The focus was firstly on time-to-digital converters (TDC) of particular relevance to the micro- and millisecond coding of time-period sensors in integrated microelectronic circuits. Another focus was circuit solutions for asynchronous processing of time-coded sensor signals, another the capacity-to-digital converters (CDC) which will function in the relevant time period, and another asynchronous infinite impulse response (IIR) filters which would find the mean of sensor signals from CDCs and TDCs. Another research contribution made was part of a new method of saving power in event-controlled systems. All these results fed into the D8016B research chip (Figure 3), which was fabricated at X-FAB GmbH in its XT018 technology. This ASIC (application-specific integrated circuit) is currently being characterised at IMMS. After that, it will be available for purposes of analysis and testing.

More on chip developments: www.imms.de

More on test engineering at www.imms.de.

Characterisation schemes for ULP (ultra-low-power) circuits

The increasing use of ULP circuits in autonomous sensor systems is creating demands that are becoming ever harder to meet. The power draw fluctuates hugely between standby and activity, which is a challenge to the associated measurement methods and measuring systems. The Green-ISAS project saw the development of new test hardware for the purpose. This was then made and successfully tested on

More detail in the specialist article.

ULP sensors, covering a current range from 1 nA to 10 mA with measurement error of less than 1%. The barrier to a market solution was thus overcome. There are full details in the article "Green-ISAS – Metrology enabling power consumption of ultra-low-power circuits to be characterised dynamically" in this annual report.

Ultra-low-power circuits for passive long-range UHF-RFID frontends

Passive RFID tags are much used in industry and can open up many new application possibilities (examples are plant monitoring or logistics) if they are equipped with integrated sensors and become an RFID sensor tag. In many cases, however, there will be a distance of several metres between the tag and the RFID reader, leaving only a few µW available for the sensor energy supply from the electromagnetic field emitted by the reader. In the Green-ISAS group, the Department of Electronic Circuits and Systems of Ilmenau TU applied itself to the task of developing ULP circuits for a suitable RFID tag frontend, then optimising it and creating it in the form of the D1029A research chip. For analytic purposes, the chip was combined onto a test board specially developed in-house with antenna structures that had been optimised.

Design methodology for application-specific electromagnetic micro-energy harvesters

An important research concern of Green-ISAS was to find optimal design solutions for energy harvesters for sensor systems, where mechanical sources of energy from the surroundings such as vibration or electromagnetic waves become the source of electrical power. Electromagnetic harvesters have specific advantages for industrial applications, being robust and heat-resistant. They generate induction voltage from magnetic fields which vary over time but they must be designed and laid out optimally for each particular use, which costs time and money. To solve the problem, the research group developed an automated, computer-assisted design methodology. This is de-

More on energy efficiency at www.imms.de.

More detail in the specialist article.

Figure 4: Compact wireless sensor driven by an energy harvester demonstrator. Photograph: IMMS.

scribed in the "Green-ISAS – design methodology for application-specific electromagnetic micro-energy harvesters" article in this annual report.

Adaptive energy management components for self-powered sensor-actuator systems

If energy harvesters are to be used well for self-powered systems, it is important that the energy harvested be converted efficiently by special means and then actually used. Because of their low alternative current and the degree of impedance matching necessary for efficient conversion, electromagnetic harvesters present particular problems which can be solved less than satisfactorily with commercially available harvester frontend chips. A number of concepts were therefore developed in Green-ISAS for suitable frontend chips and these were tested experimentally in several harvester test settings. Thanks to successful collaboration with Freiburg University it was also possible to experiment on a highly efficient research chip developed there. Other research was carried out on universal software components and a variety of hardware platforms which would control the sensor and communications functions and take full account of the available energy, the nature of the context and the demands from upstream communications partners. These could well be Industry 4.0 systems.

More on energy efficiency at www.imms.de.

Concepts for communications conforming to Industry 4.0 in systems with very limited resources

The demands placed on components by the communications architecture for Industry 4.0 and all its associated protocols are considerable. At the same time, there are only very limited resources available to autonomous sensor systems by way of computation capacity, memory and power. From these challenges arose the Green-ISAS research task of discovering the Industry 4.0 protocols and functions which could fall within the framework set by these conditions. A wide range of measured characterisation was carried out on communications platforms and protocols with the help of energy models and all was evaluated. A number of self-powered wireless sensors in various stages of completion were produced as a result (Figure 5). Stage 3, the highest, shows (in addition to the conformity with standards which is essential) a number of advantages – namely, low communications latency, the capacity for routing and plug-and-play functionality. The power needed on average is only 115 µW and so the energy supply can come from a compact electro-magnetic harvester subject to moderate excitation and low frequencies of 12 – 14 Hz which are relevant to practice.

More on communications solutions at www.imms.de.

More on Green-ISAS at www.imms.de.

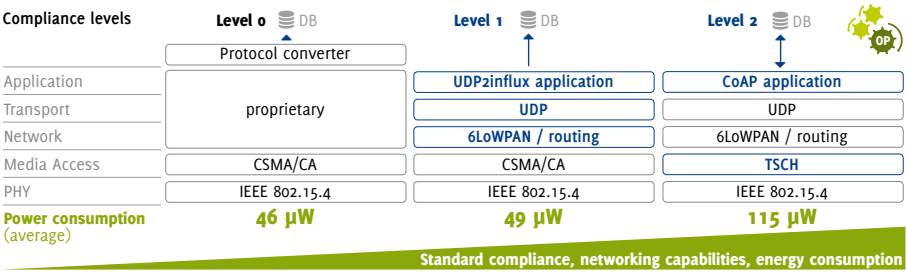


Figure 5: Stages of design complexity supporting communications protocols for self-powered wireless sensors in conformity with Industry 4.0. Diagram: IMMS.

Future prospects

In industrial practice at present, the attempt to make autonomous sensor-actuator systems compatible with Industry 4.0 comes up against a number of technological limits. Both for components and for entire systems, these limits have been pushed back in the context of the Green-ISAS research in Thüringen. The fact has been demonstrated practically in various forms (Figures 1 and 4). The results have been presented at numerous events and international scientific conferences or workshops. The set of technological building blocks developed in the project has stimulated much interest from enterprises involved in the Thüringen industrial advisory council and is now available for further exploitation. The future prospects include continuation of research into ULP circuits and unified design of harvester-based sensor systems but, most of all, transfer of the knowhow into practical industrial use.

More on Green-ISAS at www.imms.de.

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Federal Ministry
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on the basis of a decision
by the German Bundestag

Mittelstand-
Digital

Among other things, in the regular workshops promoted by the BMWi and thus free of charge, IMMS provides SMEs with practical solutions for introducing Industry 4.0 technologies to improve plant and processes. Photograph: IMMS.

IMMS' activities in the Ilmenau competence centre for SMEs and Industry 4.0*

Passing on know-how with workshops, regulars' meetings, information days and chat exchange

In the "Migration Model Factory" initiative of the Ilmenau competence centre supporting SMEs (M4.0 in short), 2018 saw an array of events organised by IMMS experts: eleven workshops, six Stammtische (regulars' meetings) or information days, and eight lectures given to third-party events. These were all free of charge and funded by the German Federal Ministry for Industry (BMWi) for the purpose of giving SMEs support as they work towards solving production problems by digital means. Besides other interested persons, the events reached 450 representatives of our region's industry. Over the year as a whole, IMMS also conducted 50 informative conversation sessions with SMEs, and from these exchanges there have arisen a number of collaborative projects with the Institute and other enterprises.

The series of M4.0 workshops named **Sensorik 4.0** (Sensors 4.0) established at IMMS in 2017 was extended in 2018 to cover Linux-based real-time-capable sensor systems and the cloud processing of sensor data. There was also a three-part workshop on OPC-UA. In these events, company chiefs, engineers and decision-makers are helped to adopt practical ideas and resources that will mean that plant and processes can be improved by the technology of Industry 4.0. With examples from practice itself,

More on the SME 4.0 project: www.imms.de.

lectures are given on how machinery can be retrofitted with a network of wireless sensors which can be used to discover and process data to underpin new schemes of diagnosis, maintenance and service and can also be connected to cloud-based services. Participants are taken step by step through all the stages of creating their own first examples, learning to use universal electronics platforms for components that are Industry 4.0 compatible, and open-source software. They see how real-time capable solutions can be put together rapidly at a reasonable price.

The three-part workshop **Industrie-4.0-konforme Kommunikation mit OPC-UA (Using OPC-UA in Industry 4.0 communications)** saw IMMS providing an opportunity for members to tackle the details of the new industrial communications norm and to gain insight into a number of case studies. Participants worked actively on the processes of communications in Industry 4.0 and on how to get components ready for them. IMMS ran several workshops on Design Thinking, also organising regulars' meetings on subjects like process data capture and the role of 4.0 sensors in the frugal use of resources. Subjects also covered were ownership of and access to sensor data; also the social intranet. All included contributions from a number of external experts with whom the members could enter into discussion.

Many of these events were a chance for IMMS to provide information on additional possibilities and options in a realistic context, using the **Industry 4.0 Test Environments**, of which there are more than 55 nation-wide. The testing and pre-marketing stages are thus subsidised by the Federal German Ministry of Education and Research (BMBF). In early 2018, IMMS was classified as the first Thüringen testing environment in the Federal German coordination centre for "Industry 4.0 Test Environments – Mobilising SMEs for Industry 4.0" (in brief, I4KMU).

More on I4KMU at www.imms.de

As a general source of information on what IMMS has to offer in M4.0 for partner companies and to give a glimpse of the possibilities, a **video film** was made at IMMS at the beginning of 2018 on IMMS in its role as "Migration Model Factory".

Watch the M4.0 video via www.imms.de.

In order to provide general information about the IMMS offers in M4.0 and to give a brief insight into an example scenario, shooting of a video on IMMS as "Migration Model Factory" took place at the beginning of 2018.

Source:
Mittelstand 4.0-Kompetenzzentrum Ilmenau (Ilmenau competence centre for SMEs).

Data retrieval from the cloud for "KSS sensors for monitoring the coolant condition" (left) and "Fabinit" demonstrator (right) for the production plan-controlled commissioning of systems. Photographs. IMMS.

IMMS puts into practice projects and demonstrators for knowhow transfer

2018 saw the conclusion of the IMMS sub-project in M4.0 known as **KSS** which is about sensors to **monitor coolant state**. Here, tests were carried out on the suitability of a sensor system made by Ilmsens GmbH, an Ilmenau start-up, to carry out fully automatic monitoring of cooling lubricants. For this purpose, two CNC milling machines and one CNC surface grinding machine of the M4.0 partner GFE were each equipped with an Ilmsens system. GFE's business is process technology and development. IMMS also installed a hybrid wireless sensor network to capture ambient conditions such as the temperature, humidity and brightness data for the workshop, sending all the details detected to an energy-efficient industrial PC, which does the initial processing and then transfers them to a data platform in the cloud for long-term storage and further processing. The outcome of this small feasibility study was proof that the start-to-finish sensor installation is, indeed, suitable for establishing relevant KSS details. Further development ideas were derived from this study and are being put into practice in a follow-up project financed by the "Land" of Thüringen.

IMMS made a demonstrator in 2018 that is capable of visualising how **production is resumed after weekends and bank holidays**. It is designed to illustrate the **Fabinit** element of M4.0 which was concerned with (re-)starts of extrusion equipment controlled by manufacturing plans. Such plant must be started and brought up to speed in such a way that the total energy consumption of a factory never exceeds a specified maximum. The technique is to monitor the energy used in machinery warm-up and and control it in association with all plant operating in the factory. At the same time, the whole process can be observed on a mobile end-user device which will issue a warning if problems arise.

More on the SME 4.0 project: www.imms.de.

Another M4.0 sub-project is **Energy Management** in which IMMS has created retrofitted systems to measure, visualise and record the energy consumption of plant and machinery simply and cheaply without invading the mechanical infrastructure. All the measurements are carried out with conventional components which are suitable for industrial use and fulfil Industry 4.0 standards.

Another demonstrator, this time in the M4.0 sub-project **Fill Level Monitoring**, shows how changes of supply in magazines can be kept under control. Here, an ultrasonic sensor detects distance of the actual from the maximum level. When this distance changes, automated messages can, for example, be sent to arrange prompt replenishment. This solution is one that can be used in many settings, including warehouses, transport and logistics.

The M4.0 sub-project **Sensors in a Suitcase 2** started in 2018. The focus is another portable demonstrator. The first suitcase solution contains wireless sensor nodes developed at IMMS, but the second suitcase has been equipped with commercially available SmartMesh® IP modules suitable for industrial use, which are just as capable of delivering a fully automatic wireless sensor network with nodes that accept routing. The nodes have been fitted initially with sensors for ambient conditions and vibrations and can be extended for other needs any time.

Yet another sub-project in M4.0 is concerned with a **Visualisation Front-End for demos and live data**, in which IMMS has been able to demonstrate the possibility of evaluating and then showing in a suitable graphical form any data from machines and sensors. This front-end is in use for several demonstrators such as sensors-in-a-suitcase 1, the UV water purifier in the Ilmenau town swimming pool and the cooling lubricant monitor described above.

More on the M4.0 project: www.imms.de.

Bodo Ramelow on a summer tour of digital matters – third week of #ZukunftThüringen starts with IMMS

On July 16th in 2018, Mr. Bodo Ramelow, Prime Minister of Thüringen, started the third week of his future-focussed summer tour (#ZukunftThüringen) by visiting IMMS, which is one of five SME 4.0 Competence Centres serving the "Land". With him came a number of representatives from the region's political, administrative and industrial circles. There were copious reports of the tour in the print media, on MDR television and on various Internet platforms.

Mr. Ramelow learnt about the work of IMMS and its role as "Migration Model Factory" in the competence centre. He visited the customer demonstrations room and other laboratories and was shown various demonstration models of how processes already to be found in industrial plant can be optimised with good cost-benefit by retrofitting networked sensors and cloud solutions. The plant can then accommodate the rising demand for products and services which are specific to a particular customer.

"Here, digitalisation is not only acting as a lever for the more efficient processes that are achievable by data networking," was Mr. Ramelow's summary. "There is another angle to networks: that of networking. Digitalisation offers these opportunities to Thüringen's industry in particular, with its dependence on small and medium-sized enterprises. Our SMEs are strengthened by building networked value chains that can hold their own in international competition. For this work, the competence centre is at the very hub."

More on the SME 4.0 project: www.imms.de.

Thüringen's Prime Minister, Mr. Bodo Ramelow (centre), visiting IMMS in Ilmenau.

Photograph: Angelika Stern, Mittelstand 4.0-Kompetenzzentrum Ilmenau (Ilmenau competence centre for SMEs).

Visit of Mr. Tankred Schipanski

On the 12th July, 2018, a visit was paid to IMMS by the Member of the Federal German Parliament (Bundestag) for the districts (Landkreise) of Gotha and the Ilm-Kreis, Tankred Schipanski who is the parliamentary spokesperson on digital matters for the CDU/CSU. Demonstration models were used to show him current work on digitalisation projects which are being funded by the federal government to support Industry 4.0, the fourth industrial revolution.

IMMS is engaged in supporting production with secure, networked, real-time, self-powered embedded systems. As an actual example, Mr. Schipanski saw a project assuring Industry 4.0 compliance for assistive systems which provide automatic analysis of networked plant. Another was an RFID sensor system operating without batteries which can be employed in the monitoring of manufacturing parameters such as temperature, pH value and humidity. He was also given a guided tour of the Time Sensitive Networking (TSN) laboratory which is a unique feature of IMMS in its role as an Industry 4.0 Test Environment mobilising SMEs (I4KMU).

More on the TSN test lab at www.imms.de

More on I4KMU: www.imms.de

A lecture and tour informed Mr. Schipanksi on the work of IMMS as the Ilmenau competence centre serving SMEs. His verdict was that "Major concerns have already made Industry 4.0 techniques their daily bread. Many small and medium-sized companies, such as are the tradition here in the Ilm-Kreis, are unable to manage without support on this front. Contributing as it does in the role of competence centre 'Migration Model Factory' and developer of Industry 4.0 practical solutions, IMMS is providing engine power to the fourth Industrial Revolution."

More on the SME 4.0 project: www.imms.de.

More on Industry 4.0 at www.imms.de

Tankred Schipanski (centre), Member of the Federal German Parliament, being shown the laboratory for Time Sensitive Networking (TSN).

Photograph: IMMS.

RoMulus – UHF RFID chip for battery-free operation of commercial sensors in I4.0 applications

Carrying out measurements on the energy-efficient UHF RFID sensor transponder chip. This chip is for operating without use of a battery a variety of commercially available digital I²C sensors requiring varied power levels. Photograph: IMMS.

Objectives and overview

Wireless sensors: key to success for Industry 4.0

Value creation is increasingly shifting from production to data-based services and platforms which will align processes and business interactions. Small and medium-sized industrial companies in particular face the challenge of securing their global competitiveness in the future not only through high-quality products and process excellence, but also through creation of new value-added services and digital business models. Core technologies such as sensors for data acquisition and wireless networking are necessary to implement these solutions. For many applications, wireless mobile sensors are essential, especially when retrofitting existing systems. IMMS has therefore researched and developed an innovative solution that combines sensors with RFID systems at low cost and without batteries, thus opening up a wide range of industrial applications.

More on Industry 4.0 at www.imms.de

More on RoMulus at www.imms.de

UHF RFID systems for longer range and parallel identification

Typically, RFID systems consist of one or more transponders (also known as tags), and at least one reader, which communicates with the surrounding RFID tags by

means of an RF (radio frequency) field. They answer with their unique identification number, enabling access checks and tracking. UHF RFID systems work, as the name suggests in the ultra-high frequency (UHF) waveband, usually between 860 and 960 MHz and they rely on the principles of far-field radiated coupling and of back-scattering. UHF RFID tags are thus capable of communicating with the reader over a much greater distance (up to five metres) than the magnetic-field-coupled high-frequency (HF) RFID tags. These tags, operating at a frequency of only 13.56 MHz, will only communicate over a few centimetres. Thanks to their high data transmission rate, UHF RFID systems are ideal for applications in which several objects must be read at the same time. They are therefore already well established in industrial environments, e.g. for tracking goods.

UHF RFID sensor systems not only for identification but also for reading out measured sensor values

If sensors are integrated directly into these UHF RFID systems, numerous industrial 4.0 application scenarios are possible. Standard protocols allow existing infrastructure to be reused with readers. The sensor data is read out using the same address range in which additional product information is stored.

Lack of energy-efficient, self-powered, flexible transponder architectures

If these UHF RFID sensor systems can be operated passively, i.e. only with the energy from the reader, they can be used for applications where batteries or wired systems are out of the question, e.g. on rotating parts. For this, energy-efficient solutions are necessary.

The state-of-the-art solution involves RFID sensor transponder ICs designed for specific applications, in which the sensor is integrated directly into the RFID chip in order to optimise energy efficiency, functionality and sensor accuracy. These ICs are not flexible enough for widespread use in several application scenarios at once.

However, most commercial RFID sensor systems are discreetly built from classic RFID transponder ICs, microcontrollers (MCUs) and individual sensor ICs. Most of the energy that can be generated from the reader is consumed by the microcontroller, which limits the range and thus the application scope.

UHF RFID chip to operate commercial sensors without battery

In this regard, IMMS has developed an energy-efficient UHF RFID transponder chip which enables different types of commercially available digital I²C sensors requir-

Figure 1:
UHF RFID transponder with IMMS-developed UHF RFID sensor transponder chip (centre) and temperature sensor (bottom right) for wireless measurements. Photograph: IMMS.

ing varied power levels to be operated on a passive basis. In this case, the chip is equipped with a flexible on-chip I²C master and a power management unit which can be individually configured. The developed chip requires no maintenance or power supply and can therefore be easily integrated into various products, machines and objects in a wide variety of application scenarios for sensor data acquisition. Such an RFID transponder IC was previously not available.

The IMMS solution in detail

Starting point: how to overcome disadvantages of existing discrete solutions

In commercial RFID sensor systems as they have been constructed to date, the sensor operations are managed by the MCU by means of SPI (serial peripheral interface) or I²C. This means that the MCU is the master and the RFID transponder tag IC and the sensors are all slaves. There are three main disadvantages to such systems.

1. **Energy efficiency:** most of the energy available is used up by the MCU, which requires approx. 100 µA/MHz. In contrast to HF RFID, UHF RFID transponders work on a very tight energy budget because there is very little far-field energy and the efficiency of the energy extraction is very low (approx. 30 – 40%). The communications range and the reading reliability of the RFID sensor are strongly limited by the microcontroller.
2. **Flexibility:** Sensor operation is not controlled directly by the RFID reader, but by the MCU. The firmware of the MCU must be programmed sensor-specifically, based on the start time, the energy consumption and the measuring period. This brings complexity and additional effort to the development and design of RFID sensors.
3. **Cost efficiency:** the MCU including the external components which it requires accounts for a high proportion of the overall cost of the RFID sensor.

New approach: Transponder architecture without microcontroller

New transponder architectures were required in order to operate digital sensors without MCUs and to overcome the aforementioned disadvantages. IMMS has there-

More on chip developments: www.imms.de

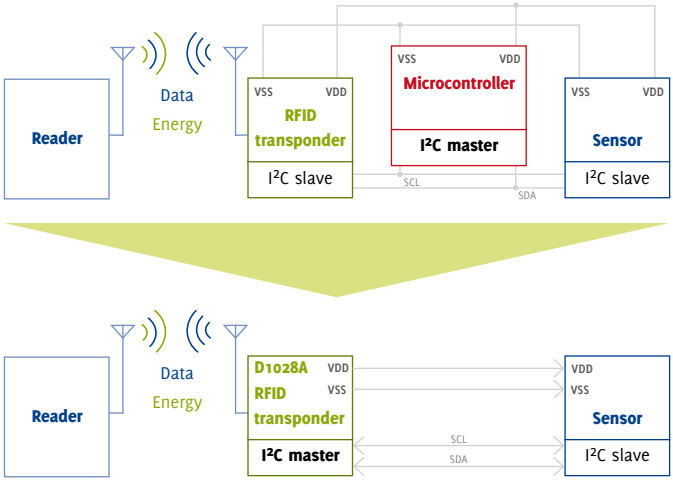

Figure 2:

Top: In conventional discrete RFID sensor systems, the sensors (slave) are controlled by the microcontroller as master.

Bottom: The microcontroller is no longer necessary in the case of RFID sensor systems using the new RFID transponder IC D1028A with an integrated (on-chip) master. Diagram: IMMS.

fore developed a new RFID transponder IC with integrated (on-chip) master in the RoMulus project (Figure 2). The master-slave communications is controlled directly by the RFID reader by writing the I²C communications information into the command registers in the transponder memory. This information is used by the on-chip I²C master to initiate the I²C transactions with the external sensors.

The IMMS RFID sensor transponder IC with I²C master

The IMMS-developed EPC-C1-G2-compatible UHF RFID sensor transponder IC can be used with the flexible on-chip I²C master and the configurable power management unit, which can supply a regulated voltage for various external sensors up to 1.8 V at a maximum current of 1 mA. The on-chip I²C master block eliminates the need for a microcontroller for read/write operations with external sensors. This reduces the power consumption of the overall system and the number of external components required to build an RFID sensor transponder.

The chip also offers the following configuration options: multiple read and write operation; combined read and write operation (write information to start sensor operation and read back acquired data after operation); start delay (time to start sensor); delay between two consecutive I²C writes (required when writing information to external non-volatile memory). The architecture of the chip is shown in Figure 3.

More on chip developments: www.imms.de

Energy storage and power consumption flow

Unique to the developed chip is the flexible power management, with which stable communications with the external I²C sensors is achieved. It provides stable voltag-

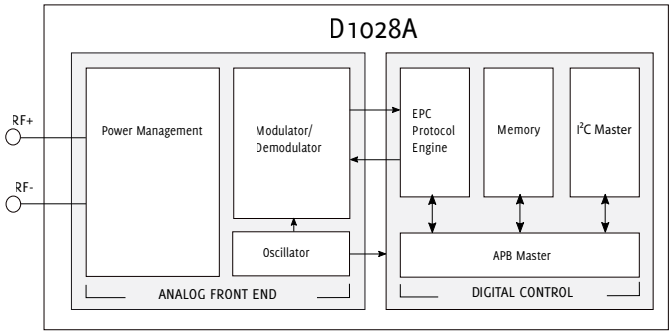

Figure 3:

Architecture of the RFID transponder IC developed at IMMS with the codename D1028A.

Diagram: IMMS.

es not only for the internal circuits, but also for the external sensors. The chip uses an external capacitor to automatically store energy while the sensor transponder is in the reader's energy field. When the required energy for system and sensor operation is reached, an internal interrupt signal "Power_OK" is initiated. From this point on, operation of the connected I²C slave chips can be initiated. The charging process of the external capacitor, the read/write sequence and the delay between two commands can be configured via standard read/write commands to take into account the types and differences in power consumption of commercially available sensors. Power management and power consumption flow with external I²C sensor are shown in Figure 4.

More on energy efficiency at www.imms.de.

Measurement and characterisation

The RFID sensor transponder IC was developed in standard X-FAB 0.18 µm technology. An evaluation board with embedded antenna for the measurement and characterisa-

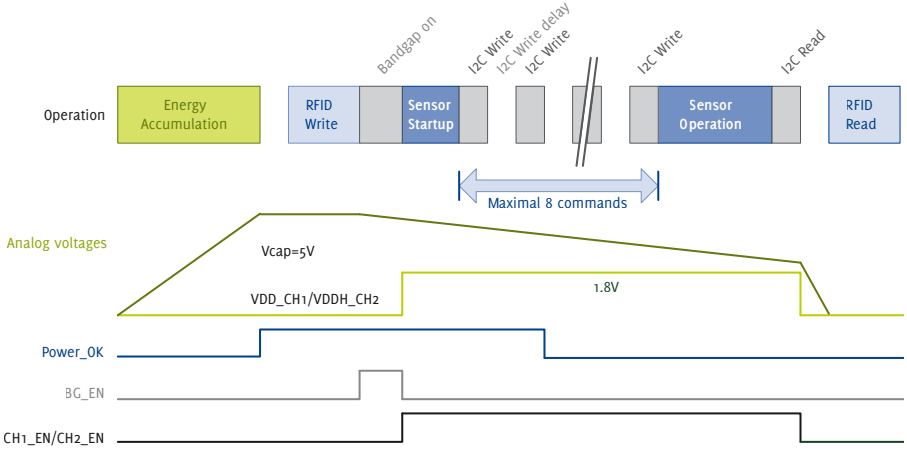

Figure 4: Power management and flow of energy consumption in the RFID transponder IC with external I²C sensor. Diagram: IMMS.

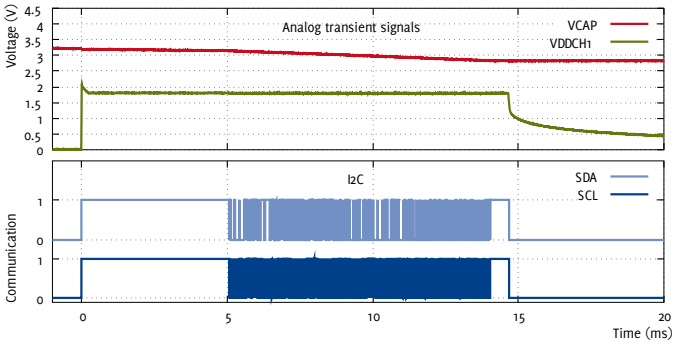

Figure 5:

In I²C operation, the RFID transponder IC supplies a stable voltage of 1.8V. The measured values confirm the functionality of the power management and the communications with an external I²C slave IC.

Diagram: IMMS.

tion of the chip was developed. For functional testing of power management and I²C communications, a commercially available I²C slave IC was connected to the transponder IC. During I²C operation, the chip supplied a stable voltage of 1.8V. The measured values shown in Figure 5 confirm the functionality of the power management and the communications with an external I²C slave IC.

Future prospects: digital added-value thanks to RFID-based sensors

The UHF RFID transponder IC developed by IMMS provides industry with a basis for developing innovative products for wireless sensor data acquisition and achieving competitive advantages with new data-driven business models. Following the measurements and the successful evaluation of the proof-of-concept, IMMS is currently working on a redesign of the chip to make it available to its industrial customers for the development of wireless products. Value creation based on sensor data will play an important role for industry in the future. IMMS is, therefore, constantly working with its strategic industry partners in developing innovative energy-saving and efficient chips.

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We thank microsensys, our business partner, for the many discussions we have had on the practical specifications for the ASIC, also for the ensuing product development and for the constructive collaboration in the context of the RoMulus project.

SPONSORED BY THE
Federal Ministry of Education and Research

The RoMulus project has been supported within the Research Programme ICT 2020 by the German Federal Ministry of Education and Research (BMBF) under the reference 16ES0362. Only the author is responsible for the content of this publication.

More on test and characterisation at www.imms.de.

More on Industry 4.0 at www.imms.de

All RoMulus publications: www.imms.de.

Green-ISAS –

Metrology enabling power consumption of ultra-low-power circuits to be characterised dynamically

Staff member at work on a measurement circuit developed by IMMS to provide dynamic characterisation of ultra-low-power (ULP) circuits. These ULP circuits are what enable self-powered functioning of networked integrated sensor systems. Photograph: IMMS.

Objectives and overview

The need for self-powered network sensors in Industry 4.0 and IoT

The key to production that is efficient, networked, automated and flexible is digitalisation. Digital monitoring of production states, production processes and the quality produced means using more and more sensor systems. Such systems are significant trailblazers for the fourth industrial revolution (also called Industry 4.0) and the IoT (Internet of things).

More on Industry 4.0 at www.imms.de

The systems are known as cyber-physical systems, or CPS. They are used at many points to capture, process and transmit measurements and control data. If existing plant and machinery are to be retrofitted with the necessary sensor systems, the systems will have to function without outside energy, at inaccessible points, among them those where it is impossible to change a battery or deliver power by cable. Here and across the whole Internet of Things, the challenges presented to integrated sensors and evaluation software are increasing all the time, as the tasks needing to

More on Green-ISAS at www.imms.de.

be done become ever more complex while the energy that can be used remains at a minimum.

New ultra-low-power circuits improve system efficiency but still cannot be validated with standard instrumentation

Increasingly, the self-powered systems are using ULP-ICs (ultra-low-powered integrated circuits). In the Green-ISAS research group, IMMS has developed ULP ICs that process signals from a temperature sensor chip with remarkable energy efficiency. They are now at the manufacturing stage. This ASIC (application-specific integrated circuit) is so designed that it requires only a tiny amount of energy. This fact is a particular challenge to the present conventional instruments measuring fluctuations in take-up of electric current during switching on or off.

More on energy efficiency at www.imms.de.

The energy needs of ULP ICs on standby are mere nanowatts but they may rise a millionfold during their customary operation. This has certain consequences for their characterisation. Their current consumption is the most important characteristic of ULP ICs. It can range from nanoamperes (nA) during standby to milliamperes (mA) in operating mode. It is thus necessary to achieve measurement of current needs across a range from 1 nA : 1 mA ≙ 1 : 10^6 – smoothly, without interruption. In these ICs, switching between standby and operation mode is a matter of fractions of a second, but recording is needed throughout the procedure. High-speed measurement is essential.

Only if the measuring instrument fulfils this requirement is it possible to investigate and characterise current consumption by consumers of electricity during actual consumption — in this case consumption by ULP ASICs in a self-powered detection system based on a sensor network. The results of the characterisation process are the foundation of the design of the energy supply within electronic systems which do not depend on an outside source. Ammeters currently available on the market do not fully meet the challenge.

More on test and characterisation at www.imms.de.

Possibility of characterising ULP ICs with the IMMS measuring circuit

In the Green-ISAS research group, IMMS has developed a circuit that measures up to the challenge. Initially designed as an auxiliary device for commercial oscilloscopes, it has been fully developed and brought into use. The hardware can measure the power consumption in a dynamic range from 1 nA to 1 mA in dependence on time

and with a measurement error below 1%. The design of the measuring circuit is such that operating voltage is kept constant at a level above the load throughout the measurement process and independently of the load current.

The IMMS solution in detail

Challenges and measurement concepts

The following table summarises the measurement parameters envisaged for the circuit developed by IMMS.

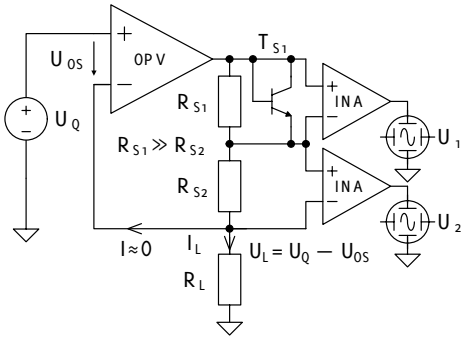
Parameters	Specifications
Load voltage range	U_L = 0 V ... 3,3 V
Load current range	I_L = 1 nA ... 10 mA ± 1 %
Frequency range	f = DC . . . 1 MHz
Voltage drop	U_{drop} < 1 mV
Noise level (<100 kHz)	I_{noise} < 1 nA

For the execution of the circuit that is shown in Figure 1, a number of concepts were investigated and their suitability checked.

Step 1: Establish load current

For a first potential type of current measurement in ULP-ICs, a resistor was inserted as a shunt between source and load. The calculation of the current load $I_L = U_S/R_S$ is made from the drop in voltage U_S across the shunt R_S. However, this passive option has the disadvantage that the supply voltage of the load U_L does match the voltage of the source U_Q so that there is a voltage drop U_{drop} in relation to the operating current.

Figure 1:



Basic structure of measuring circuit with voltage regulated at the load and an extendable dynamic range for current measurements.

Diagram: IMMS.

Step 2: Keep the operating voltage constant

To counteract this effect, an OPV (operation amplifier) is inserted in addition to the shunt resistance between source and load. This OPV then regulates the load voltage U_L to match the source voltage U_Q minus the offset voltage U_{OS} of the OPV. An instrumentation amplifier (INA) is used to measure differentially the voltage drop across the shunt, amplify it and allow it to be measured with a relevant device such as an oscilloscope. This method allows the operating voltage to be kept constant and independent of the measuring range.

Step 3: Extend the dynamic range for current measurement

To achieve the wide range of current measurement, additional modifications are required. For this, transistors are installed in parallel to the shunt resistances. As the voltage drop across the shunt becomes equal to the voltage flowing through the transistor (approx. 700mV), the transistor becomes electrically conductive and short-circuits the shunt. This method permits several shunts to be connected in series so that the varying resistance of the shunts means a much greater range of fluctuation in the measurable current is covered.

A measurement circuit with four current measuring ranges was developed and laid out in fulfilment of this scheme (Figure 2).

Characterisation of the new measurement circuit

The characterisation was carried out using a precision IV analyser with the current kept constant over time. Instead of a load, the analyser itself was used as the load and a current was generated between 1nA and 10mA. At the same time, the drops in voltage across the shunt at the outputs of all INAs were measured and the currents calculated from the results. These measurements were compared with

More on test and characterisation at www.imms.de.

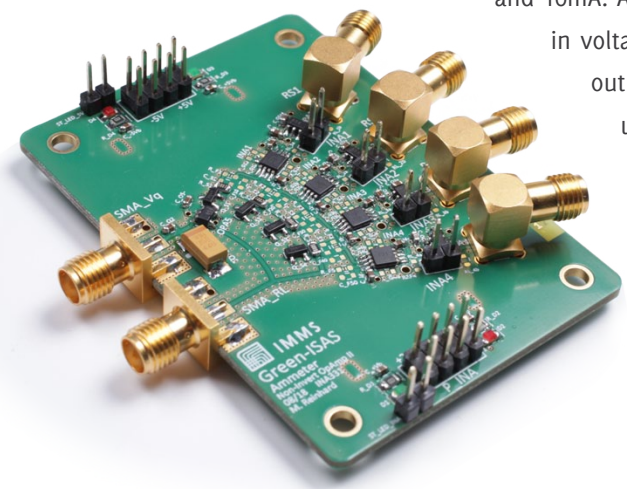


Figure 2:
The measurement circuit developed at IMMS with four current measurement ranges for time-resolved power characterisation of ULP ICs. Photograph: IMMS.

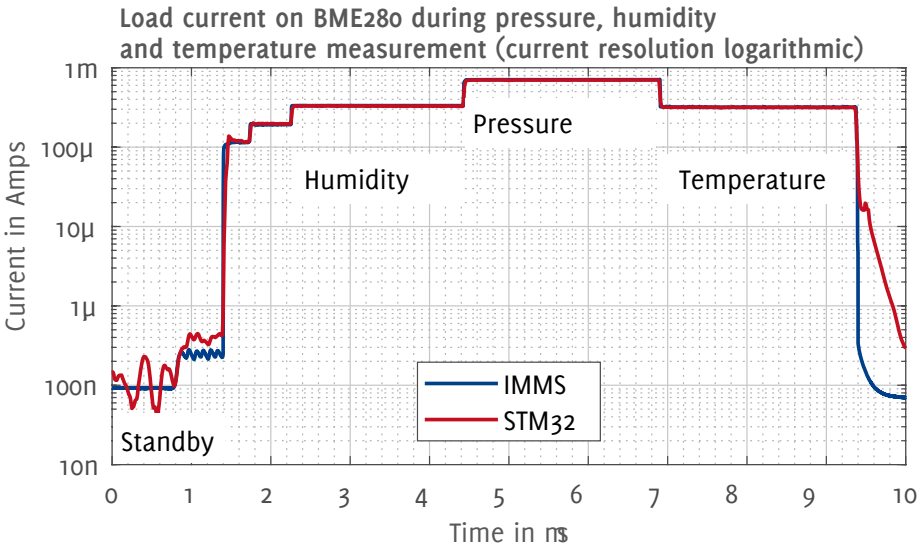
the current that was being supplied. Any deviation between the current supplied and measured across this range from 1nA to 10mA is found to be less than ±1 %. It was also possible to prove for the other parameters of the measurement IC that the values had been achieved that were the original target.

Comparative measurements using currently conventional measurement methods

What stood out was the improvement that had been achieved over results from commercially available measurement devices such as the STM32CubeMonitor-Power, which addresses a range of current from 100nA to 50mA and a bandwidth of 100kHz. The outstanding improvements are the effects of extending the range of current measured so that the minima are 1nA and raising the bandwidth so that the maxima are 1MHz. For comparison, the current consumption of the BME280 ULP sensor made by Bosch was investigated as an example. This is an IC that determines temperature, pressure and humidity. According to its specifications, the sensor requires 100nA on standby and up to 700 µA during normal operation. In the investigation, the BME280 was programmed to wake up from standby, take measurements and then return to standby. Current consumption was recorded for this period in real time. The results are given in the following Figure 4. Clearly apparent is the deviation of the STM32CubeMonitor-Power on standby from the BME280: deviation due to the limited resolution and the slow return to standby operation attributable to parasitics.

More on test and characterisation at www.imms.de.

Figure 4: Current measurements made for the Bosch sensor BME280 compared: those made with the measurement circuit developed at IMMS for ULP sensors and those made with the STM32CubeMonitor already on the market. Diagram: IMMS.



The results of the comparative measurements clearly indicate that the new IMMS measurement circuit fulfils the demands made on it. The range of varying current to be measured (between 1nA and 10mA) is shown, with a measurement error of less than 1%. The measurement circuit topology means that operating voltage is kept constant at a level above the load throughout the measurement process and kept independent of the load current.

Future prospects

The measurement circuit here presented will make exact predictions possible concerning energy required by sensor chips onto which ultra-low-power signal processing circuits are integrated or concerning the energy needs of more complex ULP systems such as wireless sensors. It will, for example, enable measurement intervals to be matched so closely to the energy available that the sensor system will operate independently of an outside energy source. The measurement circuit is, furthermore, a powerful development tool that will help optimise ULP systems in that it enables the exact way that changes in hardware or software affect energy needs to be calculated swiftly.

If the measurement circuit is to be used without an oscilloscope, it will require the addition of an evaluation and visualisation unit. IMMS is currently experimenting with compact solutions to this problem that include microcontrollers and ADCs. Measuring the drop in voltage at the shunt resistors will then be possible in parallel at a sampling rate faster than 1 MSample/s. Using the right algorithm, the microcontroller will be able to compute the resulting current without any dead time due to switchover from one shunt to another.

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ESF EUROPE FOR THURINGIA EUROPEAN SOCIAL FUND
EUROPEAN UNION European Social Fund
Freistaat Thüringen Thuringian Ministry for Economic Affairs, Science and Digital Society

The Green-ISAS research group was supported by the "Land" of Thüringen and the European Social Fund under the reference 2016 FGR 0055.

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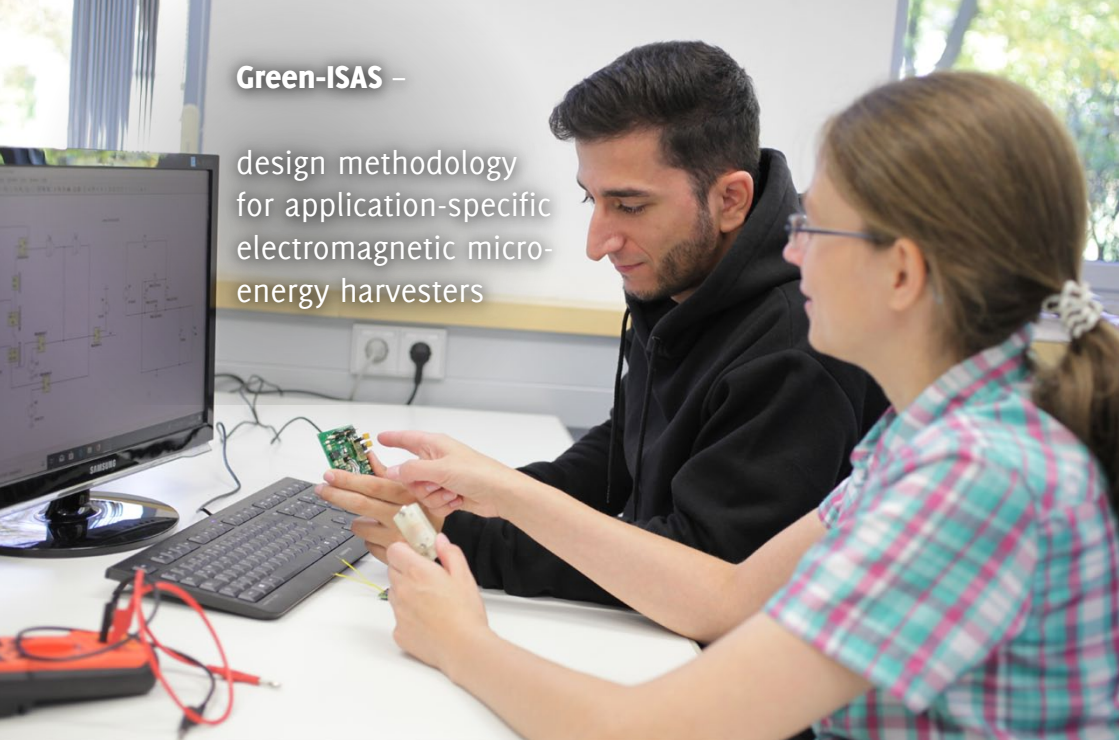


Green-ISAS –

design methodology for application-specific electromagnetic micro-energy harvesters

Working with an evaluation board for electromagnetic micro-energy harvesters which served in the verification of the design methodology developed at IMMS for the purpose. Photograph: IMMS.

Objectives and overview

Mechanical movement is everywhere in industry and logistics. By the conversion of vibration into electricity, it can even be the source of power for the smart sensors used in monitoring the vibrating plant and machinery. Energy harvesting makes it possible to turn sensor-actuator systems into self-powered components for Industry 4.0 (also known as the fourth industrial revolution). The systems, often installed at points which are difficult to access and have no connection with an external electricity supply, will record, process and transmit measurement and control data, thereby smoothing the path to automated, connected, flexible manufacturing.

More on energy efficiency at www.imms.de.

More on Industry 4.0 at www.imms.de

In the Green-ISAS research group, IMMS investigated electromagnetic energy harvesters which could reclaim energy from mechanical vibration. The aim was to achieve rapid design of optimised electromagnetic energy harvesters offering maximum energy exploitation and used for specific applications.

More on Green-ISAS at www.imms.de.

Electromagnetic energy harvesters have many faces

It is eminently possible to adapt electromagnetic energy harvesters to a variety of spatial environments. Harvesters of this type consist of at least one magnet and

one coil and generate an induction voltage from the changing magnetic field produced by their movements in relation to each other. A variety of basic structures can arise from the layout of the magnets, coils (with or without any possible ferromagnetic feedback) and any desired relative movement. To enable the suitability of the various options for the specified requirements to be automatically compared, IMMS developed rapid, inexpensive design methods for application-specific energy converters.

The IMMS design tool for application-specific electromagnetic energy harvesters

IMMS developed a design methodology for application-specific energy harvesters as part of Green-ISAS and implemented it as a design tool in MATLAB®. With the tool, designers use a graphic interface to enter into the program a number of customer-specified parameters, which could, for example, be size, geometry of the space available, vibration characteristics and power required. After taking these figures and comparing the various basic structures it has at its disposal, the tool comes up with a selection of optional designs. Performance of the task relies on a number of parameterised models which analyse and describe the behaviour of the structures. The number of structures available can be increased at any time. The uniform interface that is part of the tool also enables additional basic structures to be added later by the user.

The IMMS solution in detail

Starting point and requirements

With precisely targeted hardware and software properties for the energy-efficient Industry 4.0 components developed in the Green-ISAS project, it was possible drastically to reduce power consumption. In the course of development, demonstrators at various stages drew only 50 to 100 µW for measuring temperature and transmitting the figure in accordance with industrial standards every 5 s, thus providing a framework for autonomous power supply from electromagnetic energy harvesters and for the tool created for their design.

The power required of the electromagnetic energy harvesters is in a range up to a few 100 µW and the dimensions of the active converter structures lie in the millimetre or micrometre range. As these harvesters are converting kinetic energy to electrical power, they are able to extend the battery life of wireless sensor units or even to obviate the need for batteries altogether ([3], [4], [6], [7]).

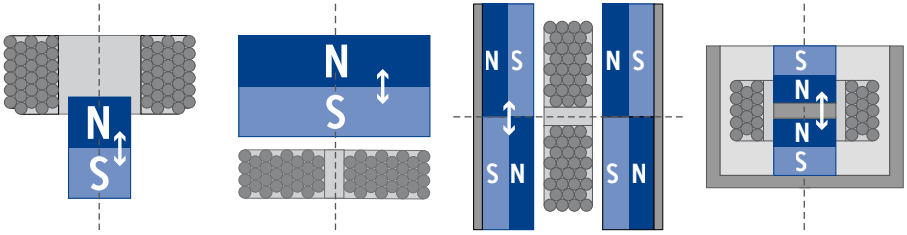


Figure 1: Examples of the wide variety of topological basic structures for electromagnetic energy harvesters. Diagram: IMMS.

Basic topologies of electromagnetic energy harvesters

As there is such a variety of excitation situations and spatial restrictions, the solution principles need also to vary. Having a variable number of magnets and coils means that there are many potential basic structures from the topological point of view, see Figure 1, so that a wide field of solutions is opened up. This field can be compressed using the systematic computation method developed at IMMS to produce not only solutions specific to the current application but to make the design of robust, application-specific energy harvesters rapid and affordable. The current density of the vibration converters will be further improved by derived optimisation algorithms ([2], [5]).

Procedure in the automated design tool

The basic procedure for the design is summarised in figure 2. The first step was to work out the concept for defining standardised specification parameters. Consideration has to be given not only to the excitation characteristics, the space available and the shape but also to the power output and the manufacturing conditions.

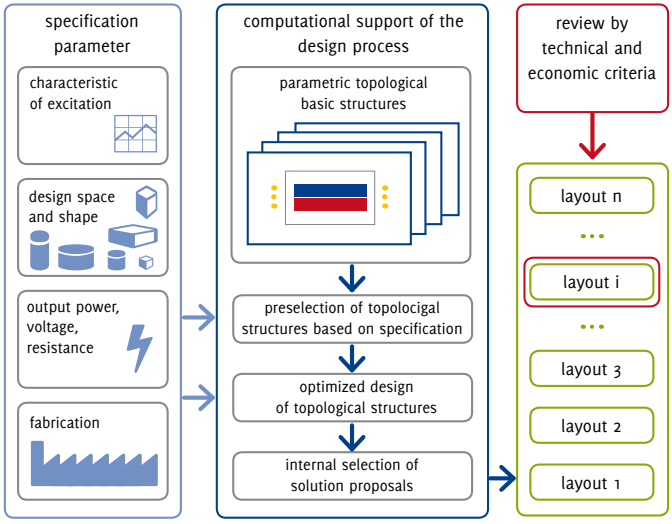


Figure 2:

Schematic design of the automated design tool.

Diagram: IMMS.

Against the background of the specification, suitable structures are preselected from the various topologies already available in the tool so that computation can be kept to a minimum. Layout variations are then worked out for these potential structures and again preselected internally. The developer can then evaluate the suggested solutions against other technical or commercial criteria.

Creation of a library of parameterised computation models for various basic topologies

The work on the design tool focused strongly on producing parameterised models for many different basic topological structures. It was particularly necessary to compute the magnetic fields for the permanent magnets. IMMS investigated a number of different approaches for the detailed description of magnetic systems and put these into MATLAB®. This method ensures special tools are unnecessary for finite element method (FEM). It was shown experimentally that the models made in MATLAB® agreed very well with the results obtained if the ANSYS Maxwell FEM program was used.

Services for FEM at www.imms.de.

Any small deviations can be explained by the fact that the analytic models argued homogenous permeability. Permeability is the term used for the magnetic conductivity of a material, i.e., for the relation between the magnetic flux density and the strength of the magnetic field. Most permanent magnets are made of rare earths belonging to the group of paramagnetic materials with permeability levels slightly above those of air and in the range between 1.05 and 1.1. In the MATLAB® implementation of the design tool a value of one is assumed in the whole space. The deviations mentioned have been regarded as negligible in comparison with the permeability values for ferromagnetic materials, which are in the thousands.

Creation of the design tool, scope of functions

Similarly, IMMS implemented the entire design tool together with its graphic user interface in MATLAB®. First the parameterised functions for frequently employed basic structures were transposed. Then particular modular groupings were investigated which involve using a number of coils. For each architecture, a dedicated function was defined so that it would be easy to extend the architecture range. The unified interface which has been implemented, establishing the data structure for input and output parameters, enables further basic structures to be added later by the user.

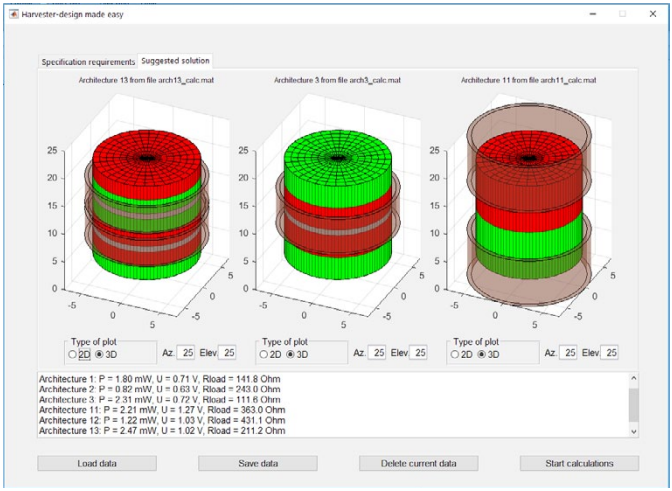


Figure 3:

Graphic user interface of the design tool.

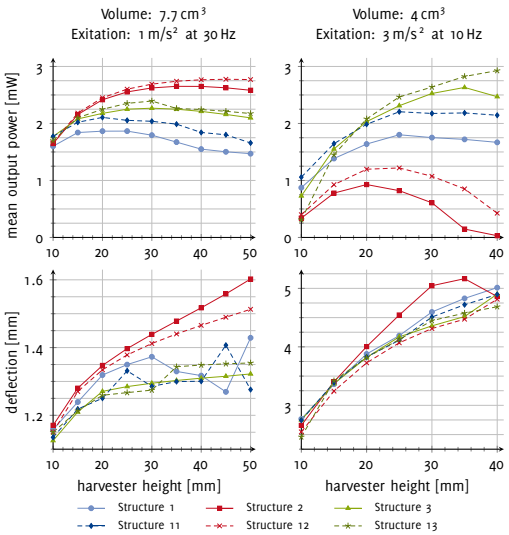
Screenshot: IMMS.

Transfer of the specification parameters

The graphic user interface is employed to enter the specification parameters. The volume, height, excitation amplitude and excitation frequency are specified for the current state. The tool computes the geometry which will give the maximum performance from this data. All geometric values which are dependent on the specific shape are stored in the program alongside the specification parameters, following the uniform data structure. All the data is saved and can then be uploaded as a parameter file to a computer-aided design application. The three structures offering the highest performance in output are also displayed on the GUI, see Figure 3.

Layout and optimisation of the electromagnetic energy harvesters

An analytical description is produced for the electromagnetic energy harvesters to take full account of the complex physical context of the mechanical-to-electrical conversion system. As a sequel to external excitation, the movable component, which is usually the magnet, is displaced. The resulting change of position produces an induction voltage in the coil which, in turn, causes mechanical damping by the current which flows. In the process, the damping affects the resultant amount of displacement and the space it takes up. The optimisation function in the tool computes the magnet and coil dimensions in such a way that the prescribed space is laid out to take close account of the necessary displacement, so that there is maximum energy output.



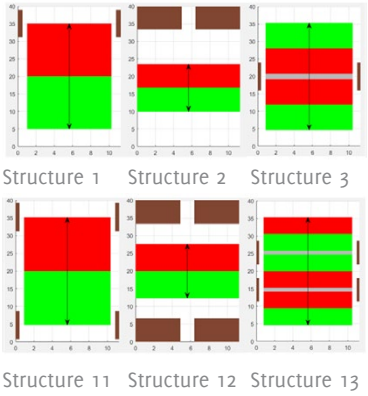


Figure 4:
Examples of output power independence height of harvester for two different scenarios. Diagram: IMMS.

Studies using the design tool to evaluate basic structures

The tool as implemented was employed in various investigations of the suitability of a number of basic structures with a range of limiting conditions ([1], [8]). Figure 4 shows an example, a comparison of six basic structures for two different scenarios. The space allowed for the harvester was in one case 7.7 cm³, the size of an AA battery, and in the other case 4 cm³, the size of an AAA battery. For purposes of comparison, the excitation selected was such that power output would be in the range of 2 mW. The larger space has higher excitation frequency but smaller amplitude, which means that the internal displacement is also smaller. The second case, on the other hand, involves considerably greater internal displacement. The frequency range considered is that which is typical of many industrial applications, a low frequency on the whole.

These investigations show that none of the structures considered offers maximum output power all the time. Modular structures which are generated by extending the basic configurations by one or more coils and further magnets as necessary (here numbered 11, 12 and 13), tend to produce more output power than do the simple structures. They are, however frequently associated with higher production costs. The structures in which the magnet is moved along the direction of the coil axis but not all the way through the coil (exemplified in numbers 2 and 12), appear to be suitable for small displacements. Where large displacements are necessary, however, the distance between coil and magnet becomes too large, with the effect that the

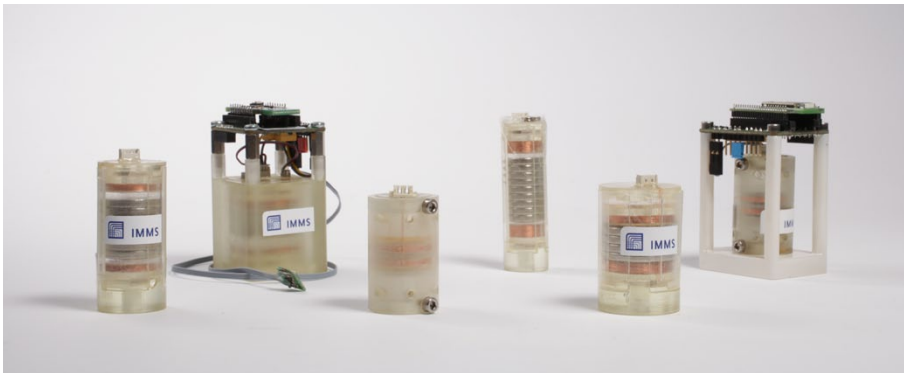


Figure 5: Selection of demonstrators (versions top left and top right have frontend circuits and wireless sensor circuits). Photograph: IMMS.

magnetic field and also the change due to relative movement are both very small. In the case of the structure with 4 cm³ of space, the dependency on height is clearly shown and thus on the relation between geometry and aspect. Where systems are somewhat flat, structure 11 can be seen to have clear advantages but for systems with substantial height structures 3 and 13 produce the best output.

Energy harvester structures manufactured to verify the tool

To verify the design following its computation, a variety of demonstrators were created with the relevant dimensions, the casings and coil cores were 3D-printed and the coils were wound. The energy harvesters thus made were characterised using a shaker to imitate the vibrations arising in plant and machinery, see Figure 6. To enable the mechanical and electrical transfer functions to be analysed separately, the displacement of the movable part was registered using a vibrometer. The description of the electrical output was produced on one hand from resistive load together with an oscilloscope and on the other from electronic frontend circuits (see examples for frontend circuits in Figure 5).

Figure 6: Measurement equipment for characterising the energy harvester using shaker and vibrometer. Photograph: IMMS.

Once the building block principle as developed has been fully implemented, the design tool is potentially a lever for efficient design of electromagnetic converters of vibration energy. Among the further developments needed will be extensions to permit the volume necessary for the energy harvesters to be calculated when the power output required is specified in advance.

The results of this work have been published in eight journals and presented at international conferences. It will serve as basis for continuing development of power supply in self-powered systems. A potential starting point for commercially viable developments based on the principles already established is, for example, the variety of excitation frequencies arising in particular applications, out of which the vibration converters will be required to generate power. IMMS is currently involved in supporting business partners on relevant applications.

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ESF EUROPE FOR THURINGIA EUROPEAN SOCIAL FUND
EUROPEAN UNION European Social Fund
Freistaat Thüringen Thuringian Ministry for Economic Affairs, Science and Digital Society

The Green-ISAS research group was supported by the "Land" of Thüringen and the European Social Fund under the reference 2016 FGR 0055. .

More on Green-ISAS at www.imms.de.

Own publications:

[1] **Influence of the design space dimensions on the power density of electromagnetic vibration energy harvesters**, B. Leistritz, *4th Workshop in Devices, Materials and Structures for Energy Harvesting and Storage, May 17-18, 2017, Oulu, Finland.*

[2] **Design Methodology for Application-Specific Electromagnetic Energy Harvesters,** B. Leistritz, W. Kattanek, *59th Ilmenau Scientific Colloquium, September 11-15, 2017, Ilmenau*

[3] **Systematischer Entwurf Plug-and-Play-fähiger Funksensoren mit Vibrations-Energy-Harvestern**, B. Leistritz, W. Kattanek, E. Chervakova, S. Krug, S. Engelhardt, A. Schreiber, *9. GMM-Workshop „Energieautonome Sensorsysteme" (EAS), February 28 – March 1, 2018, Dresden.*

[4] **Wireless Sensor System with Electromagnetic Energy Harvester for Industry 4.0 Applications**, B. Leistritz, E. Chervakova, S. Engelhardt, A. Schreiber, W. Kattanek, *Design, Automation and Test in Europe (DATE) Conference, March 19-23, 2018, Dresden.*

[5] **Efficient design of application-specific electromagnetic vibration energy harvesters for industrial wireless sensor systems**, B. Leistritz, *IDTechEx Conference and Fair, April 11-12, 2018, Berlin.*

[6] **Energieautarke Sensorsysteme für das IoT**, B. Leistritz, T. Hutschenreuther, *22. Magdeburger Logistiktage, „Logistik neu denken und gestalten", June 20-21, 2018, Magdeburg.*

[7] **Industry 4.0-type Wireless Sensor Application Powered by a Semi-automatically Designed Mini-scale Electromagnetic Energy Harvester**, B. Leistritz, F. Senf, E. Chervakova, S. Engelhardt, W. Kattanek, *International PowerMEMS 2018 Conference – December 4-7, 2018, Daytona Beach, Florida.*

[8] **Systematic comparison of basic structures for electromagnetic energy harvesters using an automated design methodology**, B. Leistritz, W. Kattanek, *International PowerMEMS 2018 Conference – December 4-7, 2018, Daytona Beach, Florida.*

All Green-ISAS publications: www.imms.de

StadtLärm

– monitoring noise pollution to support local authorities

Preventing excess urban noise is the focus of this new platform, which visualises the acoustic data it has sampled and analysed. Among the IMMS contributions is a central data turntable that serves all the components. Photograph: IMMS.

Objectives and overview

Bursts of noise pollution a challenge to municipal authorities

More on StadtLärm at www.imms.de

Noise pollution diminishes quality of life. People living in conurbations are subject to noise assaults of many kinds: sporting and other major events, building works or even individual moving vehicles. When local authorities give permission for events or building projects, they have a duty to consider noise issues and impose any necessary conditions. They have to ensure legal limits are not exceeded, check that conditions are met and deal with any complaints. It is common practice to take random samples of noise with equipment that meets the standard set by German legislation, TA Lärm, standing for the General Administrative Regulation with technical notes on noise. The sampling is relatively costly in terms of time and the deployment of field service staff.

Noise pollution monitoring to assist local authorities: a complete system

The StadtLärm (CityNoise) project has seen the development of a full new system which has been been on long-term field test in Jena, Germany, since the spring of

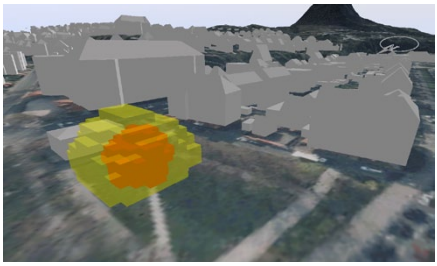

Figure 1:

Models made from noise in the surroundings using innovative software appear in 3D visualised form on maps of the city. It is possible to relate the measured data to specific events such as concerts for which permission has been given.

Source: Software-Service John GmbH.

2018. It is a system which anonymously and steadily logs noise-related data from a wide area, detected by sensors. Models made from noise in the surroundings using innovative software appear in 3D visualised form on maps of the city (in this case, Jena) or in graphs (see Figure 1). It is possible to relate the measured data to specific events such as concerts in the city centre for which permission has been given.

With the system, local authorities can observe not only the level of noise but also, using a web-based application, the type of event as classified by the system, by which they can better judge the source of any noise. They can consider both real-time and retrospective data for particular and/or longer periods. In addition, StadtLärm permits prediction of future noise from noise events of the past.

State-of-the-art machine learning is used by one of the partners in the project, Fraunhofer IDMT, to classify noise events. This classification goes beyond the level-based assessments of the TA Lärm standard. In contrast to other research projects concerned with noise pollution, the StadtLärm (CityNoise) system is specifically adapted to local authorities' administrative processes. Also, it takes account of arbitrary (as opposed to specific) sources of noise and of a noise level evaluation modelled on the TA Lärm standard. Furthermore, it is available as a robust, flexible, outdoor sensor solution based on an open, extensible software platform.

Components of the StadtLärm system

There are three overall components in StadtLärm: firstly, the **sensor platform** (a collection of a variable number of noise detectors) in which the hardware has been made by Bischoff-Elektronik GmbH and the software by IMMS and Fraunhofer IDMT. The second of the components is a **data service** provided by IMDT that processes, stores and keeps the data centrally available. The third of the components is the **StadtLärm application** for the end-user, created by Software-Service John GmbH.

More on sensor systems: www.imms.de

The three are linked by a **central "data turntable"**, which is more technically called a message broker. This uses as its protocol Message Queuing Telemetry Transport (MQTT), established for the Internet of Things. The broker enables the compo-

nents to exchange messages so that they can carry out their respective functions in a coordinated manner.

Among the IMMS contributions: the central data turntable serving all components

IMMS created the basic software platform for the noise detectors and integrated into it the pre-processing of audio data provided by IDMT. IMMS also developed the overall communications architecture of the platform and implemented the noise detectors' communications through the MQTT broker, work which included defining the communications structures and messages, providing and maintaining the broker, and establishing a central administrative component for the entire system. Additionally, the Institute integrated different types of environmental sensors into a subset of the sensors deployed in the field test, so that the platform would be even more useful and its extensibility would be demonstrated.

More on communications solutions at www.imms.de.

Details of IMMS' contribution

As the StadtLärm system was required from the first to become an open, extensible platform for possible use by different providers of information and other services, it was important to ensure that the system architecture be fully adequate and based on norms. To guarantee robust and efficient communications between the distributed components of such an open, extensible platform, the communications architecture was of central importance. It was for this reason that a broker was envisaged from the outset, as a sort of central turntable to pass the data between the components.

Also, to ensure proactive fulfilment of data protection requirements, an intrinsic Privacy by Design approach was taken. Any data that could betray personal details or identities is anonymised by pre-processing at the noise detector itself so that only abstract details, such as the noise level and the classification of noise events, are transmitted and further processed.

MQTT-based communications architecture

The choice for the broker-based communications fell on the open source standard known as MQTT (Message Queuing Telemetry Transport), which, as has been mentioned, is a protocol already much used in the Internet of Things. The advantages of broker-based communications are that access and permissions are administered centrally and that central monitoring of the communications is possible. Furthermore, every participant in this system is in physical communications with only one

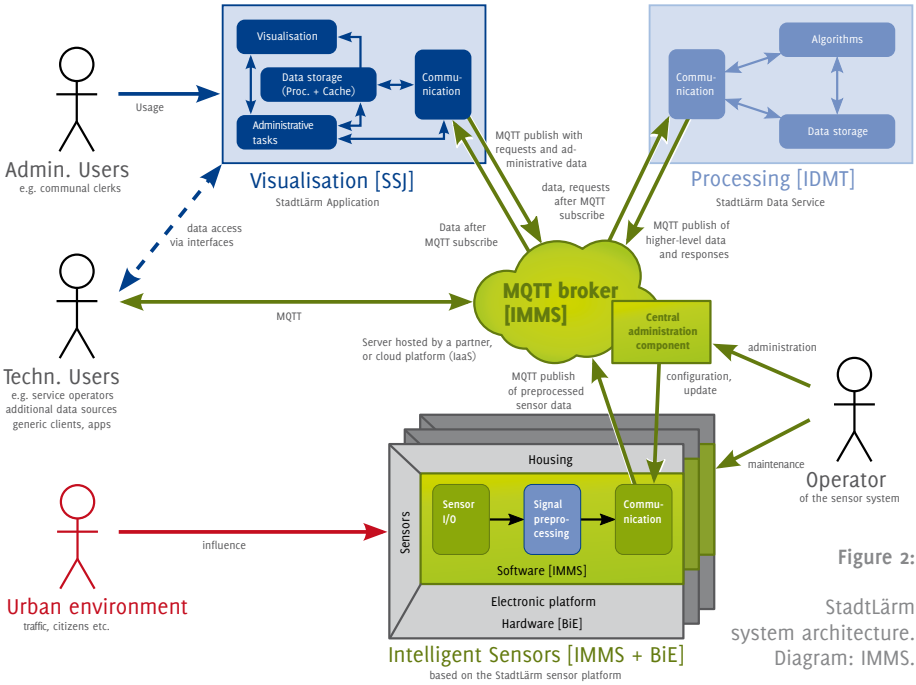

Figure 2: StadtLärm system architecture. Diagram: IMMS.

physical peer, the broker, and so never directly with other different components that potentially employ protocols of their own. MQTT has the additional advantage of being one of the less complex broker-based protocols, permitting ease of integration into even further components. An overview of the system architecture is given in Figure 2.

More on communications solutions at www.imms.de.

MQTT works through publication and subscription

Participants in the system use MQTT not to address their peers directly but to publish messages on what are called topics (news channels with ready-made names), to which other participants are able to subscribe as their means of receiving the messages. This principle is called Publish-Subscribe. For the communications to be efficient, it is crucial that the topics are set up in a hierarchical structure. In the case of this project, there were numerous negotiations which culminated in a final agreed hierarchy of topics. At the top level of the hierarchy, the topics are assembled according to system components: noise detectors, IDMT data service, admin component and StadtLärm application. Topics that are subsidiary to this level represent the individual content of a communication. If the complete system is extended to include new components, it will be possible for the hierarchy of topics to be extended, too.

IMMS' use of MQTT facilitates requests, e.g., for historical data

Because not all the communicative requirements are covered by the event-driven data processing that is enabled by Publish-Subscribe, IMMS has developed an additional convention enabling requests to be performed using MQTT. Topics denoted Request-Response in the hierarchy exhibit a fixed substructure on which both service provider and service user communicate according to a well defined regimen. The requests and responses are encoded as JSON (JavaScript Object Notation): requests have parameters and the responses have alternative attributes – result if successful or, on processing errors, error.

One example of how the Request-Response scheme is used is the retrieval of historical data from the data service, which is constantly receiving data from the sensors and storing that data. The end user can select a time period and will see the visualised details for that period after the application has requested them from the data service.

More on communications solutions at www.imms.de.

Noise sensor hardware

The acoustic sensors devised for the project are embedded systems from a custom-designed motherboard with a Raspberry Pi 3 Compute Module installed on it as processing unit. The systems are laid out in such a way that they can use mobile communications and remain very flexible in terms of where they can be sited. Thus they all have a mobile radio modem.

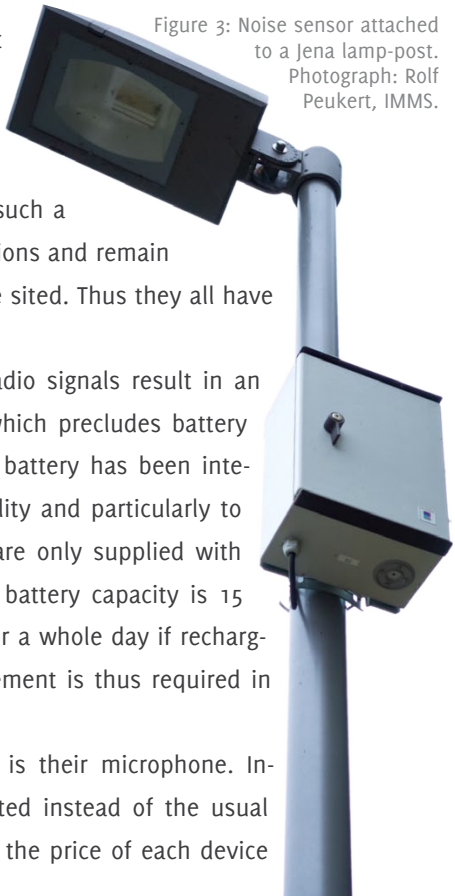

Figure 3: Noise sensor attached to a Jena lamp-post. Photograph: Rolf Peukert, IMMS.

The computing load and the mobile radio signals result in an average power draw of about 10 watts, which precludes battery operation over a long period. However, a battery has been integrated into the system to maintain flexibility and particularly to facilitate installation on lamp-posts that are only supplied with electricity at night (see Figure 3). As the battery capacity is 15 watt-hours, the system can be operated for a whole day if recharging takes place overnight. Battery management is thus required in both hardware and software.

At the detecting heart of the sensors is their microphone. Inexpensive MEMS microphones were selected instead of the usual costly measurement microphones, so that the price of each device

Figure 4:

Noise sensor with additional sensors for ambient conditions.

Photograph: Rolf Peukert, IMMS.

could be kept to a minimum. This approach has proved to be adequate for the quality of result needed.

A subset of the systems put to field testing was additionally equipped by IMMS with a weather station to detect environmental conditions (Figure 4). Data on weather are not only of interest to the city of Jena but are also relevant for the audio processing. The integrated weather station also underscores the platform extensibility in the light of future exploitation of the platform.

More on sensor systems: www.imms.de

Noise sensor software

It was the job of Bischoff-Elektronik as partner in the project to develop the noise sensors and encase them in weather-proof housing; it was the job of IMMS to provide the system and application software to run on this hardware and integrate the audio processing provided by IDMT.

More on system integration: www.imms.de

For their basic system, the noise detectors make use of **Embedded Linux** relying on the Raspbian distribution. IMMS carried out the adaptation, tailoring the kernel to the requirements of the project. The IDMT audio processing was fundamentally consonant with the platform, having been implemented in Python. Nonetheless, there were additional aspects to manage, such as communications links and remote maintenance.

It was therefore necessary for IMMS to implement an application-specific component capable of handling **MQTT communications**, obtaining the pre-processed data from the IDMT software, and transmitting them in near-real time. The component, implemented in **Go**, also communicates with the central administration component via

MQTT. It transmits status information periodically and is capable of remote configuration and instruction. It also captures and transmits environmental data in the case of sensors equipped by IMMS with additional environmental monitoring components.

Central administration components

When a system consists of a variable, possibly extensible, number of devices, all needing their data to be processed, monitored and configured, it makes sense to have a central administration component. IMMS therefore created one in **Java/Kotlin** using the **Spring framework**. The noise detectors register themselves with this central administration component. The admin component then maintains a directory of detectors in which not only their individual ID in the system but also other meta data like location and status are listed. The admin component publishes its data periodically using MQTT and also makes it available for access by request. For the field test, the admin component is being run on a server at IMMS, as is the broker.

System monitoring

To monitor the overall state of the system both in the field test and in later commercial use, the central admin component continuously stores information concerning the system state (such as the communications load on the broker) and the field devices (such as running time and battery charge) in an **InfluxDB** time-series database. The information stored in the database is then visualised on dashboards realised using the open-source software **Grafana**, see Figure 5. The dashboards allow intuitive insight into the current system state and hindsight into longer historical periods. Of particular interest is the charging or discharging behaviour of the batteries, or the stability of the mobile communication.

More on system integration: www.imms.de

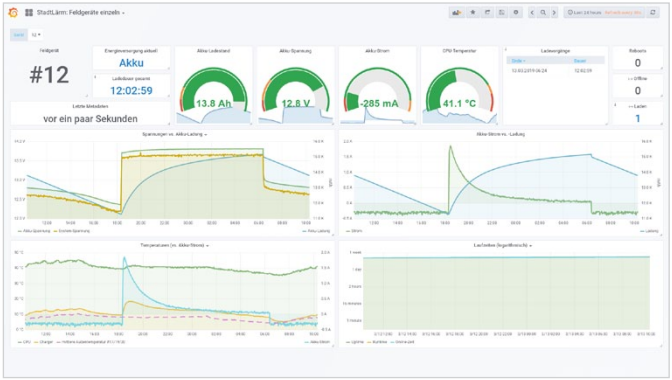

Figure 5:

Visualisation of the state of a noise detector on a dashboard.

Screenshot: IMMS.

Field testing

As of spring 2018, a pilot installation which contains the components and services described above has been in place on the Obere Aue and surrounding area in the city of Jena, Germany. The actual installation has 13 noise detectors, three of which are also equipped with environmental sensors. The software components on the server side are hosted by the respective partners in the project. The city's Environmental Development Department has access to the web-based StadtLärm software, gaining experience with the novel system.

Future prospects

The present laws in Germany do not permit a system such as that in StadtLärm to replace the established method of measuring at the point of immission. The system can, however, provide support that enables the labour-intensive measuring (which is done manually) to be better targetted.

At the time of publication of this report, valuable results are already coming in. The systems are proving stable in the field, the audio classification is of high quality and the end-users express approval. These results all offer a number of starting points for further work.

IMMS and its partners have received a number of inquiries from third parties who are interested in evaluating the system not only for the measurement of urban noise but also for a variety of different applications where noise level monitoring and acoustic event classification are required.

The system created will also, in future, act as foundation for noise pollution prediction based on previously recorded acoustic events. With the support of an appropriate model it is not unthinkable that, even during the event approval process, the potential noise pollution could be seen in simulation, such as a football match in the stadium which is due to coincide with a concert in a nearby park.

More on StadtLärm at www.imms.de

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All StadtLärm publications: www.imms.de

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

ZIM Zentrales Innovationsprogramm Mittelstand

The StadtLärm project has been funded by the Federal Ministry for Economic Affairs and Energy (BMWi) by resolution of a decision of the German Federal Parliament under the reference ZF4085703LF6.

fast wireless – inverted pendulum demonstrates new data transfer concepts for 5G

Operating the inverted pendulum which IMMS has created to demonstrate 5G data transfer concepts. Photograph: IMMS.

Objectives and overview

Today's mobile radio technology too slow to cope with many future applications

Real-time mobile data transmission is the basis for a variety of new applications. Examples of these applications are car-to-car communication, inter-machine communication and the "tactile Internet". All require the interaction of a large number of participants or, better, of sensors, which must have very short signalling times with delay (known technologically as latency) of only milliseconds, and data and signal connections that are so absolutely reliable that there are no outages. None of today's wireless technologies is up to these requirements. For example, the LTE (Long Term Evolution) standard was developed mainly for high data throughput.

"Fast wireless" worked on minimising latency in basic 5G technology

The "fast wireless" project, therefore, explored, developed and evaluated basic technology for fifth generation (5G) mobile communications with minimal latency so that mobile devices and control units can network in real time. A major focus was on developing transmission concepts that allow the principles of low latency and high reliability.

More on fast wireless at www.imms.de

IMMS' contributions to the future means of 5G communications

IMMS defined the requirements for real-time operating systems that will communicate by 5G, supported the other partners in the project on the specifications of suitable interfaces between the communications layers and developed components which will permit latency-critical elements to be partitioned into their hardware and software elements. The technology developed in the project has been used by IMMS in a demonstration model, applying the algorithms of the project partners.

As future machines or robots will be operating in closed-loop regulation systems to achieve process optimisation on the basis of data transferred by 5G, IMMS has cooperated with Dresden University of Technology to create an inverted pendulum demonstrating the principle. The pendulum shows that a 5G wireless signal route with minimal latency is, indeed, essential for such new applications but also that all the hardware and software in the system must be configured to work in real time.

More on communications solutions at www.imms.de.

Control of an inverted pendulum with low latency data transfer demonstrates the new principles for 5G

The aim of the system is to maintain the vertical orientation of the pendulum in its state of unstable equilibrium. The pendulum is 9 cm long and stands upright on a 0.2 mm narrow edge on a moving linear axis, see Figure 1. To ensure it stays in its orientation and position, the pendulum is observed by a camera. To keep it actively in balance, its angle is constantly communicated by wireless in real time to the control system of the axis, using the new 5G mobile radio standard. The data would arrive too late if technology currently in use, such as LTE, were used: the pendulum would fall over. The latency of the data transmission in the IMMS demonstrator is with just 100 µs per data packet well below the target of 1 millisecond required for the 5G standard.

IMMS has thus done more than implement a complete prototype system with its new algorithms and communications components; more than show a practical application of low-latency communications in cellular radio. It has also provided a clear demonstration of the significance of low latency for the benefit of an audience unfamiliar with the subject.

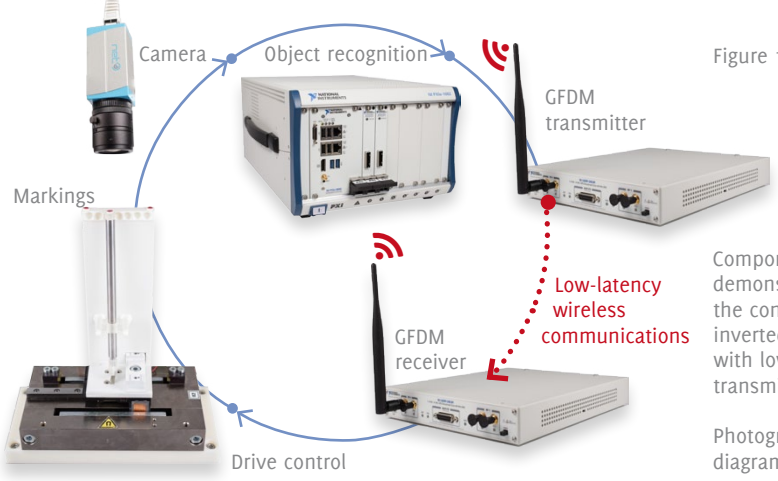

Figure 1:

Components of the demonstrator for the control of an inverted pendulum with low-latency radio transmission.

Photographs and diagram: IMMS.

The IMMS solution in detail

5G requirements, real-time

Latency, the time that signals spend travelling, is a crucial factor in real-time communications. The latency in UMTS networks (also known as 3G) is around 100 milliseconds and that in LTE networks (4G) around 30 milliseconds. In comparison, the latency to which 5G networks aspire is, at 1 millisecond, extremely brief. This means that if a data packet is sent using 5G on layer 4 (the transport layer) of the OSI reference model for the network protocols (TCP), the data packet must arrive on layer 4 of the target within a single millisecond.

Design of the demonstrator

As the movable linear drive on which the pendulum is standing freely has the capability to achieve very high acceleration on one of its spatial axes, control of its movement must be appropriately fast. To be able to calculate the angle of the pendulum a red marking was applied to its top and to two other fixed points in its vicinity. The tilt of the pendulum is registered from above by means of a camera. Image data from this camera is transmitted via Gigabit Ethernet to an embedded controller running the object detection algorithms. The tilt angle calculated in this manner is communicated wirelessly to a control unit whose job is to keep the pendulum vertical by moving the linear drive (Figure 1). Two GFDM units (reception and transmission) are used for the wireless transmission of the data. GFDM (Generalized Frequency Division Multiplexing) operates with a waveform similar to that of 5G.[1]

1 *Details in: N. Michailow et al., "Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks," in IEEE Transactions on Communications, vol. 62, no. 9, pp. 3045-3061, Sept. 2014, DOI: 10.1109/TCOMM.2014.2345566.*

Latency demands of the demonstrator

The propagation time for the signal, or latency, has a direct influence on the stability of the control system. If the latency is too long, the controller becomes unstable and the equilibrium of the pendulum cannot be maintained. The total latency is composed of various parts: the captured image has to be digitised within the camera, buffered and transmitted to the embedded controller by Gigabit Ethernet. At the controller, the data packets have to be received and the object detected. The result of this computation are the coordinates of the three markings. The coordinates are forwarded to the GFDM transmitter, which is implemented in a programmable hardware component, an FPGA (Field Programmable Gate Array) belonging to the USRP (Universal Software Radio Peripherals). Then the coordinates are transmitted through a wireless link to the second USRP of the receiving unit. After this, the data is transferred by wire to the linear drive controller. To maintain the pendulum in its verticality on the drive being used, a total delay of approx. 22 ms must be kept.

Real-time operating system

To ensure that the demanding real-time conditions would be met by the demonstrator, a Linux real-time operating system was implemented on the embedded controller. This makes it possible to run all the stages of the communications stack and the various other software components in a deterministic way. Furthermore, using typical methods of a real-time operation system (f.e. tracing), latency measurements were carried out, to characterise and optimise the real-time performance of the embedded controller.

More on communications solutions at www.imms.de.

Object detection

To find a suitable **algorithm** for detecting the pendulum position, IMMS worked from theory and experiment on a variety of standard procedures employed in image processing. The choice fell on the following three variants.

1. **Feature detectors** for example, BRIEF (Binary Robust Independent Elementary Features), ORB (Oriented FAST and Rotated BRIEF), MSER (Maximally stable extremal regions): with these, features extracted from a reference image are found by the algorithm in the current image independently of the difference in coordinate transformation (scaling, rotation, displacement). The position of the pendulum is established from the transformation of the original feature vector as compared with the current image.

2. **Hough circles:** the edges of circular marks in the experimental setup are found by the Hough transform method. Their position serves as the starting point for measuring the pendulum deflection.
3. **Colour filter:** marking points in the same colour at various points in the experimental setup are selected by means of appropriate filters. Their position serves as the starting point for finding the pendulum tilt.

The runtime of these algorithms was empirically determined using various examples. The colour filter algorithm was selected on the basis of the test results and its easy implementation. Only colour markings of the pendulum setup at the points relevant to position and angle detection are required.

For **image data transfer** and camera configuration IMMS used a library from the Aravis project.[2] This library is part of a FOSS (Free and Open Source Software) project providing means to access industrial network cameras made by different manufacturers in a generic way. It proved to be a useful tool for configuring the camera and the image data transfer.

IMMS created a **graphic user interface** for configuring the object detection algorithms. For this the QArv[3] program was used as basis and extended accordingly. Relying on the Aravis library, this program provides access to the camera used for the demonstrator and its parameters. It also allows to apply simple image filter functions, capture single camera frames or record and store the complete video data stream.

Using functions of the OpenCV[4] image processing library, IMMS implemented an add-on filter for QArv which is used to determine the **pendulum position**. The basic steps in getting the position from the colour marking points on the pendulum are as follows:

1. transformation of the camera image from RGB to HSV colour space,
2. filtering of the image content through threshold value (minimum and maximum) filters – on the parameters hue, saturation and value,
3. optional transformation (erode-dilate-erode) to minimise interference.

2 *https://github.com/AravisProject/aravis*
3 *http://www.ad-vega.si/en/software/qarv/*
4 *https://opencv.org/*

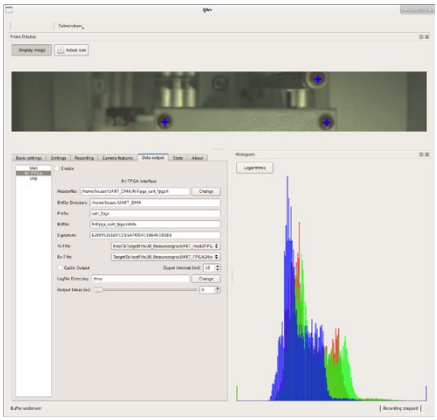

Figure 2: Main QArv window with the coloured markings detected by the filter algorithm. Screenshot: IMMS.

During runtime the parameters for all these stages can be adjusted on the graphical user interface and then stored. This helps for instance to quickly adapt the demonstrators setup under changed lighting conditions. In addition, the live camera feed can be displayed at various interim stages of the image processing. This allows to observe the effects of changes to individual parameters more exactly. Figure 2 shows the main QArv window with the colour markings detected by the filter algorithm.

System simulation and controller design

In order to establish certain parameters for the mechanical construction and to test whether the timing conditions for the wireless data transfer could be met in theory, the setup was simulated at IMMS as a classic feedback loop model. This simulation was used to calculate the maximum allowed dead time for the controller input values which occur during image processing and image data transfer. Also, the for a stable operation required minimum controller cycle frequency (which corresponds to the cameras frame rate in the demonstrators setup), was calculated using this way.

More on open/ closed-loop controls at www.imms.de.

As the drive has only a short travel distance of 68 mm, it was only possible to use a relatively short pendulum: 90 mm. The result was a pendulum in almost constant movement.

The first step was to correct the geometrical imaging error due to the curvature of the camera lens. This imaging error is computed using a third-order polynomial. Correction computation gives the angle at a resolution of ≈0,04°, accurate to ±0,2°.

The **control algorithm** was implemented on a 32-bit fixed-point microcontroller. It was a challenge to establish suitable control parameters for the system. The highly dynamic pendulum and the short travel distance demanded very rapid reaction on the part of the control system on pendulum movement. However, the camera has a relatively low frame rate and so the sampling rate for angle measurement has a maximum frequency of 150 Hz. Also, the latency of 20 ms plus jitter constitutes a considerable impact on the speed of controller reaction.

Figure 3:
Equipment created at IMMS to demonstrate the inverted pendulum, including casing and integration of all control parts. Photograph: IMMS.

Under the conditions here described, the usual methods of designing robust control systems, such as pole placement or linear-quadratic regulation (LQR) could not be applied. Thus an iterative experimental approach to determine the necessary control parameters was used.

Implementation and setup

The next stage was to implement the radio transmission and test it. These tasks were shared with Dresden University of Technology, a partner in the project. To achieve the necessary start-to-finish short latency, it is also essential to ensure that the radio interface used is one with the lowest possible latency. The framework used must support small data packets and the modulation and demodulation must work with a minimum of delay.

The GFDM implementation developed at Dresden University of Technology operates in a bandwidth of 20 MHz and with packets lasting a mere 16 µs. As such it is highly suitable for low-latency transmission.

In contrast to the CP-OFDM wave form of 4G, GFDM supports short symbols, while at the same time greatly reducing out-of-band interference. The increased design space enables waveform parameters to be set for a wide variety of scenarios. The simple modulation and demodulation achieves latency of less than 100 µs per data packet and this was sufficient to maintain the pendulum in its state of unstable equilibrium. The GFDM physical layer was implemented in the software-defined radio system (SDR) of National Instruments.

For the physical equipment, a casing was designed and made. To improve illumination, LED lighting was integrated and a domed plexiglass cover under which all the control components were kept was created.

Conclusions and Outlook

The demonstrator proves that it is feasible to achieve wireless, highly reliable, extremely low-latency communications for applications with a closed-loop control system; in this case maintaining an inverted pendulum in its constant state of unstable equilibrium by means of a movable linear drive, object recognition and suitable control algorithms.

The 5G mobile communications standard will be a vital factor in progress towards smart manufacturing. In this project, IMMS has gained vital knowledge concerning the use of low-latency wireless communications in closed- and open-loop control of machinery and plant. The Institute can now incorporate this knowledge into industrial applications for SMEs and in possible new areas such as agriculture.

More on fast wireless at www.imms.de

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As part of the *fast* cluster project, the *fast wireless* project is funded by the German Federal Ministry of Education and Research (BMBF) in its "Twenty20 – Partnership for Innovation" programme under the reference 03ZZ0505J.

fast wireless publications: www.imms.de

RESEARCH SUBJECT

INTEGRAED SENSOR SYSTEMS FOR BIOLOGICAL ANALYSIS AND MEDICAL TECHNOLOGY

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ECSEL Joint Undertaking

In the ADMONT* project, IMMS has developed a modular RFID transponder chip that collects data on air pressure, humidity and temperature via connected commercial individual sensors with standard interfaces and sends them contact-free to an NFC-enabled RFID readout unit. The batteryless RFID transponder chip and the sensors are powered by the reader's energy field. In addition to bioanalytical applications, a variety of other sensor application scenarios are possible. IMMS has developed an app for Android smartphones to read the measurement data. Photograph: IMMS.

Research subject "Integrated sensor systems for biological analysis and medical technology"

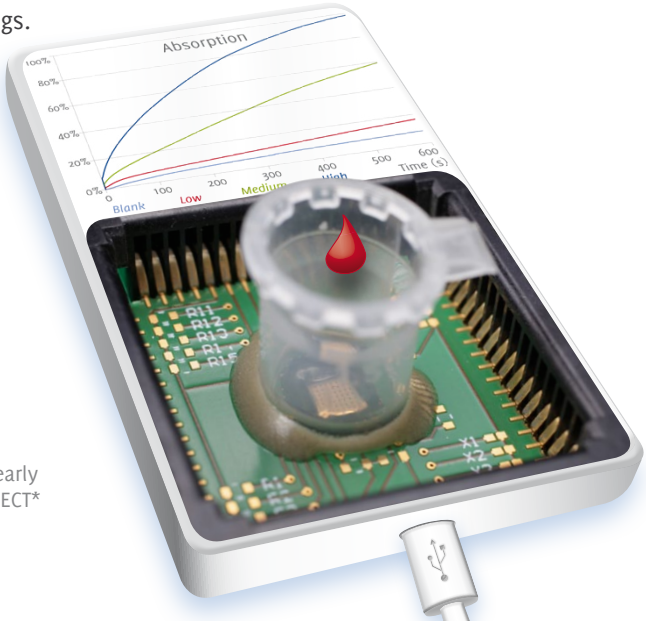
Increasing life expectancy in our societies lead to a rise of serious diseases such as cancer, cardiovascular disorders and dementia and to a growth of related expenditures for diagnostic analysis and therapy. Our research on microelectronic biosensor systems for medical diagnostics and personalised medicine contributes to reduce health service costs and to improve patients' quality of life.

Photograph: IMMS.

IMMS applies a variety of sensor principles to the simultaneous detection of different biological and chemical measurands with the help of one integrated electronic device so that diagnosis is more conclusive and less prone to error.

The work is based on familiar (and thus relatively inexpensive) standard semiconductor manufacturing processes which are adapted to new approaches and specific applications by means of particular functionalisation of surfaces and the use of biocompatible material. Our solutions should pave the way to conduct fast, reliable, cost-efficient and automated point of care tests, such as cancer screenings.

Projects in this field at www.imms.de.



Concept sketch of a mobile point-of-care diagnosis system.

The module containing PCB, ASIC and reservoir has been incorporated into the experimental setup for early cancer diagnosis in the INSPECT* project.

Diagram/photograph: IMMS.

Highlights of 2018 in our research on integrated sensor systems for biological analysis and medical technology

ADMONT* – passive RFID transponder chip as flexible bridging interface for biosensors

Working in the ADMONT project, in 2018 IMMS concluded its development of a passive NFC-enabled RFID transponder chip (NFC: near field communications), which can act as a flexible bridge interface for a variety of bio-sensors. Passive RFID transponders receive their energy wirelessly from the reader and any interfaced sensors can also be operated with this energy. This makes them an attractive solution for battery-free wireless sensor systems in diagnostic applications. Thanks to its compatibility with the NFC transmission standard, measured values can also be read and evaluated directly with smartphones and other mobile devices.

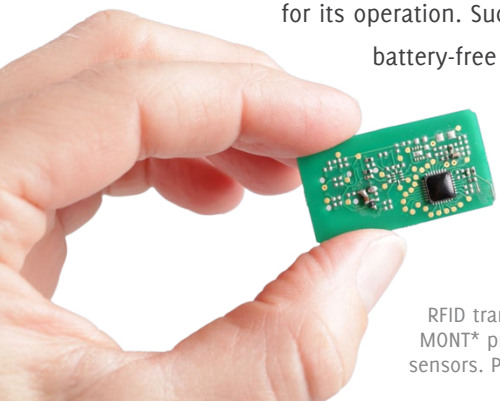
RFID transponder chip for diverse life science applications

With the RFID chip developed by IMMS, life science applications, including point-of-care diagnostics, can become faster and more cost-effective. This also applies to the laboratory automation process, where temperature, pressure and humidity have to be monitored in real time to ensure sample quality under stable environmental conditions.

More on RFID in ADMONT at www.imms.de

There exists a need for developing flexible and energy-efficient transponder architectures

IMMS developed its RFID chip because although there did exist optimised RFID chips with integrated sensors for particular uses, they were not flexible enough for use in wide application scenarios. Additionally, there exist commercial RFID chips to which individual sensors can be connected, but these solutions require microcontroller for its operation. Such solutions are frequently unsuitable to battery-free RFID tags as the microcontroller takes up the majority of the energy (about 100 µA/MHz) which is supplied by the reader, leaving only very little for the sensor operation.



RFID transponder chip developed by IMMS in the ADMONT* project for battery-free operation of commercial sensors. Photo: IMMS.

Flexible RFID sensor-transponder chip as bridge between NFC and I²C

The IMMS RFID chip supports a variety of commercially available digital I²C sensors with varying power needs. It can supply a regulated voltage for external sensors of up to 2.2 V with maximum current of 10 mA. No microcontroller is required to support the read/write operations with the sensors. This reduces the power consumption of the whole system and the number of external components required to build an RFID sensor-transponder.

INSPECT* – development of an opto-electronic CMOS biochip for quantitative detection of prostate cancer

Against the background of the preliminary investigations carried out in 2016 and 2017 under the INSPECT project, IMMS in 2018 finished developing an opto-electronic ASIC (application-specific integrated circuit) for quantitative diagnostics in prostate cancer and developed a prototype with metrological components for use in mobile point-of-care measuring instruments. The design of the system is such that quantification is possible with even less than a nanogram of the suspect antigen per millilitre.

More on RFID in ADMONT at www.imms.de

Details & video on INSPECT at www.imms.de

Target: rapid, early testing for cancer with exact quantification

There are certain types of cancer for which the patient's doctor could well test rapidly on the spot, avoiding the need for costly, time-consuming lab tests. The rapid diagnostic tests in common use only give a qualitatively "yes" or "no" answer. Perspectively microelectronic-based rapid tests shall give doctors quantitatively precise diagnostic information with as little effort as the merely qualitative test strips. The precise quantification has so far involved sending in samples to laboratories that

IMMS has developed an opto-electronic CMOS biochip and a test system for the quantitative detection of prostate cancer.

Photograph: IMMS.

have major, complex equipment. If prostate cancer is to be diagnosed at a very early stage, concentrations of PSA (prostate-specific antigen) at around one nanogram per millilitre need to be detected. Although the presence of PSA may be an indicator of cancer, it is constantly being produced in the male body. It varies in concentration as men age and if they are suffering from infections or mechanical irritation. Continuous personalised PSA monitoring enables reliable early diagnosis and an early start to treatment.

Initial experiments with microelectronics and a mobile test system as background to chip development

Together with its business partner Senova, IMMS has developed a microelectronic-based functioning prototype system for early diagnosis of prostate cancer. The system serves to investigate parameters significant for cancer screening and to provide exact data on irradiance and particle concentration in patient samples. At the heart of the prototype is a chip previously developed by IMMS for proof of the existence of infections. Using this functional model, the partners had already carried out investigative experiments in various stages to lay out the INSPECT ASIC and had shown in 2017 that the presence of nanoparticles of gold in the tiniest of quantities and with minimum measurable optical density of 0.009 bel could be proved by means of opto-electronic analysis. These particles are commonly employed in diagnostic procedures to render bio-markers visible and thus optically detectable.

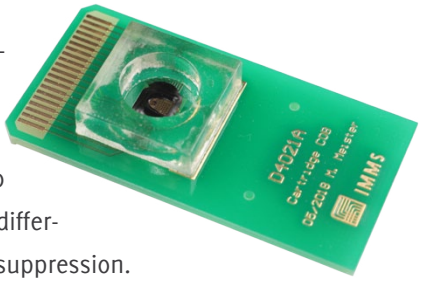
Details & video on INSPECT at www.imms.de

Development of an opto-electronic CMOS biochip after the preliminaries

It is on the basis of this work and other investigations that IMMS has laid out the ASIC to be applied specifically to cancer screening. In particular, close attention has been paid to signal processing where there is only a tiny differential between signals; also to efficient noise suppression.

The aim was for the system to cover an optical density measuring range between 0.01 and 1 bel, so that it would be possible to analyse antigen present at less than 1 ng per ml.

IMMS developed an ASIC specific to this purpose which was manufactured in 2018. The chip is smaller and more cost-effective than that used in the initial experiments



INSPECT ASIC developed in 2018 for cancer diagnostics. Samples are put directly on the chip in a cartridge which is plugged into a device connected to PCs for further analysis.

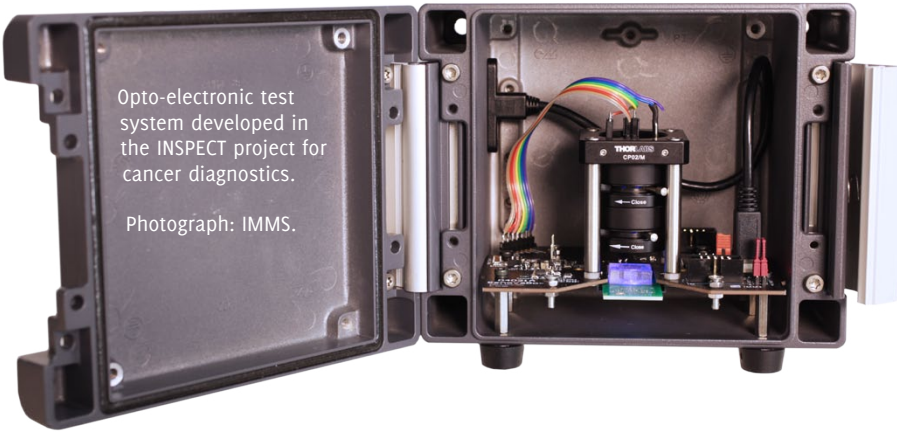
Photograph: IMMS.

and the new chip architecture permits yet more exact measurements with less noise. The ASIC developed also includes an Analog-to-Digital-Converter (ADC) for the initial processing of the measured analogue values. This simplifies the ensuing signal processing and facilitates standardised output to data processing systems. Digitalised signals from the measurements make them less vulnerable to external interference.

For the opto-electronic measurements of the biochemical reaction of PSA, IMMS has developed a compact, mobile, light-proof box device which can be connected by USB to a PC or laptop. From the computer, the software created by IMMS enables the test to be controlled and the results to be shown and further processed. The sample is inserted into the reaction chamber situated above the ASIC, and both are plugged into the circuit board as a cartridge. Control of both ASIC and LED unit is carried out on the circuit board. 3 LEDs with different wave lengths produce homogenous illumination at a fixed distance from the chip. They illuminate the sample at constant luminous intensity for the duration of the test.

IMMS' partner in the project, SENOVA, has undertaken the functionalisation of the chip surfaces for immobilised PSA antigens and has already carried out analyses of samples with various concentrations of PSA. If PSA is present in the sample, this is proved because biochemical reactions cloud the sample to an extent that varies with the concentration. The clouding is analysed opto-electronically from the brightness scale. The development of the chip and the results obtained from biological samples will be published in detail on conclusion of the project in 2019.

Details & video on INSPECT at www.imms.de



Opto-electronic test system developed in the INSPECT project for cancer diagnostics.

Photograph: IMMS.

MEDIKIT is a project in which IMMS is developing the microelectronics for a modular, mobile diagnostic aid enabling early recognition of common modern illnesses by measuring fluorescence on a time-resolved basis. One of the designers is shown busy on chip design. Photograph: IMMS.

EFRE EUROPE FOR THURINGIA EUROPEAN REGIONAL DEVELOPMENT FUND

EUROPEAN UNION

Start of MEDIKIT* – mobile diagnostic systems for diseases of our time

The earlier and the more reliably cancer and heart failure are diagnosed, the greater are the chances that treatment will be successful. Between them, cancer and heart failure caused one in four of all deaths in the EU in the years 2011 to 2016. Against this background there is an urgent need for new, efficient methods of early diagnosis.

IMMS has been working since April 2018 in the MEDIKIT joint project which aims to advance such early diagnosis with quantitative analysis for each individual patient. The IMMS focus is on portable modular systems. The goal is to produce a device which can rapidly detect the relevant biomarkers and will work in the general practitioner's surgery without any additional reagents, devices or materials. IMMS' project partners Senova GmbH and oncgnostics GmbH are providing the molecular and immunological methods for the detection of various biomarkers by special assay designs.

IMMS working on sensors for time-resolved measurements of fluorescence

The measurement takes place using an integrated opto-electronic sensor system developed by IMMS which captures the time-resolved fluorescence. The samples requiring analysis are placed directly onto the microelectronic chip, to which the bio-marker or markers are bonded selectively. The fluorophores which are part of the markers are subjected to light excitation, emitting photons for the chip to detect. The time-resolved fluorescence measurement technique is applied to the emission that follows cessation of the excitation. Because the method enables details of even the weakest of light sources to be quantified, the sensor works with extremely high sensitivity. This sensor system is being integrated into a cartridge device by another of IMMS' partners, ALS Automated Lab Solutions GmbH in Jena.

MEDIKIT at www.imms.de

Lecture given by Senova and IMMS at the CiS/IMMS workshop "New Sensor Solutions for Biology and Medicine", Erfurt, 23rd October 2018.

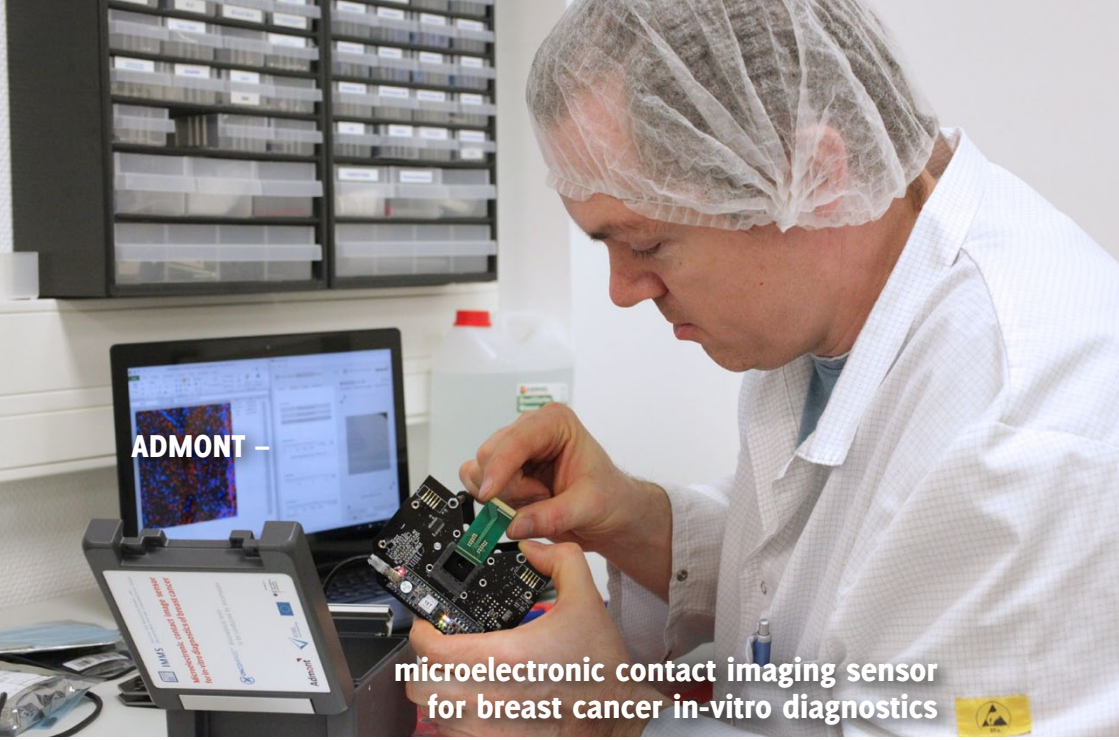
Photograph: IMMS.

CiS/IMMS workshop on New Sensor Solutions for Biology and Medicine

Thirty representatives from science and industry brought their interest in new sensors and technologies for application to biology and medicine with them to a workshop on 23rd October, 2018. It took place at the invitation of CiS and IMMS for an exchange of subject knowledge. Presentations were given by representatives from a number of companies and institutes involved in research: CiS research institute (CiS Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH), FhG Institute for Applied Optics and Precision Engineering of Jena, the Fraunhofer project centre for microelectronic and optical systems in biomedicine, the company getemed (sic) Medizin- und Informationstechnik AG, IMMS, and the enterprises oncgnostics (sic) GmbH und Senova Gesellschaft für Biowissenschaft und Technik mbH.

The subjects extended from sensor systems acting in invasive or non-invasive medical situations, point-of-care diagnostics, cell analysis and lab-on-chip possibilities. They shed light also on sensors for vital signs, detectors based on scattered light and fibre optics, the investigation of germs and pathogens, and optical monitoring of archaea in biogas generation plant. IMMS and Senova together spoke of their joint development, creation and testing of a photometric system which relies on a CMOS sensor array for fast, reliable, point-of-care diagnosis in cases of prostate cancer. Together with another partner, oncgnostics, IMMS presented the microelectronic sensor system and procedure they have together created to catch uterine cancer early, in a fast and reliable routine.

More events at www.imms.de



IMMS has developed an opto-electronic testing system to enable precise diagnosis of breast cancer. The prototype is currently being employed by Oncompass Medicine Hungary Ltd. for investigations using cell samples. Photograph: IMMS.

Objectives and overview

Video on the ADMONT system: www.imms.de

Breast cancer is the disease with the highest number of new cases and the highest mortality rate among women worldwide.[1] The more precisely the various types and stages of breast cancer can be differentiated, the better can effective treatment be found and the risks related to treatment be reduced. For example, active pharmaceuticals can be prescribed that block the multiplication of cancer cells[2] by inhibiting the growth factor receptor HER2[3].

HER2 is a protein present on the membrane of every healthy breast cell. However, in the case of 20 – 30 per cent of carcinomas[4] it is present in very high quantities and stimulates an increased growth of the cancer cells. The more HER2 protein is present, the greater is the efficiency of the medication. If there is little HER2 protein present,

1 *https://doi.org/10.3322/caac.21492 (Figure 7)*

2 *www.krebsinformationsdienst.de/tumorarten/brustkrebs/moderne-verfahren.php.*

3 *HER2: human epidermal growth factor receptor, https://www.krebsinformationsdienst.de/tumorarten/brustkrebs/diagnostik.php#inhalt25.*

4 *DOI: 10.1056/NEJMp058197.*

the treatment is inefficient but still causes its serious side effects. This makes it very important to determine in each individual patient what is the level of HER2 before deciding how to proceed with treatment.

Classic detection methods for HER2 protein do not always provide a clear basis for therapeutic decisions

The primary examination of tissue samples taken from cancer patients to determine whether the protein is over-expressed is relatively simple and inexpensive: the procedure is called immunohistochemistry (IHC).

The HER2 proteins are stained and then examined by experts under the microscope. The classification of the samples usually reflects the extent and intensity of the colour in the four levels: none, weak, moderate, and strong. The classification will depend on the observer and may vary from laboratory to laboratory.[5]

Treatment, which is expensive and frequently associated with major side effects, is usually prescribed only for cases in the "strong" group. The "moderate" and "weak" results are not usually decided upon before there has been further analysis. This entails FISH (fluorescence in-situ hybridization), a much more complex but also much more exact, gene-based sampling method that addresses the cause of the increased production of HER2.[6]

Microelectronics to be used to quantify HER2 protein presence in a single step procedure

The disadvantages of the classic HER2 testing carried out during diagnosis of breast cancer are not only the fact that more than one stage is involved in cases of doubt (involving the delay and expense of two procedures) but also the fact that the first stage, which is applied to every tissue sample, is a subjective, not so far quantifiable, visual classification.

In the ADMONT research project, therefore, the aim has been to determine the quantity of HER2 protein present in a rapid, definitive and reliable manner using an inexpensive opto-electronic method. IMMS has developed for the purpose a microelectronic testing system for in-vitro diagnostics in the laboratory. The system visu-

5 *https://www.breastcancer.org/symptoms/testing/types/ihc*

6 *„Untersuchung der Expression des Onkogens HER2 beim Mammakarzinom" J.-P. Rey, S. Fournier, C. Duc, C. Girardet, ZIWS; M. Stalder, CONSILIA, Sitten*

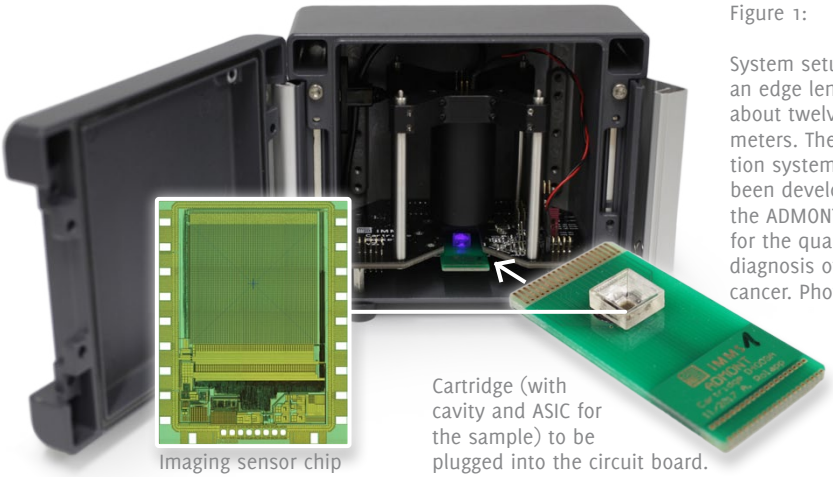


Figure 1:

System setup with an edge length of about twelve centimeters. The detection system has been developed in the ADMONT project for the quantitative diagnosis of breast cancer. Photographs: IMMS.

alises all the IHC levels relevant to treatment choices and is capable of recognising differences in luminance produced by different quantities of stained HER2 protein for each cancer cell in a fluid sample. The number of HER2 proteins can vary in this procedure from a very few to several million.

The prototype which has been developed (Fig. 1) can be used for both fluorescence-based and absorption analysis. The cell samples and the associated marker substances for the HER2 are analysed using contact imaging, having actually been applied directly onto the surface of the imager-chip in a fluid reservoir (cavity). There is no need for an extra optical system such as lenses and filters. The chip has been designed by IMMS to respond to very weak light signals. It is positioned on a plug-in module that can be pushed into a PCB. The PCB is inside a light-proof box containing an extinction LED. The box has an USB interface for connection to a PC and is controlled from a graphic user interface which enables the data to be evaluated or forwarded to alternative evaluation software.

More on system integration: www.imms.de

More on chip developments: www.imms.de

The prototype is currently being employed by Oncompass Medicine Hungary Ltd. (partner in the ADMONT project), for single-stage investigations quantifying HER2.

The IMMS solution in detail

Principles of the biochemical analysis

The design of the optoelectronic system for detection of the over-expression of HER2 in breast cancer cells is based on well established analytic methods.

In the case of IHC there are different detection approaches. In immunfluorescence, which is one variant of IHC, the HER2 is recognised by means of specific antibodies and rendered visible by means of appropriate fluorophores. Experts assess the degree of colouration under the fluorescence microscope. This involves using light of particular wavelength to excite fluorescent markers, which then emit light of different wavelength, thus producing the image. Colour filters in the microscope prevent the stimulus light reaching the image displayed.

Another established HER2 analysis method is based on enzymes (for example HRP) which change a substrate to a coloured product in a reaction controlled by the enzymes. The colour molecules alter the absorption properties of the sample and are evaluated under the microscope.

Essentials of electronic system, analytic procedure

Design of the system for fluorescence analysis

The mobile testing system developed at IMMS has been designed for the requirements of fluorescence analysis but it is equally suitable for analysis of light absorp-

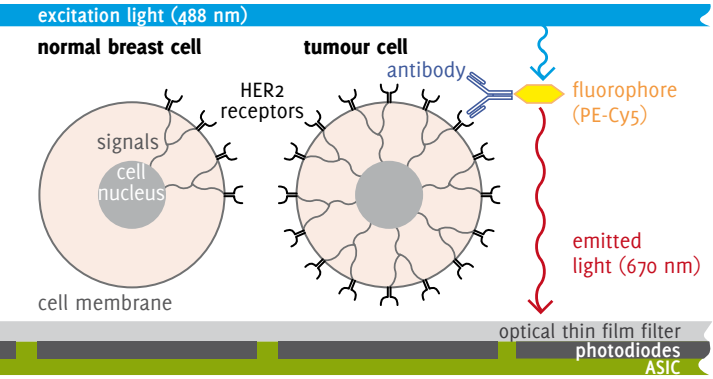


Figure 2:

Proof of over-expression of HER2 proteins using fluorescence markers.

Diagram: IMMS.

tion. It can therefore be used for both IHC approaches. Samples containing individual breast cancer cells are prepared with fluorophores or enzymes and investigated on the principles of the biochemical analysis procedures described above. Instead of the (fluorescence) microscope, the less expensive opto-electronic measuring system (see Figure 2) is used to quantify the HER2 proteins present.

In the case of fluorescence-based detection Oncompass Medicine has selected the fluorophore PE-Cy5 for the bio-analytical tests. This substance is subjected to excitation by the LED in the mobile testing system with a light of wavelength 488 nm

and in response it emits light at wavelength 670 nm for the analysis. In order to block the excitation light and separate it from the emission light used for measurement purposes, a thin-film optical filter is to be deposited directly on the chip surface by a service provider. The light emitted by the fluorophores is detected by the photodiodes on the chip. The light intensity provides information about the concentration of the fluorescent markers and thus about the HER2 proteins.

Use of the system for absorption analysis

The optoelectronic analysis system can detect very fine differences in brightness and is thus also suitable for investigation of biomarkers or analytes based on light absorption.

For its investigations on absorption-based analysis with the opto-electronic system Oncompass Medicine selected the enzyme AP (alkaline phosphatase). The HER2 proteins labelled with AP induce a colour reaction after addition of a substrate, darkening the chip surface with a purple precipitate. The so prepared samples are placed in the system's cavity around the imager chip and illuminated by the LED. If the appropriate reaction takes place in the sample, the staining substances on the chip can be detected. The result is compared with reference measurements from samples without cells and from samples with unlabelled cells and from this can be derived the concentration of analyte or biomarker indicated by the colouration.

More on system integration: www.imms.de

Chip architecture

At the heart of the system is a newly developed **CMOS imaging sensor** which has been optimised specifically for the demands of contact imaging in bio-analysis applications. The integrated circuit has a resolution of 64x64 pixels with pixel size of 25 µm, the average diameter of the tumour cells. For the semiconductor technology, the 350-nm process XH035 made by X-FAB has been employed.

The more than 4000 pixels supplied by the chip can deliver statistically significant statements on more than 4000 tumour cells. The chip is optimised for extreme sensitivity at very low luminance, with low noise while imaging. The optical signal from the cells is collected by the photodiodes of the pixels, converted into an electrical charge, integrated, amplified and then converted from analogue to digital.

More on chip developments: www.imms.de

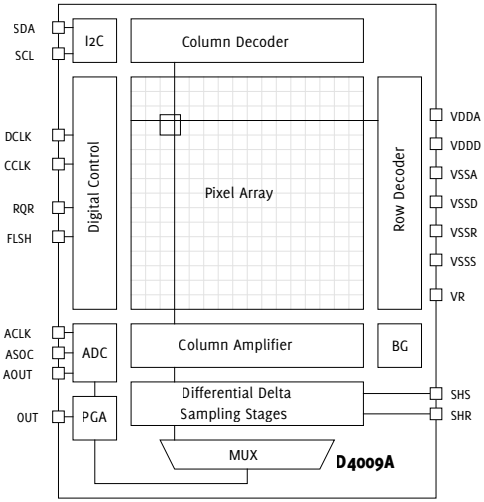


Figure 3: schematic circuit diagram of the imaging sensor. Diagram: IMMS.

Figure 3 shows the schematic diagram for the imaging sensor circuit. Besides the actual imaging field and driver circuit, the overall circuit contains the sampling stages for the intermediate storage on the clipboard of the output signal from the pixels, an adjustable signal amplifier (PGA) for low-noise pre-amplification of the signal and finally an integrated 12-Bit SAR ADC. The chip is also provided with an I²C interface for configuration purposes and a band gap (BG) to enable internal reference voltages to be generated.

A special feature of the circuit architecture is the **distributed pixel amplifiers** which achieve the necessary sensitivity for analytical applications, with detailed differentiation at low light intensities and, at the same time, almost no imaging noise. To reach this goal, the pixels of the conventional 3T-pixel topology (which works without feedback) have been extended by a complete back-coupled amplifier. This amplifier has been divided pixel-wise into differentiation pairs, and column-wise into a folded-cascode amplifier.

To ensure high signal quality, the chip employs a minimal **digital control unit**, so that there is as little disturbing activity as possible on the chip while the imaging is taking place. Such activity might interfere with the output signal. The imaging process is thus controlled by external signals which are generated by an **FPGA**. The images are captured according to the rolling shutter principle. In consequence, the individual cells making up the image are very slightly staggered in time from one to the next. This imaging method is associated with the 3T pixel architecture used and can in theory lead to distortion of the image if its content is changing rapidly. In the present application scenario it can be said that this effect is of no significance.

More on chip developments: www.imms.de

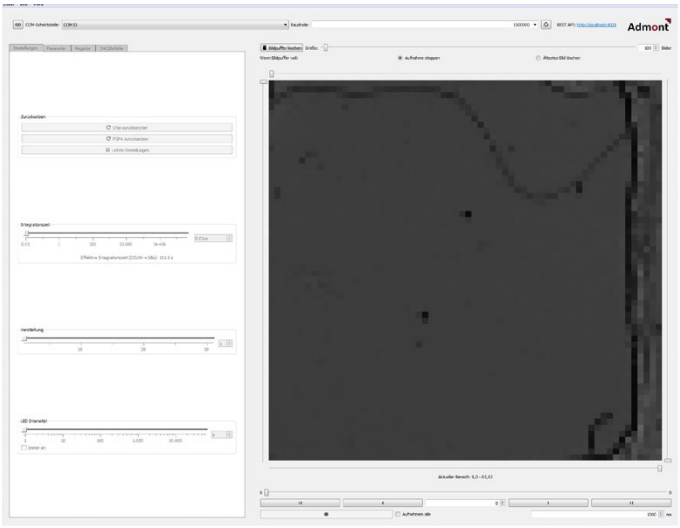


Figure 4:

GUI for the operation of the analysis system.

Screenshot: IMMS.

User interface and evaluation of the sensor data

The user can operate the measuring chamber using a GUI developed at IMMS, see Figure 4, a program which allows the various image sensor settings to be configured and the procedure control to be synchronised. Here the user can capture images individually or as interval series for later evaluation in detail.

More on system integration: www.imms.de

The program also offers the possibility of operating the measuring chamber from a network interface using a REST API (representational state transfer interface). The measurement and evaluation can also be automated via this network interface.

The post-processing can be done with any software that supports HTTP as application protocol for the interface. The project partners, who investigate living cells in the biological laboratory, have thus been equipped with an interface in a familiar PC environment. An Excel spreadsheet has been created with macros for accessing the REST API as a foundation for extraction and visualisation of the biomedical relevant data and can be further developed by partners who have no programming experience, see Figure 5.

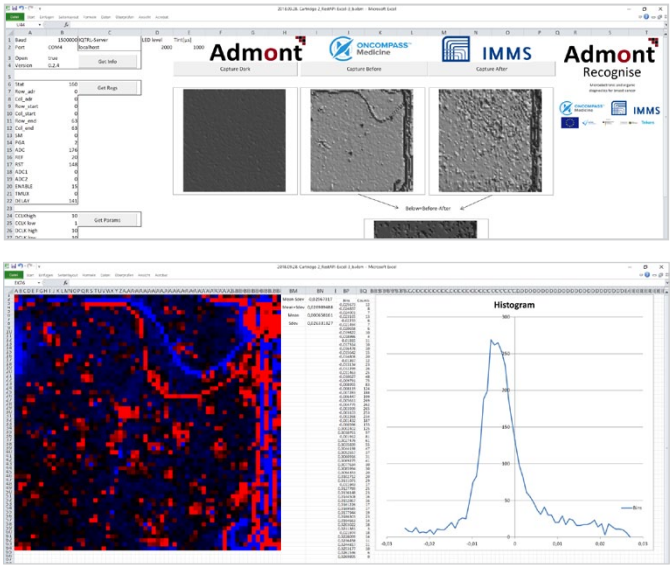


Figure 5:

the data extraction and visualisation for the analyses appear in Excel via the REST API interface. Shown are test fluids.

Screenshots: IMMS.

Future prospects

IMMS has developed a prototype system of in-vitro diagnostics for breast cancer cells to quantify the HER2 proteins present. Not only a fluorescence analysis but also a light absorption analysis can be carried out. The flexibility is supported by software developed in-house for the purpose. The data processing and visualisation can take place either in the software directly or via an interface using external tools.

Partner in the project, Oncompass Medicine Hungary Ltd., has started to evaluate the system in respect of breast cancer cells. The results will be employed by IMMS for further development and used as a foundation for the design of systems identifying antibody substances with different fluorescence or light absorption properties. The system can also be used in follow-on projects aimed at improving analysis procedures.

Contact person: Dr.-Ing. Valentin Nakov, valentin.nakov@imms.de

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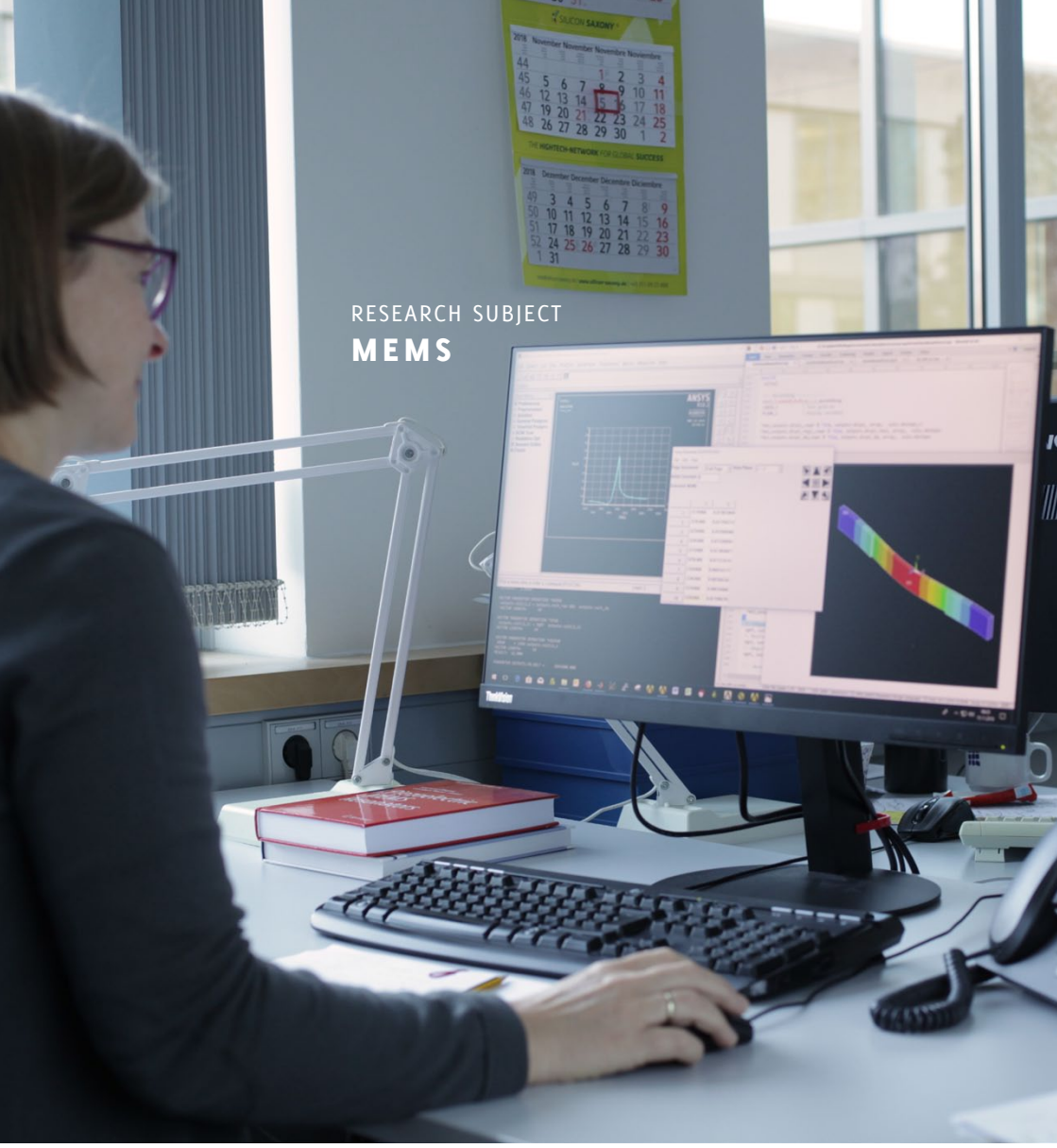
ECSEL Joint Undertaking

The ADMONT project has received funding from the ECSEL Joint Undertaking under grant agreement No 661796. This Joint Undertaking has received support as Innovation Action from the European Union's Horizon 2020 research and innovation programme, the German Federal Ministry of Education and Research (BMBF) and Finland, Sweden, Italy, Austria, Hungary. The IMMS sub-project "Design of intelligent in vitro diagnostic und bioanalytical sensor and actuator systems" has received funding under the reference 16ESE0057.

ADMONT at www.imms.de

All ADMONT publications: www.imms.de.



RESEARCH SUBJECT

MEMS

IMMS is a part of the MagSens research group working on MEMS sensors which will in future be capable of detecting weakest magnetic fields, such as those found in biomedical technology. The image is of one of the simulations, using ANSYS, of the transfer characteristics of a magneto-strictive piezoelectric MEMS beam structure. Photograph: IMMS.

The MagSens research group, led by Ilmenau TU, is funded by the German "Land" of Thüringen and the European Social Fund under the reference 2017 FGR 0060.

ESF EUROPE FOR THURINGIA
EUROPEAN SOCIAL FUND

EUROPEAN UNION
European Social Fund

Freistaat Thüringen
Thuringian Ministry for Economic Affairs, Science and Digital Society

Research subject Micro-electro-mechanical systems (MEMS)

Extending only over an area of a few square millimetres, MEMS (micro-electromechanical systems) combine micromechanical sensors and actuators with control electronics in a single device. The fields in which IMMS concentrates its R&D activities are MEMS-based electronic systems for innovative applications in industrial measurement technology, automation and control engineering and for special new growth areas such as the life sciences and biomedical technology. New approaches, such as the MEMS energy harvesting modules developed by IMMS, will make 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 been continuously applying itself to extending its MEMS design capabilities. The Institute works in close cooperation with MEMS process development and manufacturing partners, itself focusing on the design of new mechatronic systems solutions. IMMS puts another main emphasis of its work on the characterisation and testing of MEMS components and modules by setting up specific laboratory equipment and by means of non-destructive measurement methods.

Projects in the MEMS field at www.imms.de.

Highlight of 2018 in our MEMS research: Start of work in the MagSens* research group: ultra-sensitive MEMS sensors to detect the weakest of magnetic fields

Ultra-sensitive magnetic field sensors so far available require elaborate cooling

In today's medicine, low magnetic fields in the human body need to be measured with high accuracy and no physical contact. An example is the non-invasive investigation of neuronal activity in the brain.

The MagSens project at www.imms.de.

Other fields are those of geology, archaeology and materials science. In these, also, the sensors used to date are those based on superconductive quantum interference devices, SQIDS. The disadvantage of SQUIDS is their huge requirement for cryotechnology: before they can be put to use, their temperature must be brought down to –196°C.

The aim of the research into magnetoelectric MEMS sensors is to enable measurement without cooling

The MagSens research group, led by Ilmenau TU, has, therefore, since January 2018, been investigating magnetoelectric MEMS as an alternative form of sensor that may be capable of measuring very weak magnetic fields without needing to be chilled in this way. The sensor principle underlying the research is based on multi-layer systems on magnetostrictive and piezoelectric materials.

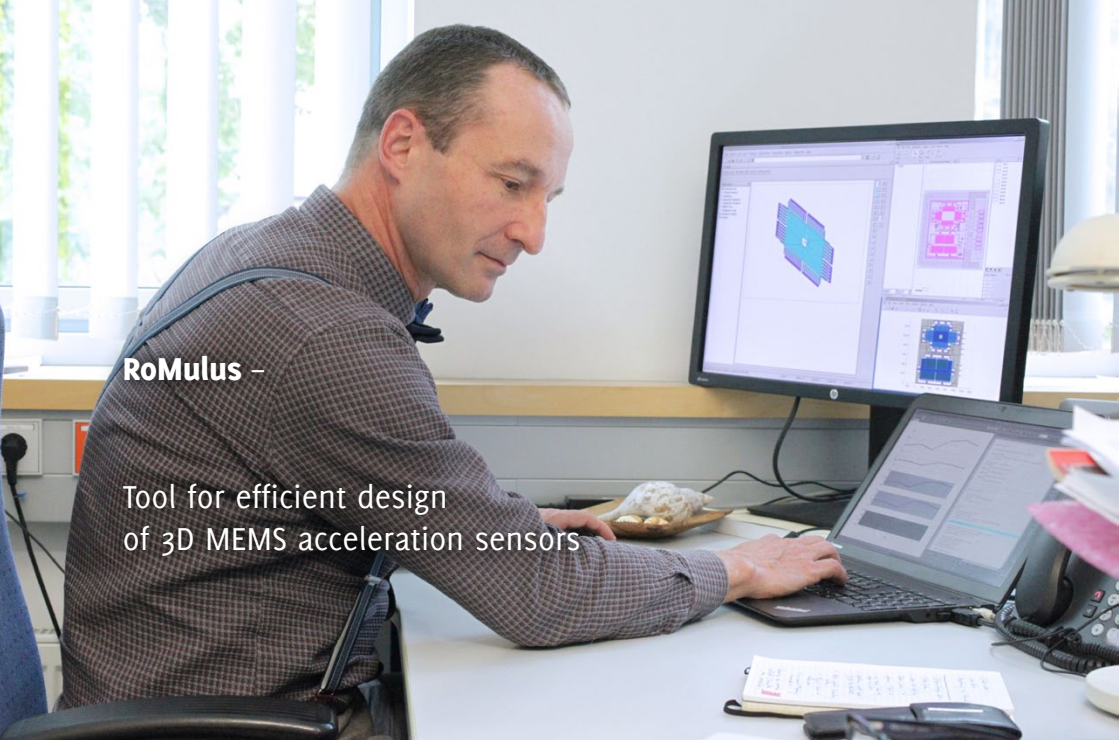
The research method is to calculate and simulate the theoretical conversion efficiency in relation to the chosen geometrical parameters and layered materials of the MEMS sensor. One thing IMMS is doing here is modelling the sensor principle in ANSYS, an FEM software, which is enabling the Institute to derive design rules and guidelines applicable to the development of varieties of magnetoelectric sensor systems and to build up a library of the characteristics, fit functions and basic geometrical shapes.

Services for FEM at www.imms.de.

The partners in the group will fabricate the magnetoelectric multi-layer systems on the basis of the comprehensive conversion efficiency results, carry out analyses and then use them for practical test structures and, eventually, for the processing of magnetoelectric MEMS.

The next stage will see IMMS engaged in the systems integration and validation. Here, the magnetoelectric MEMS that have been developed and created in the project will firstly have their conversion efficiency measured and secondly their suitability as sensors tested.

The MagSens project at www.imms.de.



RoMulus –

Tool for efficient design of 3D MEMS acceleration sensors

Work on the design tool developed by IMMS for the automated design and largely automated layout of multidimensional acceleration sensors. Photograph: IMMS.

Objectives and overview

Although in the field of microelectronics a highly automated, computer-aided design procedure has long been used in the design of integrated circuits, there has to date been no commensurately adequate methodology or design software for silicon-based micromechanical components. Among the many uses of MEMS (the acronym stands for microelectromechanical systems) are inkjet printer head control, microphones, sensors for the gyroscope in smartphones and acceleration and RPM sensors. Indeed, they are the source of all the measurements taken in modern cars to support safety systems (e.g. to regulate driving dynamics, or to serve TPMS, tyre pressure monitoring systems). Having been used for the first time in a mass product in 1994 when Bosch produced integrated pressure sensors, they have had a short history to dated but their use has grown rapidly and consistently over several years, particularly under the impetus of the automotive industry. Development cycles are getting shorter and shorter, which, because it increases competitive pressure on sensor development, also puts pressure on development costs.

More on RoMulus at www.imms.de

Present MEMS design tools are laid out for simulation and require much manual input

It has only been for something more than 10 years that software tools have been available so that MEMS design and simulation could use library elements. The tools are not adequate to test how far the designs are feasible with available technology. They also lack layout elements which might ensure efficiency in the layout process. It is possible, admittedly, to calculate manufacturing tolerances using the tools but the calculations do not lead to optimised design. Nonetheless, to design MEMS, it is necessary to know which topologies are feasible to fabricate. And, moreover, optimisation functions make a great deal of sense in such a tool as there are many individual sensor parameters, often affecting more than one parameter in the specification – but these have not so far been implemented, either.

IMMS tool provides MEMS designs already automatically optimised and cognisant of technological specifications

This has led to IMMS developing further the design tool from the MEMS2015 project for 1-dimensional acceleration sensors to achieve for multi-dimensional acceleration sensors a tool for automated sensor design and largely automated layout design. First, the original tool was laid out for use in house to design 3-dimensional acceleration sensors which would extend the functionality of TPMS (tyre-pressure-monitoring systems).

More on MEMS2015 at www.imms.de

TPMS are one of the growth drivers in the market for MEMS. They already contain not only pressure sensors and RFID but also a one-dimensional acceleration sensor. This last ensures that it is only when the tyre is rotating that values are measured and transmitted by RFID. The effect is to extend the battery life of the TPMS. In contrast, 3-dimensional acceleration sensors enable the forces to be measured which are generated by changes in speed and direction, so that data can be obtained on the driving dynamics. An acceleration sensor of this kind measures all translatory degrees of freedom, even for instance the lateral acceleration affecting the tyres.

The tool developed at IMMS will provide automatic design for such 3D acceleration sensors to accord with customer specifications. At the core of the tool is a two-stage design strategy enabling technological tolerances to be observed and optimal sensor

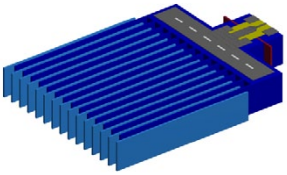


Figure 1:

Comb structure of library element, together with layout element for electrical contact.

Diagram: IMMS.

design achieved so that a minimum of space is used for the sensor. Higher-order library elements are another feature of the new tool. Besides the function and design elements they contain layout elements which greatly help in automation of subsidiary steps in the layout process. The manual work is then only needed for the wiring.

The IMMS solution in detail

Functioning and basic structure of sensor

All acceleration sensors depend on the same principle – a movable mass suspended on springs is subjected to acceleration. The various different types are distinguished by the way which this displacement is detected. In the XMB10 technology made by X-FAB, the detection is capacitive, in that the distance between a fixed and a movable electrode structure connected to the displaced mass changes. Usually differential comb structures like that shown in Fig 1 are employed.

For multi-dimensional capacitive acceleration sensors, a range of basic structures is in principle a possibility. These structures may be distinguished by number of acceleration components and/or degrees of freedom used in the detection of the movable mask. The criteria for selection of suitable basic structures will be the geometrical area of the sensor and the cross sensitivity between the acceleration components to be measured and both selection criteria must be kept as small as possible. A sensor with three masses, one for each degree of freedom, has low cross-sensitivity but its area is not optimal. On the other hand, a sensor supplied with only one mass is small in area but will have high cross-sensitivity because there is only one spring system for all three degrees of freedom. For the sensor size and the cross-sensitivity parameters, a sensor with two movable masses is the optimum – one for the planar directions of movement (x/y) and one for the z axis relating to them. It is not possible to implement any other basic structures in the technology. For instance, sensors possessing the coupled mass systems to be found in the literature cannot be fabricated with this technology.

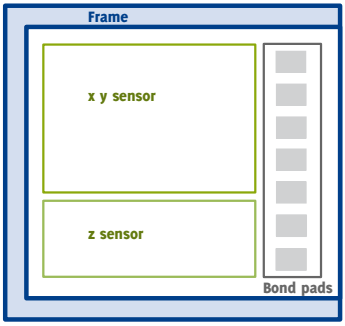


Figure 2: Structure of sensor (schematic diagram). Diagram: IMMS.

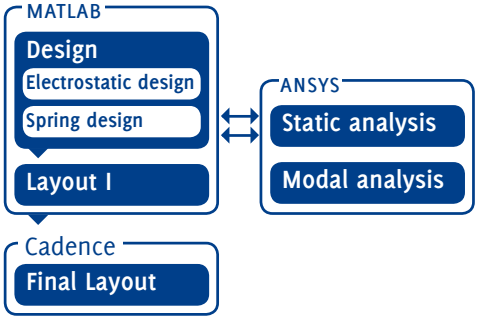


Figure 3: Structure of design and layout process. Diagram: IMMS.

Two-stage design strategy for the IMMS tool

The design process starts with the customer specifications, which define the required parameters: these may be the maximum acceleration to be measured, the sensitivity (changing capacity related to acceleration due to gravity, usually given in fF/g), the non-linearity (maximum deviation of output signal from a reference line in %), resonance frequency and shock resistance, etc. The tool can then generate a sensor with minimum area, in every case following a two-stage design and layout process. The stages serve the purpose of minimising the deviations (which can always arise because of technological tolerances) from the originally specified parameters for the sensor.

Highest tolerances necessary at etching processes

The fabrication process of greatest relevance for the design strategy because of necessary tolerance is the etching of springs and interdigitated structures out of the sensor layer, which may be 15, 30 or 75 µm thick. Ideally the etching would have only a vertical effect, through the thickness. In reality, however, the etching solution attacks the silicon not only in the vertical direction but also sideways. This underetching alters the width of springs and interdigitated comb fingers and, additionally, the gap between the fingers.

These changes in geometry have two self-contradictory effects – on one hand, if there is a positive undercut, greater displacement of the sensor because of the narrower spring dimension results, and on the other hand there will be a lower change in capacity because of the greater distance between the fingers in the interdigital structures. These contrasting effects can be usefully exploited to reduce to a minimum the influence of manufacturing tolerances in the sensor features.

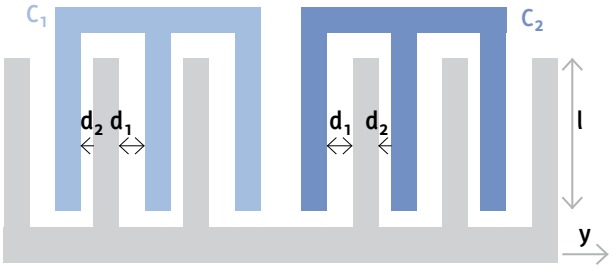


Figure 4:

Differential interdigital structure (schematic of principle).

Diagram. IMMS.

Design in two stages minimises effect of manufacturing tolerances on sensor features

In a first step the electrostatic parameters are determined – which will probably be the number n, length l and distances (d_1 and d_2) between the fingers in the interdigitated structures and the displacement for the movable mass Δy including the spring constant (assuming a virtual spring), see Figure 4. The second stage is then to optimise the width of the spring so as to minimise tolerance effects and then to compute the length of the spring.

The modelling and simulation methods used for the design were selected on the criteria of computing speed and accuracy of the model. When the capacities are being computed, fringing fields must be taken account of. The tool applies the methodology of conformal mapping for this. Commercially available finite element (FEM) programs, which are controlled from the tool for both modelling and simulation, are used to calculate spring stiffness and eigenfrequency. There are interfaces in the tool for ANSYS and MEMS+.

Services for FEM at www.imms.de.

Example of design and layout

By way of demonstration, the tool was used to create the design and layout of an exemplary 3D acceleration sensor with specifications meeting the requirements of a TPMS. 500g is asumed as maximum acceleration, and further specifications are sensitivity of 0.1fF/g and maximum non-linearity of 1%. The optimisation goal is to achieve the smallest possible sensor area with regard to minimum costs. The following is the specific design flow associated with the demonstrator.

xy sensor unit

The xy sensor unit has differential comb units in x and y symetrically arranged so that only a little cross-sensitivity results. Meander springs at the corners of the movable mass permit its inplane displacement. The cut-out at the centre of the

Step 1	Max. displacement (determined by nonlinearity)
Step 2	Finger parameter (determined by step 1 and sensitivity)
Step 3	Spring parameter (determined by step 1 and step 2)

Figure 5: Sensor-specific design flow. Diagram: IMMS.

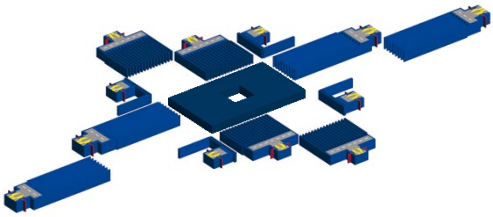


Figure 6: xy sensor unit (exploded view with library elements). Diagram: IMMS.

movable mass is an essential element of the layout, serving as seating for stoppers to prevent damage to the sensor from shock events.

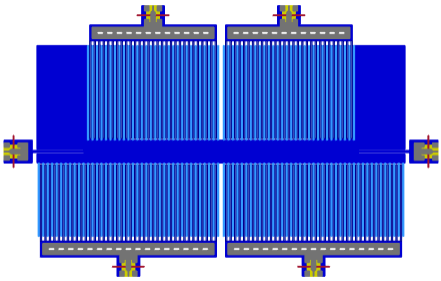
The specification allows a square space for the 3D acceleration sensor, so that both sensor units basically have a rectangular area available. Consequently, the xy sensor unit, requiring the same change of capacity in x and y, must have a different number and length of comb fingers in each direction.

z sensor unit

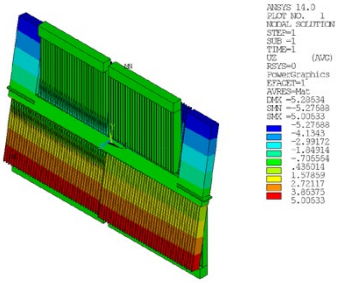
In the z sensor unit, the movable mass is suspended on torsion springs. Its mass is asymmetrically distributed, so that acceleration causes torsion in the mass and displaces it. This displacement is detected by the recessed fingers.

Layout

Basically, the layout is achieved by creating the "real world" which will surround the functional sensor units and providing wiring, including pads for electrical contact. The first step is carried out by the tool automatically using Boolean algebra while adhering to the design rules. The design process ensures that there are electrical contacts already available as library elements. The wiring that joins the electrical



a) z sensor unit



b) static simulation

Figure 7: z sensor unit. Diagram: IMMS.

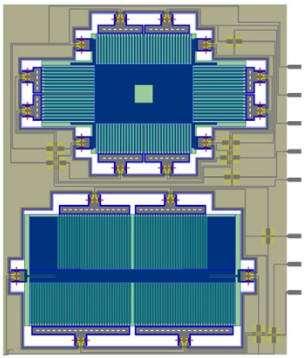


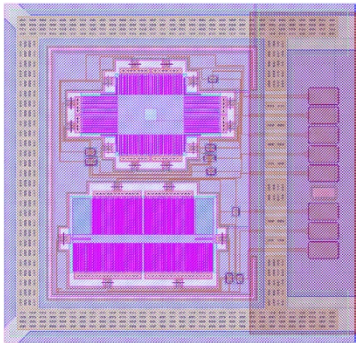
Figure 8:

Sensor layout:

◂ after stage 1

final layout ▸

Diagram: IMMS.



contacts and connects them to the pads is carried out manually except where wires cross. The ”crossing“ layout element is always inserted automatically. In the second step, the X-FAB process design kit is used to add further layout elements specific to the fabrication technology.

Future prospects

Having developed the design tool for multi-axis acceleration sensors, IMMS is now capable of acting as an X-FAB design house, i.e. designing customised sensor systems efficiently for a range of companies requiring such sensors in X-FAB technology. The intention is to apply the methodology used in creating this tool to further types of sensor which lend themselves to fabrication with X-FAB’s open technology platforms. Examples are pressure and RPM sensors.

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SPONSORED BY THE

Federal Ministry of Education and Research

The RoMulus project has been supported within the Research Programme ICT 2020 by the German Federal Ministry of Education and Research (BMBF) under the reference 16ES0362. Only the author is responsible for the content of this publication.

More on RoMulus at www.imms.de

All RoMulus publications: www.imms.de.

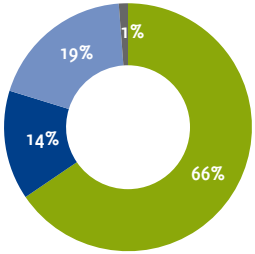
PROOF THROUGH FACTS AND FIGURES

Preparing to take measurements in the clean room measuring lab at the Erfurt section of the Institute. Photograph: IMMS.

Facts and Figures 2018

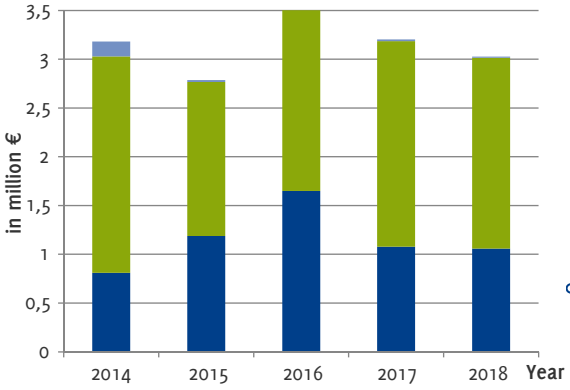
Staff structure:

Scientists
Employees Administration/Apprentice
Students (FTE)
Other assistants



Project revenues:

Revenues from industry / Public funding / Others



There were 84[1] people employed at IMMS in 2018. Of these, 55 were research scientists and there was the FTE[2] of 16 students if they had been occupied full-time in our research and development. Our scientific staff members were thus around 85% of our full complement.

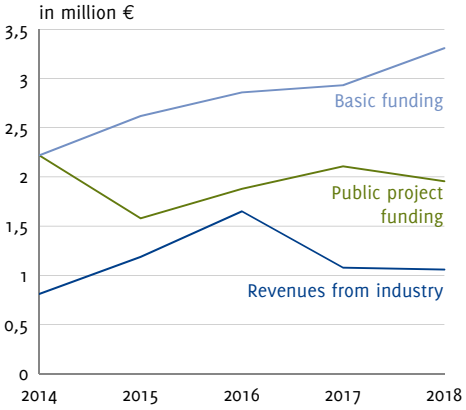
The FTE of 16 actually represents 36 students who took the opportunity of interning in research at IMMS. In 2018, at IMMS, two dissertations for the degree of BSc and 9 for the degree of MSc received supervision. 7 of the employees at IMMS were working on their PhD.

For IMMS, attracting and retaining motivated, highly qualified staff is a vital survival factor. With its commitment to the training and teaching of students, IMMS increases its chances of drawing superbly qualified graduates onto its staff.

Earnings from projects were around 11% lower in all than those of the previous year. On the other hand, earnings from investigations commissioned by industry grew, while those from public major research projects developed in the opposite direction. This trend is also reflected in the project revenue figures, which show a drop of around 9%. The revenue from industrial research (listed as "revenues from indus-

1 *On average across the year*
2 **FTE** *Full time equivalent. For purposes of comparison, all the hours worked are converted into an abstract number of full-timers.*

Pillars of financial support

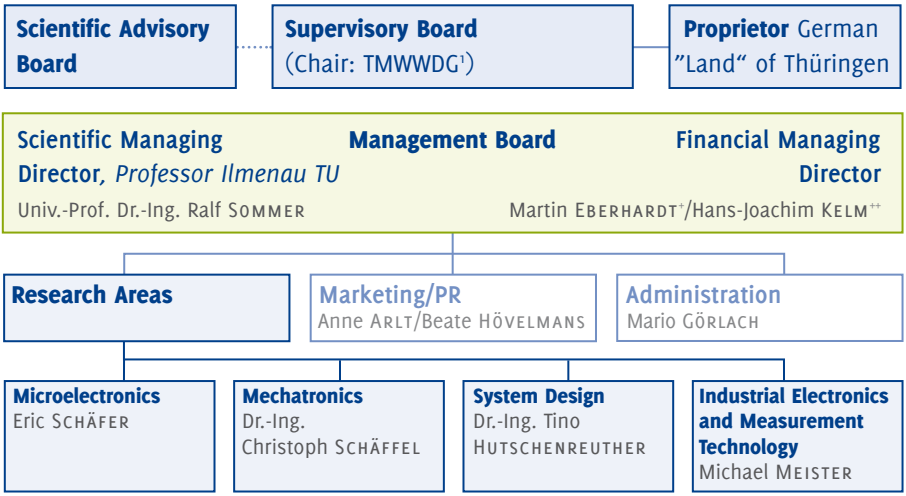


try") was not very different from last year, dropping by approx. 2%. This is largely due to the fact that commissions were completed by year end and the payments for them arrived only in 2019. There were 37 projects conducted in partnership with industry that were concluded in 2018. Revenue from public major research projects was around 7% below that of the previous calendar year. 9 such research schemes were successfully concluded in the year covered by this report. Having worked on our strategy in 2018, we are confident that in the years to come up to 2030 we have a good foundation which will enable us to attract more public major research projects and industrial income.

The recognition and acceptance met by IMMS as a competent research partner is revealed, as has long been the case, in the numerous projects which take place jointly with partners from industry. The aim is early conversion of innovative research results into industrial applications. It is here, perhaps above all, that the high competence of IMMS at transferring the results of its research work into the development and creation of actual products for outside enterprises is demonstrated.

As in previous years, the "Land" of Thüringen once more ensured that conditions remained stable by underpinning the Institute with steady support. In particular, to ensure execution of the strategic aims, it was possible to launch internal research groups. Thüringen's support of IMMS as an official Institution continues to mean that we have all the backup needed to support industry, especially the SMEs of Thüringen, with our innovative, eminently practicable solutions from research.

More on funding at www.imms.de.



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- Jörg Wende, IBM Deutschland GmbH Dresden, Consultant Hybrid-Integration and Industry 4.0

Lectures, lecture series

Prof. Dr. Ralf Sommer

at Ilmenau University of Technology, Department Electronic Circuits and Systems:

- Grundlagen der analogen Schaltungstechnik, lecture and tutorial, BSc 3rd sem.
- Rechnergestützte Schaltungssimulation und deren Algorithmen (EDA), lecture and tutorial, BSc, MSc
- Modellierung und Simulation analoger Systeme, lecture and tutorial, BSc

Prof. Dr. Hannes Töpfer

at Ilmenau University of Technology, Department of Advanced Electromagnetics:

- Theoretische Elektrotechnik I und II, lecture, BSc 4th/5th sem.
- Schaltungen der Quanteninformationsverarbeitung, lecture, MSc 2nd sem.
- Elektromagnetische Sensorik, lecture, MSc 2nd sem.
- Technische Elektrodynamik, lecture, MSc 2nd sem.
- Supraleitung in der Informationstechnik, lecture, MSc 1st sem.
- Project seminar ATET, lecture, MSc 2nd sem.

Events

Workshops / IMMS as host, organiser or co-initiator

4th M4.0-Stammtisch Sensorik 4.0 (Regulars' Table on Sensors 4.0 of the SME 4.0 Competence Centre Ilmenau (M4.0)) "Produktionsdatenerfassung", 22 Feb 2018, IBYKUS AG Erfurt *(lecture, organisation, moderation)*

4th M4.0-Workshop Sensorik 4.0 (M4.0 Workshop Sensors 4.0) „Linux-basierte echtzeitfähige Sensorsysteme", 08 Mar 2018, IMMS Ilmenau *(lecture, organisation, moderation)*

DT Workshop of the New Work Thüringen Meetup: "Design Thinking – das neue Denken!", 09 Apr 2018, Erfurt *(Workshop)*

M4.0-Stammtisch Kollaboration (Regulars' Table on collaboration) "Das digitale Büro", 09 May 2018, IHK Erfurt *(organisation, moderation)*

TFTF 2018 14. Thüringer Forschungs- und Technologieforum, 15 May 2018, TU Ilmenau *(guided tour at IMMS Ilmenau with demonstrators; IMMS as co-exhibitor)*

M4.0 Workshop with the IRP e.V. "Unterstützungsbedarfe kleiner und mittlerer Fertigungsunternehmen zu Digitalisierungsthemen", 24 May 2018, Ilmenau *(lecture, workshop, moderation)*

Current events at www.imms.de.

5th M4.0-Stammtisch Sensorik 4.0: "Vorrausschauende Wartung", 31 May 2018, IL Metronic Ilmenau *(lecture, organisation, moderation)*

Visit by Tankred Schipanski (Member of the German Bundestag), 12 Jul 2018, IMMS Ilmenau *(2 lectures, guided tour, demonstrators)*

Visit by Bodo Ramelow (Prime Minister Thüringen, Germany), 16 Jul 2018, IMMS Ilmenau *(2 lectures, guided tour, demonstrators)*

TEAG-Ausbilderworkshop (workshop for apprenticeship trainers) 02 Aug 2018, IMMS Ilmenau *(lecture, guided tour, demonstrators)*

Visit by the TMASGFF: Visit of representatives of Thüringen's Ministry of Labour, Social Affairs, Health, Women and Family, 15 Aug 2018, IMMS Ilmenau *(lecture and demonstrators)*

6th M4.0-Workshop Sensorik 4.0 "Ein Schritt in Richtung Industrie 4.0 – Industrie-4.0-konforme Kommunikation mit OPC-UA", 30 Aug 2018, IMMS Ilmenau *(organisation, lectures, moderation)*

Workshop "Design Thinking", 06 Sep 2018 and 11 Sep 2018, Berufsschule Pößneck, *(organisation, workshop)*

6th M4.0-Stammtisch Sensorik 4.0: "Datenrecht, Datenhoheit – Wem gehören die Sensordaten und wer darf wie und wann damit etwas tun?", 13 Sep 2018, FALCOM GmbH Langewiesen *(organisation, moderation)*

Mittelstand 4.0: Regionalkonferenz (regional conference of the SME 4.0 Competence Centre Ilmenau) "Arbeit 4.0 konkret", 18 Sep 2018, Erfurt *(workshop)*

M4.0-Infotag (information day) "Informationstag an den Modellfabriken Vernetzung und Migration", 23 Oct 2018, IMMS Ilmenau and TU Ilmenau *(lecture, guided tour, demonstrators)*

7th M4.0-Workshop Sensorik 4.0: "Industrielle Kommunikation mit OPC-UA", 25 Oct 2018, IMMS Ilmenau *(organisation, moderation)*

Workshop "Neue Sensorlösungen für Biologie und Medizin" (workshop on new sensor solutions for biology and medicine) by IMMS/CiS Forschungsinstitut für Mikrosensorik GmbH/CiS e.V., 23 Oct 2018, Erfurt *(organisation, 2 lectures, moderation)*

7th M4.0-Stammtisch Sensorik 4.0 "Ressourceneffizienz durch Sensorik 4.0", 08 Nov 2018, solvimus GmbH Ilmenau, *(lecture, organisation, moderation)*

8th M4.0-Workshop Sensorik 4.0 "Sensordatenverarbeitung in der Cloud", 06 Dec 2018, IMMS Ilmenau *(organisation, lecture, moderation)*

Current events at www.imms.de.

Trade fairs/Exhibitions

11th Gewerbeausstellung Steinbach-Hallenberg (industrial exhibition), 07 – 08 Apr 2018, *(IMMS as co-exhibitor of the SME 4.0 Competence Centre Ilmenau, FerMeTh joint booth – Cluster for production engineering and metalworking Thüringen)*

IDTechExShow International technology fair with 9 conferences, 11 – 12 Apr 2018, Berlin *(lecture)*

3rd Thüringer IT-Leistungsschau (IT exibition), 12 Apr 2018, Erfurt *(IMMS as exhibitor of the SME 4.0 booth, demonstrators, lectures)*

Hannover Messe 2018, 23 – 27 Apr 2018, Hannover *(IMMS as co-exhibitor of SME 4.0 at the LEG Thüringen joint booth; demonstrators)*

MEDICA 2018, 12 – 15 Nov 2018, Düsseldorf Trade Fair *(IMMS as co-exhibitor, joint booth Diagnostik-Netzwerk Berlin-Brandenburg)*

Publications

Conferences with contributions by IMMS – an overview

Jenaer Technologietag (technology day), "Digitale Arbeitswelten – Auf in die Neue (Arbeits-) Welt", 31 Jan 2018, Ernst-Abbe-Hochschule *(2 workshop sessions, lecture)*

9th GMM Workshop of the German VDE/VDI Society for Microelectronics, Microsystems and Precision Engineering "Energy Autonomous Sensor Systems", 28 Feb – 01 Mar 2018, Dresden *(lecture)*

TuZ 2018 30th GI/GMM/ITG Workshop – Test methods and reliability of circuits, 04 – 06 Mar 2018, Freiburg, Breisgau *(lecture and specialist poster)*

GeMiC 2018 German Microwave Conference, 12 – 14 Mar 2018, Freiburg *(lecture)*

DATE 2018 Conference on Design, Automation and Test in Europe, 19 – 23 Mar 2018, Dresden *(2 specialist posters, 1 demonstrator)*

IEEE SSD 2018 The 15th International Multi-Conference on Systems, Signals and Devices, 2018 19 – 22 Mar 2018, Hammamet, Tunisia *(lecture)*

IEEE RFID 2018 The 12th Annual International Conference on RFID, 10 – 12 Apr 2018, Orlando, Florida, USA *(Vortrag)*

CDNLive EMEA 2018 Cadence User Conference, 07 – 9 May 2018, München *(lecture)*

edaWorkshop18 Workshop on Electronic Design Automation, 16 – 17 May 2018, Hannover, *(lecture, EDA Achievement Award 2018)*

Workshop "Cross-Clustern ist heute" of LEG Thüringen (State Development Corporation of Thüringen), 23 May 2018, ComCenter Erfurt *(lecture, moderation for the idea generator)*

Current events at www.imms.de.

Thüringer Maschinenbautag 2018 (mechanical engineering day), 07 Jun 2018, Erfurt *(specialist poster, demonstrator)*

Neuarbeiten Extended (new work extended) "Industrie 4.0 und Neuarbeiten", lecture and workshop event of B-S-S Business Software Solutions GmbH, 20 Jun 2018, Erfurt *(keynote speech)*

22th Magdeburger Logistiktage (logistics days) "Logistik neu denken und gestalten", 20 – 21 Jun 2018, Magdeburg *(lecture)*

ATIoT 2018 International Summer School on Advanced Technologies based on Internet of Things (ATIoT), 21 Jun 2018, Chemnitz *(tutorial, 3 lectures)*

SMACD 2018, 15th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design, 02 – 05 Jul 2018, Praha, Czech Republic *(lecture)*

OMTS I4.0 Network Event of the Innovation Network Optical Measurement and Sensor Technology for Industry 4.0, 03 Jul 2018, Deggendorf *(lecture)*

OPTILIZE I4.0 Network event of the Innovation Network for Optical Technologies and Photonics for Industry 4.0, 16 Jul 2018, Jena *(lecture)*

ISPS 2018 14th International Seminar on Power Semiconductors, 29 Aug 2018, Praha, Czech Republic *(lecture)*

FDL 2018 Forum on specification & Design Languages, 10 – 12 Sep 2018, München *(lecture)*

Analog 2018 16th GMM/ITG conference (German VDE/VDI Society for Microelectronics, Microsystems and Precision Engineering / VDE's Information Technology Society), 12 – 14 Sep 2018, München-Neubiberg *(lecture, specialist poster)*

19th Heiligenstädter Kolloquium "Technische Systeme für die Lebenswissenschaften" (Colloquium on technical systems for life sciences of the iba Institut für Bioprozess- und Analysenmesstechnik e.V.), 24 – 26 Sep 2018, Heilbad Heiligenstadt *(2 lectures)*

Smart Sensors 2018 Conference on Smart Sensors – mechanistic and data driven modelling of DECHEMA e.V., 01 – 2 Oct 2018, Frankfurt/M. *(specialist poster)*

Technologietag 2018 "Akustische Verfahren zur Qualitätsprüfung – Berührungslos, zerstörungsfrei & sicher integriert" (Fraunhofer IDMT's technology day on acoustic methods for quality testing), 09 Oct 2018, Erfurt *(lecture)*

DASIP 2018 Conference on Design & Architectures for Signal & Image Processing, Demo Night, 10 – 12 Oct 2018, Porto, Portugal *(demonstrator, specialist poster)*

elmug4future 2018 technology conference "Smart Sensors & Related Applications" of the Elektronische Mess- und Gerätetechnik Thüringen eG (ELMUG), 16 – 17 Oct 2018, Erfurt *(2 lectures, co-exhibitor)*

Current events at www.imms.de.

IUS 2018 IEEE International Ultrasonics Symposium, 22 – 25 Oct 2018, Kobe, Japan *(co-author specialist poster)*

ASPE 2018 33rd Annual Meeting of the American Society for Precision Engineering 04 – 9 Nov 2018, Las Vegas, Nevada, USA *(lecture)*

PowerMEMS 2018 Micro and Nanotechnology for Power Generation and Energy Conversion Applications, 04 – 7 Dec 2018, Daytona Beach, Florida, USA *(demonstrator, 2 specialist posters)*

Reviewed Publications

Hybrid scheme to enable DTN routing protocols to efficiently exploit stable MANET contacts, Silvia Krug[1]. Matthias Aumüller[2]. Jochen Seitz[2]. *EURASIP Journal on Wireless Communications and Networking, October 2018, Volume 2018,* **DOI: doi.org/10.1186/s13638-018-1248-5.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Communication Networks Group, Technische Universit at Ilmenau, PF 100565, 98684 Ilmenau, Germany.

Towards alternative 3D nanofabrication in macroscopic working volumes, M. Kühnel[1]. T. Fröhlich[1]. R. Füßl[1]. M. Hoffmann[6]. E. Manske[1]. I. W. Rangelow[2]. J. Reger[3]. C. Schäffel[5]. S. Sinzinger[4]. J-P. Zöllner[3]. *Meas. Sci. Technol. 29 (2018) 114002,* **DOI: doi.org/10.1088/1361-6501/aadb57.** [1]Institute for Process Measurement and Sensor Technology, Technische Universität Ilmenau, D-98684 Ilmenau, PO Box 100565. [2]Institute for Microelectronics and Nanoelectronics, Technische Universität Ilmenau, 98684 Ilmenau, PO Box 100565, Germany. [3]Institute for Automation and Systems Engineering, Technische Universität Ilmenau, 98684 Ilmenau, PO Box 100565, Germany. [4]Optical Engineering Department, Technische Universität Ilmenau, 98684 Ilmenau, PO Box 100565, Germany. [5]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [6]Ruhr-Universität Bochum, Lehrstuhl für Mikrosystemtechnik, Universitätsstraße 150, ID 05 / 441, 44801 Bochum, Germany.

Modeling Pitch Perception With an Active Auditory Model Extended by Octopus Cells, Tamas Harczos[1,2,3]. Frank Markus Klefenz[1]. *Front. Neurosci., 25 September 2018,* **DOI: doi.org/10.3389/fnins.2018.00660.** [1]Fraunhofer Institute for Digital Media Technology, Ilmenau, Germany. [2]Auditory Neuroscience and Optogenetics Laboratory, German Primate Center, Göttingen, Germany. [3]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Design of Quasi-synchronous Finite State Machines Using a Local On-demand Clocking Approach, Athanasios Gatzastras[1]. Dominik Wrana[1]. Tobias Wolfer[1]. Georg Gläser[2]. Benjamin Saft[2]. Eric Schäfer[2]. Eckhard Hennig[1]. *Analog 2018, 16. GMM/ITG-Fachtagung, München-Neubiberg, 12-14 September 2018,* Proceedings: *https://www.vde-verlag.de/proceedings-en/454754003.html.* [1]Hochschule Reutlingen, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

All publications at www.imms.de.

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* Funding

- The **ADMONT** project has received funding from the ECSEL Joint Undertaking under grant agreement No **661796**. This Joint Undertaking has received support as Innovation Action from the European Union's Horizon 2020 research and innovation programme, the German Federal Ministry of Education and Research (BMBF) and Finland, Sweden, Italy, Austria, Hungary. The IMMS sub-project "Design of intelligent in vitro diagnostic and bioanalytical sensor and actuator systems“ has received funding under the reference **16ESE0057**.

- The **ANCONA** project on which this publication is based has been funded by the German Federal Ministry of Education and Research (BMBF) within the Research Programme ICT 2020 under the reference **16ES0210K**. Only the author is responsible for the content of this publication.
- The **RoMulus** project has been supported within the Research Programme ICT 2020 by the German Federal Ministry of Education and Research (BMBF) under the reference **16ES0362**. Only the author is responsible for the content of this publication.
- The **sUSe** project is funded by the German Federal Ministry of Education and Research (BMBF) by resolution of the German Federal Parliament under the reference **ZF4085709P08**.
- The **MEMS2015** project has been funded by the German Ministry of Education and Research (BMBF) in its IKT 2020 programme under the reference **16M3093**.

- The **fast wireless** project is funded by the German Federal Ministry of Education and Research (BMBF) in its "Twenty20 – Partnership for Innovation" programme under the reference **03ZZ0505J**.

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- The **StadtLärm** project has been funded by the Federal Ministry for Economic Affairs and Energy (BMWi) by resolution of a decision of the German Federal Parliament under the reference **ZF4085703LF6**.

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag
ZIM Zentrales Innovationsprogramm Mittelstand

- The **Ko²SiBus** project is funded by the DFAM (German Research Association for Automation and Microelectronics e.V.) via the AiF (German Federation of Industrial Research Associations) as IGF project by the Federal Ministry of Economics and Energy under the reference **19574 BG** by a resolution of the German Federal Parliament.

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag
DFAM
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AiF Forschungsnetzwerk Mittelstand

- The "**Mittelstand 4.0 – Kompetenzzentrum Ilmenau**" (centre of excellence in Ilmenau serving SMEs) is part of the funding initiative "SME 4.0 – Digital Production and Work Processes" which is funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) within the funding programme "Digitising SMEs – Strategies towards digital Transformation of Business Processes". IMMS is funded under the reference **01MF16005C.**

Supported by:
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Mittelstand-Digital

- The **INSPECT** project in which these results have been achieved is jointly funded by the federal "Land" of Thüringen with the reference **2015 FE 9159** and by the EU in the EFRE (regional development) context.
- The **MEDIKIT** project in which these results have been achieved is jointly funded by the federal "Land" of Thüringen with the reference **2017 FE 9044** and by the EU in the EFRE (regional development) context.

EFRE EUROPE FOR THURINGIA EUROPEAN REGIONAL DEVELOPMENT FUND
EUROPEAN UNION

- The **Green-ISAS** research group is supported by the "Land" of Thüringen and the European Social Fund under the reference **2016 FGR 0055**.
- The **MagSens** research group is supported by the "Land" of Thüringen and the European Social Fund under the reference **2017 FGR 0060**.

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Freistaat Thüringen

- The infrastructure equipment which has been purchased under the **REMEDIA** heading (the German acronym stands for extension of means of measurement for biomedical applications) was funded by the "Land" of Thüringen in its Guidelines on support for research under the reference **2018 FGI 0008**.
- The infrastructure equipment which has been purchased under the **PraezEm** heading (the German acronym stands for metrological instruments to investigate influences on accuracy and electromagnetic sensitivity) was funded by the "Land" of Thüringen in its Guidelines on support for research under the reference **2018 FGI 0007**.
- The **TSN** infrastructure project "Research Platform for Data-intensive Real-Time Cyber-physical Production Systems" was funded by the "Land" of Thüringen under the reference **2017 FGI 0006**.
- The **SensorLab** infrastructure project was funded by the "Land" of Thüringen under the reference **13027-514**.

DFG Deutsche Forschungsgemeinschaft

- IMMS has been a supported member of the FOR 1522 **MUSIK** research group and is funded by the DFG (German Research Council) within the sub-project 5 under the reference **SCHA771/2-2**.
- The **Research Training Group 2182** on Tip- and laser-based 3D-Nanofabrication in extended macroscopic working areas (NanoFab) is funded by the German Research Foundation (DFG) under the funding code **DFG GRK 2182**.

More on funding at www.imms.de.

Abbreviations

5G *Fifth generation mobile radio standard*

ADC *Analog-to-digital converter*
API *Application programming interface*
ASIC *Application-specific integrated circuit*

BMBF *German Federal Ministry of Education and Research*
BMWi *German Federal Ministry of Economic Affairs and Energy*

CDC *Capacity-to-digital converter*
CMOS *Complementary metal–oxide semiconductor*
CP(P)S *Cyber-physical (production) system*

DFG *German Research Foundation*

EDA *Electronic design automation*
EFRE *European Regional Development Fund*
ESF *European Social Fund*

FEM *Finite element method*
FISH *Fluorescence in-situ hybridization*
FPGA *Field programmable gate array*
FTE *Full-time equivalent*

HER2 *Human epidermal growth factor receptor*

IC *Integrated circuit*
IEEE *Institute of Electrical and Electronics Engineers*
IHC *Immunohistochemistry*
INA *Instrumentation amplifier*

MCU *Microcontroller unit*
MEMS *Micro-electro-mechanical system*
MQTT *Message queuing telemetry transport*

NFC *Near field communications*

OPC-UA *Open platform communications unified architecture*
OPV *Operationsverstärker, operation amplifier*

PGA *Programmable gain amplifier*
PMU *Power management unit*
POCT *Point-of-care test*
PSA *Prostate-specific antigen*

REST *Representational state transfer*
RF *Radio frequency*
RFID *Radio-frequency identification*

SME *Small and medium-sized enterprises*
SQUIDs *Superconductive quantum interference devices*

TDC *Time-to-digital converter*
TSN *Time-sensitive networking*
TPMS *Tire-pressure monitoring system*
TU *Technical university*

ULP *Ultra-low-power*

WSN *Wireless sensor network*

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Legal format: GmbH (German equivalent of limited company)
Court of registration:
Amtsgericht Jena, Gemany
Registered no.: HRB 303807
VAT registration number under § 27a UStG: DE 177 527 119

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