IMMS

ANNUAL REPORT

2019

Contents

Frontispiece: RFID chip for battery-free operation of commercial sensors, developed by IMMS in the ADMONT project. The chip is embedded as an RFID inlay on a flexible substrate from SMARTRAC (an Avery Dennison Company). Photographs and composition: IMMS.

Prof. Dr. Ralf Sommer and Dipl.-Kfm. Martin Eberhardt with the SONAPHONE device which was honoured by TÜV Süd in 2019. Photograph: IMMS.

Thank you for reading the IMMS report for 2019!

The year 2019 saw IMMS and SONOTEC together achieving third place in the competition for industrial innovation, **TÜV Süd Innovationspreis** for the development of the SONAPHONE. This competition is run throughout Germany. It honours small and medium-sized companies that have developed particularly innovative solutions in collaboration with a university or research institute and established them on the market.

More on the TÜV Süd Innovation Prize 2019

We are very proud of the prize, for it recognises exactly what we at IMMS stand for: We lend our strength to SMEs as their strategic partner by carrying out applied R&D in microelectronics, mechatronics and system engineering and transferring scientific research results into practical applications.

At the same time, the prize spurs us on to the innovations of the future with which we will help advance the "Land" of Thüringen. Since there is often a gap of 5 – 10 years between scientific research results from universities and a market-ready product, and since product development cycles are speeding up all the time, it is our Institute's **strategy** to work in internal research groups geared to applications in fields where we foresee high innovative potential and will be able with our expertise to open up competitive advantage for our industrial partners. One of the two internal research groups financed by the Thüringen government focusses on high-precision drives, the other on integrated system solutions for life science applications.

More on the research group for high-precision drives

The research groups give valuable stimulus to the meeting of many of our upcoming challenges. At the same time, they themselves benefit from results and experience gained in IMMS' current R&D projects.

In the **INSPECT** project, concluded in 2019, our Institute developed a system for the diagnostics of prostate cancer, to prove and accurately quantify the presence of the specific antigen. It was possible for our Thüringen R&D partner to test samples directly on chip, revealing antigen concentrations down to approx. 1 nanogram per millilitre, as is necessary for quantitative diagnostics. In the **ADMONT** project, we have developed an RFID transponder chip for flexible, battery-free operation of biosensors. In a contactless process, measurement data is sent to an NFC-capable RFID readout unit, such as an NFC-capable smartphone.

In addition, we have solved industrial product development problems in various fields of research. In the **INPOS** project, with partners from Thüringen, we developed an integrated direct drive that moves objects in six dimensions with nanometre precision. The drive enables wafer layers with thickness of a mere few nanometres to be processed during semiconductor manufacture. In the **IRIS** project, we have developed new measurement methods that enable micro-electro-mechanical systems (MEMS) to be subject to quality inspection in the course of production when already encapsulated. The focus was on parallel measurements on sensors and dynamic excitation of passive MEMS. In the **Ko²SiBus** project, again with partners, we have developed the means of cost-effective monitoring of Ethernet-based communications cables to protect connected manufacturing chains during manufacture. In the **AgAVE** project, we worked on Industry 4.0 conformity for an assistance system enabling automatic analysis to take place across complex industrial plant. The aim was to support the monitoring of the condition of interconnected machinery by means of a cross-manufacturer communications system.

We also contributed wireless meshed sensors to the **Digital Engineering** research group of the Bauhaus University in Weimar. The network of sensors was intended to achieve widespread continuous, long-term monitoring of physical features of buildings so that construction activity could be simulated and effects on the internal climate and energy saving estimated.

In order to transfer results from our R&D projects into the **Thüringen** economy, we contribute to networks, offer events for SMEs in the "Mittelstand 4.0" (SME 4.0) Competence Centre Ilmenau, and engage in dialogue with regional economic players at events like InnoCON Thüringen. As their springboard, the IntelligEnt researchers into AI methods for microelectronics design whose group was formed in 2019 and

› *INPOS*
› *INSPECT*
› *ADMONT*
› *Ko²SiBus*
› *AgAVE*
› *Dig. Engineering*
› *IRIS*
› *Contents*
* *Funding*

More on the research group for integrated sensor systems

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

presented at InnoCON build upon results submitted by IMMS for the Thüringen research award in 2019.

We integrate **young scientists** into research and development as early as possible by means of student placements, BSc and MSc dissertation support and an effort to establish collaborative scientific projects. We are therefore particularly delighted that Maximilian Wiener, who has trodden this path with us, won a Silver Leaf award in the field of microelectronics at PRIME 2019, the international conference for doctoral students.

Developing competitive advantages for our collaborating companies, providing targeted support for young scientists, involving oursleves in professional associations, clusters and committees – these are all activities for which the regional government of Thüringen provides the financial foundation and we express our **thanks** in the name of the whole team at IMMS.

We thank most emphatically the members of our Board of Directors and Scientific Advisory Board for their commitment... together with you all, we constantly reflect on our ideas and our strategy and how to put them into practice so as to live up to our claim to be a transfer institution.

We would like to extend our thanks, too, to Ilmenau TU and all research partners for the excellent exchange of thoughts that inspires our research work and helps us solve the problems presented by industry.

Last but not least, our thanks go to all sponsors, friends, R&D partners and people who support us in our work and share in our shaping of the future. Without the inspiration they give and their trust in us we should find many of the challenges much less easy to meet.

But it is above all our staff members who help us meet the challenges by bringing to bear their expert knowledge and their personal skills. Thank you for your constructive and trusting cooperation and for your active commitment to our common future!

Together with you, the IMMS team would like to work on the next batch of upcoming ideas. Some of them are already to be found in the results in this report and we hope you find it enjoyable to read.

R. Sommer   M. Eberhardt

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

Dipl.-Kfm. Martin Eberhardt
Financial Managing Director

More on the Silver Leaf Award

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

Martin Eberhardt appointed Financial Managing Director at IMMS

› INPOS
› INSPECT
› ADMONT
› Ko²SiBus
› AgAVE
› Dig. Engineering
› IRIS
› Contents
* Funding

Martin Eberhardt at www.imms.de.

"I am looking forward to further progressing the Institute jointly with my colleague Ralf Sommer and the IMMS team, so that we shall be able to continue transferring vital innovations to the relevant enterprises. My thanks are due to Hans-Joachim Kelm, who over the past years, together with Ralf Sommer, manoeuvred IMMS GmbH into a sound position."

Martin Eberhardt became the Managing Director with responsibility for the Institute's business and administration on February 1st, 2019. Mr Eberhardt (55) bears the title Diplom-Kaufmann, which is the German equivalent of MBA.

Martin Eberhardt is a graduate of the Georg August University, Göttingen. His career has led him through audit and management roles in the steel, mechanical engineering and pharmaceutical industries into the management of research, most recently at CUTEC, the environmental research institute in Claustal.

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. IMMS is working on shared research projects with many of the University's departments across the range – electrical engineering and computer science, mechanical engineering, information technology and automation. 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 industrial clusters. Valuable impetus is given by the groupings. They are the chance to pool skills, use partners' technology and develop joint marketing strategies.

Selection of joint projects

IntelligEnt*: Reseach group on AI and Machine Learning for the design and verification of complex systems

Since 2019, under the name IntelligEnt, IMMS and the group in the Ilmenau TU Department of Computer Science and Automation concerned with Software Engineering for Safety-Critical Systems (SECSY) have been working together on application-oriented ideas for machine learning in microelectronics design which can be tacked on to existing methods and tools. The aim is to harness the immense potential of machine learning for chip designers, supporting them with content and science so that both costs and risks will be significantly reduced at the stage when integrated analogue and mixed-signal systems are being designed.

More detail on IntelligEnt at www.imms.de.

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

Until 2020, the MagSens research group, led by Ilmenau TU, is investigating magnetoelectric MEMS as a way of measuring very weak magnetic fields for medical and other settings. Magnetic field sensors so far available with this sensitivity require serious cooling, down to –196 °C or colder. 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

More detail on MagSens at www.imms.de.

cooling. Among IMMS' contributions are the FEM (finite element modelling) and the simulation of the sensor principle.

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

13 PhD students will continue to work till 2022 in the NanoFab Research Training Group (RTG) 2182 on a project funded for 4.5 years by the DFG (German Research Council). One of the researchers is at IMMS; the work is on tip-based and laser-based three-dimensional nanofabrication techniques applied to large (macroscopic) areas. Acting as 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. At IMMS, a drive system is under development that permits high-speed, multi-axis processing of objects with nanometre accuracy.

More detail on NanoFab at www.imms.de.

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

The IMMS contribution is, as "Migration Model Factory", to put its shoulder 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 which will underpin new diagnostic, maintenance and service concepts. Combining open-source software with universal electronics platforms for components that are Industry 4.0 compatible is a powerful means of achieving real-time-capable innovation fast and affordably.

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

Joint encouragement of young academics

One 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. Besides this, Professor Sommer himself is involved in teaching not only in foundation subjects but also on the MSc courses. IMMS is both trainer and motivator to students who are offered highly practical and industrially relevant placements, illuminating guided tours and themed events.

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 entitled "Images, Sounds, Numbers – How is a Film Made?" He demonstrated to more than 600 youngsters in their fifth and sixth years of schooling by means of fun examples and interactive experiments how it is possible for tunes and monsters and monsters' terrible tones to be turned into a thrilling film.

Visit to the microelectronics location Erfurt-Southeast on the Student Day in February 2019, with which IMMS, together with X-FAB and Melexis, for the second time had put together a varied program with lectures and guided tours to inspire students for a career in microelectronics. Photograph: IMMS.

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

Research subjects for students at www.imms.de.

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 2019 saw 27 students being supervised at IMMS. Furthermore, there are 8 IMMS researchers currently pursuing doctoral studies at various universities.

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

Ilmenau and Erfurt "long nights": lectures, hands-on exhibits and ideas for student dissertations to work on at IMMS

In all, about 600 visitors came to IMMS for the Lange Nacht der Technik in Ilmenau on Saturday, 11th May 2019 and for the Lange Nacht der Wissenschaften in Erfurt on Friday, 8th November – people of every age from the primary school pupil to the pensioner, both lay people and experts in their fields.

Ilmenau and Erfurt "long nights" with hands-on exhibits, demonstration models from IMMS R&D, and programming as child's play.

Impressions can be found in two videos.

In this picture: RFID solutions for the battery-free operation of sensors.

Photograph: IMMS.

Research subjects for students at www.imms.de.

Videos of these events at www.imms.de.

Hands-on exhibits, demonstration models from IMMS R&D, and programming as child's play

IMMS' staff had prepared exhibits and demonstration models enabling visitors as young as six to have hands-on experience of the results of current R&D work carried out by the Institute with its industrial partners. One exhibit was the SONAPHONE, which works with ultrasound to detect leaks in compressed air systems. This very special scanner was developed by SONOTEC and IMMS to underpin optimum manufacturing efficiency by means of preventive maintenance and it won a 3rd prize, the TÜV SÜD Innovationspreis, in 2019. The IMMS presentation also included prototypes showing how early stages of cancer can be recognised electronically. Visitors were able to test battery-free sensors in RFID systems. Here, the RFID reader, which can be an NFC-enabled smartphone, supplies contact-free power to the sensor chip that is sending detected data to it for processing. Other sensors were shown operating wirelessly with power supplied by means of inductive energy harvesting made possible by conversion of vibrations in their immediate surroundings.

In association with lectures and lab tours on the subject of testing and characterisation of microelectronic systems, there was also a portable testing set for chips which function with great accuracy at above 300°C and improve manufacturing efficiency. The offerings concluded with a chance for children to try out programming in both Ilmenau and Erfurt at staffed stations, using lines of code or the GUI. One option was to get LED lettering to start moving around, another to switch a light on with a gesture, another to create sounds, yet another to conduct the on-screen activity of cartoon characters. An unscheduled extra was the "singing Tesla coil" which the Ilmenau rain caused to move from the University campus onto the gallery in the IMMS foyer.

Ilmenau and Erfurt "long nights" with hands-on exhibits, demonstration models from IMMS R&D, and programming as child's play.

In this picture: SONAPHONE – Ultrasonic testing device for maintenance 4.0 Impressions can be found in two videos.

Photograph: IMMS.

Videos of these events at www.imms.de.

Lectures and tours on chip design with testing

The ”How do you Design a Chip?“ lectures included live showings of the design tools used and prototypes created at IMMS. From the Ilmenau ”Heat Tests for Microelectronics“ talks and the Erfurt guided tours showing the clean-room lab, the visitors got a glimpse of the testing and characterisation that ensues on chip manufacture. As with the designing of the chip, there is usually no standard solution to the problem of testing its functions. For example, if microelectronics designed to work at 300°C have to be tested, it will not be long before standard test equipment simply melts away.

Offers of student dissertations to work on at IMMS

It happens that the high-temperature testing equipment is the result of a BSc project supervised at IMMS and it was the (meantime) graduate and his supervisor who were the demonstrators. There were other exhibits, too, that were presented by student colleagues of both genders. Both evenings included many indications of the supervision offered at IMMS and of the outcome of students’ research efforts. Several members of the research staff were, indeed, able to recount how they had come to join IMMS after internships or paid part-time jobs.

Founding of an Open Roberta Coding Hub, first in mid-Germany – Ilmenau TU, Fraunhofer IDMT and IMMS turning programming into child’s play

ORCH stands for Open Roberta Coding Hub. The first in central Germany was opened in Ilmenau on 02.12.2019, providing new, digital workshop possibilities for both schoolchildren and teachers. As an extracurricular activity, Roberta teachers give free guidance to pupils on how to make a game of bringing mini computers and robots to life. The local TU’s Schülerforschungszentrum (Schools-in-Research Centre) initiated the Ilmenau Coding Hub together with IMMS and Fraunhofer Institute for Digital Media Technology IDMT . Bundling the activities in which for many years all 3 partners have encouraged local youthful research talent, the Hub is a single, flexible facility not tied to one place, motivating girls and boys at school towards careers and degrees in engineering and the natural sciences.

Research subjects for students at www.imms.de.

2. December 2019: opening of the Coding Hub. Pupils of Ilmenau's Assisi School, where Sven Engelhardt (IMMS) looks after the Computer Club, Informatik AG.

Photograph: IMMS.

Open Roberta Coding Hub – can travel, equipped for flexible use

Robots are activated in the coding workshops in conjunction with Roberta teachers and modern technology, using the Open Roberta programming platform developed at the Fraunhofer Institute for Intelligent Analysis and Information Systems IAIS. Accessing the technology intuitively, children, young people and also their teachers are helped to learn how to write programs. Open Roberta is available online; it can be called up by all the usual browsers. However, it is customary for the individual coding hubs to have their own location. The one for Ilmenau is largely designed as a travelling lab. The Roberta teachers and the equipment will go wherever someone is interested in holding a programming workshop. The mobile laboratory is fitted out with laptops, LEGO® Mindstorms® kits and microcontrollers. As well as the travelling system, all three initiators of the Ilmenau Coding Hub intend also to offer in-house workshops under the Open Roberta flag.

Initiators' commitment

It is **IMMS'** practice to host up to 40 student interns each year for work experience or dissertation preparation, thereby showing them opportunities in Thüringen's innovative companies. But enthusiasm for engineering and its issues needs to be awoken much earlier. And so Sven Engelhardt, one of the IMMS researchers, has been supporting the Informatik AG (Computer Club) in Ilmenau's Franz von Assisi school ever since 2014. In it, children are introduced to various freely available programming environments which enable them to control different sorts of hardware and grow in engineering knowledge in the fields of circuit and sensor technology.

Fraunhofer IAIS has been supporting educational projects in MINT (mathematics, computer science, natural sciences and technology) since 2002 with the Open Roberta programming platform in the Roberta – Learning with Robots (Lernen mit Robotern) project. Jointly with partners from our region, Fraunhofer IAIS, with the support of the Google Digital Garage, regularly sets up coding hubs across Germany and trains teachers for the regional hubs – as is happening now in Ilmenau.

Since 2008, the Schools-in-Research Centre of the **Ilmenau TU** has been an element of the Fraunhofer IAIS Roberta Initiative educational project. The Ilmenau Coding Hub represents a continuation of cooperation already begun where there has been a Roberta Regional Centre since 2010.

Now, thanks to the cooperation of the three units, Ilmenau TU, Fraunhofer IDMT and IMMS, staffing and technical resources have been combined to present children and young people with regular mobile coding hub events wherever required. For the current planned events and further details of the Ilmenau Open Roberta coding hub, go to **www.tu-ilmenau.de/roberta**.

More Detail: www.tu-ilmenau.de/roberta

Silver Leaf Award at the PRIME 2019

PRIME is an international conference (on Ph.D. Research in Microelectronics and Electronics) for young researchers and on July 18, 2019 in Lausanne, Switzerland, at PRIME 2019, Maximilian Wiener won the Silver Leaf Award for his contribution. It was entitled "Design of a Capacitive Humidity Sensor Frontend with an Adaptive Resolution for Energy Autonomous Applications". Mr. Wiener has been with IMMS since

Maximilian Wiener was awarded the Silver Leaf Award at the international conference for young researchers in microelectronics PRIME 2019 for his work (supervised at IMMS) on energy-autonomous measurements with an energy-efficient sensor front-end.

Photograph: PRIME 2019.

2015 and received supervision here first as a paid part-time student assistant, then as an intern and for his BSc and MSc dissertations. Immediately after writing his MSc dissertation in 2018, he became an Analogue IC Design Engineer at IMMS. His award-winning contribution is based on his dissertation for the MSc and indicates ways of helping agriculture with parallel energy-autonomous measurements of soil moisture and air humidity using sensors with an energy-efficient front-end. This front-end contains all the components needed in connecting sensors via I^2C to an RFID master chip. The low power consumption means that operation is possible without any additional power supply.

Mr. Wiener had added extra circuit components to the sensor front-end which enable the dynamic range to be set anywhere between 51.55 pF and 824.82 pF. Differently sized capacitive sensors, detecting in this case air humidity and soil moisture, can thus be read out with a single, configurable sensor front-end. As 9-bit resolution is maintained, the C_LSB can range from 100.686 fF to 1.61 pF. There is another special feature. It is possible to eliminate the static part of a sensor capacitance, the part containing no information relevant to the measured value. Thus, valuable sensor resolution is not wasted on the static component with its unchanging measurement information. The full resolution of the transducer can then be used for the dynamic part of the sensor capacity, which is proportional to the humidity.

Research subjects for students at www.imms.de.

Dr.-Ing. Silvia Krug works as Software Architect Embedded Systems at IMMS and also supervises students and colleagues who start their scientific work at IMMS.

Photograph: IMMS.

Voices of scientists at IMMS

Dr.-Ing. Silvia Krug, Software Architect Embedded Systems at IMMS

Research subjects for students at www.imms.de.

"I have been working at IMMS for almost 10 years now with some breaks in between. As a Bachelor student, I was looking for an internship and a topic for my Bachelor thesis and found a suitable one at the System Design department. This initial project was very interesting and also challenging. I therefore decided to continue my Master studies in Ilmenau with the possibility to work as a Hiwi in the System Design department. As a result, I was fulfilling various tasks regarding Wireless Sensor Networks. This included i.e. developing Hardware as well as implementing drivers and protocols for embedded Linux and TinyOS.

After finishing the Master thesis, I had an offer to start working immediately at IMMS as researcher. However, the challenges that a PhD in the DFG funded RTG 1487 "Self-Organized Mobile Communication Systems for Disaster Scenarios" posed, made me chose a position as PhD candidate at the Communications Networks Group at the Technische Universität Ilmenau. Despite that, I always kept a possible return to IMMS in mind. My PhD topic was focused on research regarding robust communications for rescue forces in disaster scenarios by evaluating hybrid routing in heterogeneous, delay-tolerant Ad hoc networks. This research benefited from knowledge and experience that I had built during my time at IMMS. While being a PhD candidate, I stayed in contact with the System Design department i.e. to work on joint project proposals.

The constant contact, especially with Dr. Hutschenreuther, and the resulting exchange on scientific topics and R&D trends at IMMS made it easy for me to consider a position at IMMS at the end of my university time. As experienced researcher, I wanted to develop my own ideas and continue working in research projects that build the base for further application oriented projects at IMMS.

Today, I am back at IMMS and enjoy versatile tasks. These include various development tasks to implement innovative solutions with practical relevance. Currently, I am implementing solutions regarding sensors for laboratory equipment and environmental monitoring and also do project management activities. Besides that, I am developing my own research topic on the analysis of distributed IoT systems. One important factor for me is to always share my knowledge with colleagues and supervise students in a way that will enable them to become and want to become colleagues one day. By sharing knowledge, I am able to return the favors I received as a student at IMMS. In addition, I enjoy helping new colleagues, joining us as researchers after their studies, with my experience obtained at IMMS but also during my time at university.

My current position allows me to continuously develop myself further regarding various aspects. This enables me to stay curious and combine many interests in a way of life-long learning. One personal goal is therefore to work on a Habilitation with a focus on my IoT research.“

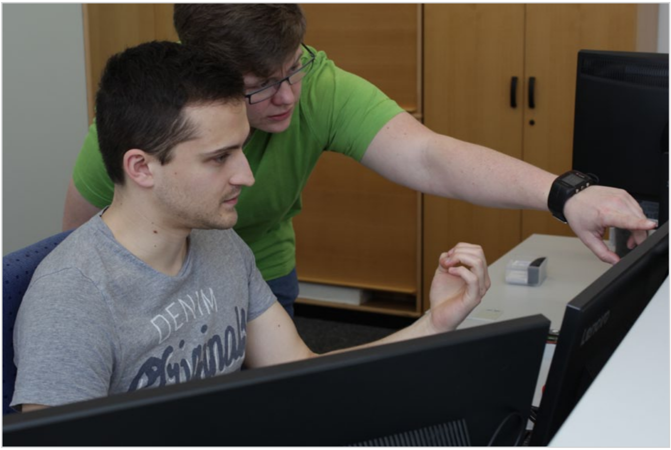
Sebastian Miethe, M.Sc., Embedded Software Engineer at IMMS

”Already during my bachelor studies at the Ilmenau TU and especially during my master studies in electrical engineering, I was mainly concerned with communications technology. It is ubiquitous in today’s world due to mobile radio, wireless sensor networks and digitalization of almost every sector and therefore more important than ever. There are many exciting research questions to be answered, which is why I wanted to write my thesis in this topic. Due to the research and development in the field of wireless sensor networks at IMMS, I was offered interesting topics for writing a master thesis. I was already familiar with the institute due to its closeness to the university as well as through a presentation by Professor Sommer in one of his lectures.

IMMS has always supported students with practice-oriented topics and methods that are possibly not available at universities. Here, many students of the TU work on their final theses or as assistant scientist and the supervision conditions at IMMS are very good. This, and the technical know-how helped me to work on my master thesis with the title ’Evaluation of the interoperability of different protocol implementa-

Research subjects for students at www.imms.de.

Voices of colleagues at www.imms.de.



Dr.-Ing. Silvia Krug and Sebastian Miethe, M.Sc., Embedded Software Engineer at IMMS.

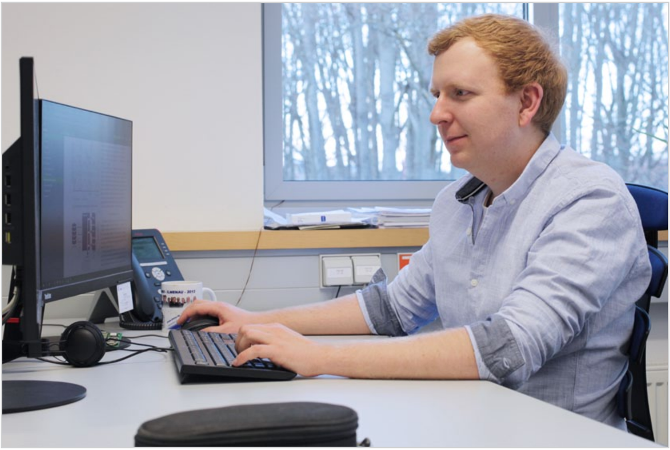
Photograph: IMMS.

tions for wireless sensor networks', which was supervised by Silvia Krug. She gave me feedback and impulses that helped me to set the right focus. After successfully defending this work, I started directly working at IMMS as a research assistant in the department of system design. I am still very well looked after, and now I am starting my first own publications.

Research subjects for students at www.imms.de.

In the EXPRESS project, I am currently working on the application of technology in agriculture, for example, the use of wireless sensor networks in viticulture and fruit-growing to record microclimatic parameters for early warning of fungal infestation or the monitoring of soil water content for efficient irrigation management in dry periods. Within the project we can test several of these techniques on experimental plots, which will also serve as a showcase for farmers to introduce them to the new techniques. The agricultural background gives the project practical application scenarios that require interdisciplinary thinking and action. The contact to other project partners and the exchange with agriculturists about their views and problems create many interesting insights into topics that are new to me and make 'EXPRESS' an exciting project."

EXPRESS at www.imms.de



Tom Reinhold, researcher at IMMS, here at work on the integration of AI algorithms into measurement processes to improve their efficiency.

Photograph: IMMS.

Tom Reinhold, researcher at IMMS

"Having elected to study electrical engineering and information technology at Ilmenau TU, I was in touch with IMMS at a very early stage because of Professor Sommer and the course on Principles of Analogue Circuit Design.

Joining the Industrial Electronics and Measurement (IEM) division of IMMS first for the obligatory basic placement and later as a part-time paid employee gave me a close-up view of the life of an engineer. Open, subject-based discussions helped me not only to solve any problems with my work but also to apply to practice the theory I was learning.

When I wrote my dissertation for the BSc at IMMS, I really enjoyed designing a demonstrator for high temperature circuits in the HoTSens project and to make and test that demonstrator, in which the circuits still work at temperatures as high as 300°C. My tasks did not only involve electrical engineering but also the resolution of issues in heat, mechanics and computer science. This highly varied and yet very specific project reinforced even at that stage the interest I had in keeping to this line of study.

Research subjects for students at www.imms.de.

I have stayed true to IMMS right up to today and after completing my MSc dissertation on 'Evaluation of RFID system parameters and investigation of RFID sensor circuits in practice' I am still here as a paid IEM researcher focusing on interesting projects that are hot off the press. In one of these projects, I am currently integrating AI algorithms into measuring procedures to increase their efficiency. One of the reasons why working at IMMS gives me so much pleasure is the fact that I have chance to put my own ideas into practice."

Voices of colleagues at www.imms.de.

Dr. Denis Dontsov, Managing Director, SIOS Meßtechnik GmbH. Photograph: SIOS Meßtechnik GmbH.

Dr. Denis Dontsov, SIOS Meßtechnik GmbH

"With our NMM-1 Nano-Positioning and Nano-Measurement Machine we have produced at SIOS Meßtechnik GmbH a system capable of measuring very small objects (up to 25 x 25 x 5 mm³) in 3D at a resolution as fine as 0.1 nm. The NMM-1 has a variety of operation modes enabling the position of the object to be changed or measurements to take place in either continuous scan or step mode. As it is equipped with various probe systems, many different sophisticated customer-specific tasks are possible, which may include the tasks of measuring precision parts like micro lenses, membranes or hardness testing indenters or of positioning, manipulating, processing and measuring objects in micro-electronics, micro-mechanics, optics, molecular biology or microsystems engineering.

In the INPOS project, for future applications which will require considerably larger working ranges, we have again put our faith in IMMS' expertise in nanodrives, continuing excellent collaboration with them that started more than 10 years ago. Joining forces also with Ilmenau TU, we have succeeded in developing a novel six-dimensional direct drive with air bearing, which can move objects sideways through a space of diameter 100 mm and up or down through a height of 10 mm with precision on the nanometer scale. IMMS developed the planar drive system with its lift and drive units and the open- and closed-loop control. We have also worked hand-in-hand with IMMS on the system architecture and the concept as a whole, collaborating on integrated design, construction, commissioning and characterisation of the system. We are more than satisfied with the result. The positioning results achieved clearly have high potential for resolving detailed enquiries from future customers and for new types of SIOS nanopositioning systems offering a significantly extended field of measurement. We feel we have a significant advantage over the usual commercial solutions in that we consistently use guide systems which are effectively friction free on all the axes of movement while at the same time integrating pneumatic compensation for gravity so that the inefficiency due to bearing the weight of the measured object is always reduced almost to zero.

More on the INPOS project in this report.

The skills and professionalism available at IMMS, the extremely high quality assurance and the results themselves already speak volumes, but we also appreciate the systematic, task-focused culture of the colleagues at IMMS and not least the natural, communicative way they work with us. We should like to continue working closely with them in the future so that their system solutions continue to be included in products made at SIOS GmbH."

www.sios.de

Friedrich Becker, TURCK Electronics GmbH

"Turck is one of the leading manufacturers in industrial automation. As specialists in sensor, fieldbus, connection and interface technology, RFID systems and Human-Machine Interfaces(HMI), we offer development and manufacture of highest-level automation electronics which increase efficiency and open up options for the machinery of many industries. In the search for the best possible solution to our customers' automation needs, we are in constant touch with them.

Friedrich Becker, Head of Software & Communications, TURCK Electronics GmbH. Photograph: TURCK Electronics GmbH.

Many of our customers are in search of predictive defect detection in Ethernet cables. In manufacturing, these data transfer cables connecting different machines are at times under heavy mechanical strain, sometimes to breaking point. While engineers search for the elusive faults and problems and carry out repairs, long hours can be lost with processes stopped.

As chair of the committee accompanying the Ko²SiBus project I had the chance to advise and help on the development of solutions that might ensure these mechanical faults were foreseen so that downtime was avoided. The project united the efforts of IMMS, Offenburg University and Chemnitz University of Technology (TU) to solve how to provide continuous, affordable signal monitoring for industrial bus systems.

More on Ko²SiBus in this report.

With its experience in the spheres of signal processing and integrating communications and systems for industry, IMMS contributed significantly to the execution of the science which the partners in Chemnitz and Offenburg derived from theoretical principles in cable diagnostics and communications interfaces. The role of IMMS was to design an embedded system and develop the appropriate circuit concepts.

The outcome is a system able to track physical signal parameters in the Ethernet cables. It uses integrated analogue and digital components, reporting deviations to a monitoring centre – a system which has been proven in a demonstration model built jointly by IMMS and the other partners.

I see the project results as highly promising and shall continue to accompany the partners through the next stages, when the system is incorporated into industrial plant and subjected to evaluation. In my view, there is huge potential in integrating these concepts directly into Ethernet-based fieldbus devices. I also view IMMS' style of working as having great potential. The IMMS developers think through the entire production chain from the pure science to the industrial application and they come up with convincing solutions. This means that IMMS is a valuable partner in innovative work extending well beyond the Ethernet problems here considered. I intend to enter into further joint work with IMMS, including projects of the DFAM[1]."

www.turck.de

Dr. Michael Neubert, Baker Hughes Inteq GmbH

"We are an energy technology company that provides solutions for energy and industrial customers worldwide. Built on a century of experience and with operations in more than 120 countries, our innovative technologies and services are taking energy forward – making it safer, cleaner and more efficient for people and the planet. We are committed to bringing radical transformation to the oil and gas industry and delivering unparalleled improvement in industrial yield for our customers. To achieve this, we are committed to digital transformation, developing solutions for our products e.g. for predictive maintenance, full reliability and the optimisation of production and earnings.

Increasingly, we are implementing our electronic modules with the help of integrated circuits in order to meet the high demands on the functionality and reliability of our tools while at the same time maintaining a high level of circuit complexity. This is a major project for which we have sought the expertise of IMMS. We have come very much to appreciate the know-how and determination of the staff of the Institute.

1 DFAM: Deutsche Forschungsgesellschaft für Automatisierung und Mikroelektronik e.V., the German research council for automation and microelectronics.

For ASIC developments such as those of Baker Hughes INTEQ GmbH, IMMS offers all phases as a package or as partial services from the feasibility study, development of specifications and virtual prototypes, circuit and layout design, characterisation and test to qualification and transfer to production. Photograph: IMMS.

I would like to take this opportunity of expressing my sincere thanks for the reliable, flexible, friendly cooperation that we find at IMMS. I look forward to yet more shared projects in future.“

Dr.-Ing. Michael Neubert, Drilling Services, Oil Field Services, Baker Hughes INTEQ GmbH, Celle.

www.bakerhughes.com

More on chip development: www.imms.de

Dr. Alexander Maier, Fraunhofer IOSB-INA

”At the Fraunhofer IOSB Industrial Automation Centre (INA) in Lemgo, NRW, Germany, we offer application knowledge for industrial automation. Smart connectivity, analysis, monitoring and user-centered design of technical systems are what we are good at. As support for their digital transformation, we provide our business partners with living labs in the form of the SmartFactoryOWL together with Lemgo Digital. We worked with IMMS as early as 2012 in this area. At that time, IMMS developed wireless networked sensors that captured data on energy use while production chains were operating, to increase manufacturing efficiency and to underpin our task of detecting and avoiding inefficient energy input-output ratios during manufacture.

Dr. rer. nat. Alexander Maier, Head of Machine Learning group, Fraunhofer IOSB Industrial Automation Centre (INA). Photograph: Fraunhofer IOSB-INA.

Having had such good cooperative experience, we kept in touch and grew the original project concept to become AgAVE. Again we formed a perfectly complementary team, developing an assistance system which could analyse complex connected machinery automatically, to find faults quickly and reduce costs. On our side, the job was to contribute machine learning methods for local investigation of cause and effect at machine level, and, at the global level to deliver results capable of human interpretation and to generate instructions for the entire production chain.

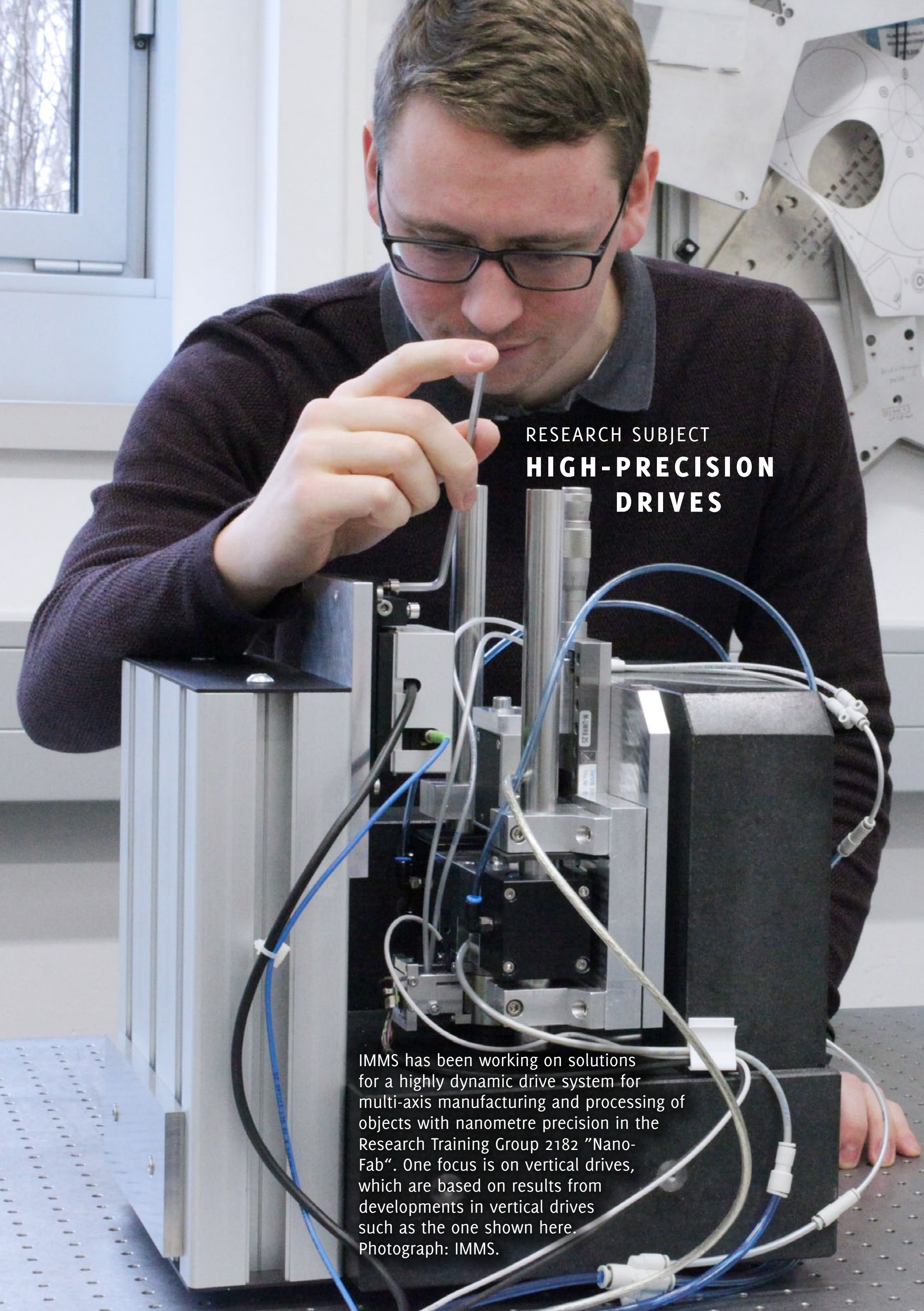
IMMS' job was to develop the means by which the two levels could communicate with each other as required in Industry 4.0 and to support us in the accomplishment of a practical demonstrator with fully connected sensors. Together we succeeded in demonstrating on actual plant how the assistance system learns the decision rules and discovers cause-and-effect links in separate machines and modules, finding possible root causes.

We very much appreciate not only the sound, practical engineering knowledge of the IMMS staff concerning Industry 4.0-compatible protocols and systems but also the personal contact and the constructive manner of IMMS' collaboration. And so we shall be delighted if we can tackle upcoming subjects together."

www.iosb-ina.fraunhofer.de

More detail in the specialist arrticle on AgAVE

More testimonials at www.imms.de.



RESEARCH SUBJECT

HIGH-PRECISION DRIVES

IMMS has been working on solutions for a highly dynamic drive system for multi-axis manufacturing and processing of objects with nanometre precision in the Research Training Group 2182 "Nano-Fab". One focus is on vertical drives, which are based on results from developments in vertical drives such as the one shown here. Photograph: IMMS.

Research subject **High-precision drives**

› INPOS
› INSPECT
› ADMONT
› Ko²SiBus
› AgAVE
› Dig. Engineering
› IRIS
› Contents
* Funding

The continuous reduction in the size of the structural elements of technical products in many different sectors increases the demand for precision machinery with which tiniest structures and objects can be measured and manufactured with high accuracy. There are many such objects having spatial extents from millimetres to centimetres, while surface characteristics and functional elements are just a few microns or nanometres in size and have to be positioned with a precision less than one nanometre in the production process.

To blaze the trail for the manufacturing of components from the macro-world with the precision that is associated with the micro- and nano-world, we conduct research on the scientific fundamentals and technical solutions to implement nanopositioning systems acting over long distances of travel. Our highly dynamic integrated multi-coordinate drives move objects with the same accuracy over distances of several hundred millimetres within the shortest time. Our solutions are intended for use under vacuum, in cleanrooms and sites with particular requirements for thermal insulation and elimination of vibrations.

Projects in the field of high-precision drives: www.imms.de.

Example: High-precision drive for laser dicing in semiconductor production in use

IMMS' research and development work on a planar drive system has been incorporated into systems with which thin 12" silicon wafers are separated into microelectronic chips by laser dicing in semiconductor production worldwide. Compared to conventional mechanical sawing processes the system allows a productivity improvement of up to 500 per cent. Savings from wafer surfaces through much narrower cutting paths bring additional benefits. The laser dicing system is produced in series by our partner ASM Laser Separation International (ALSI).

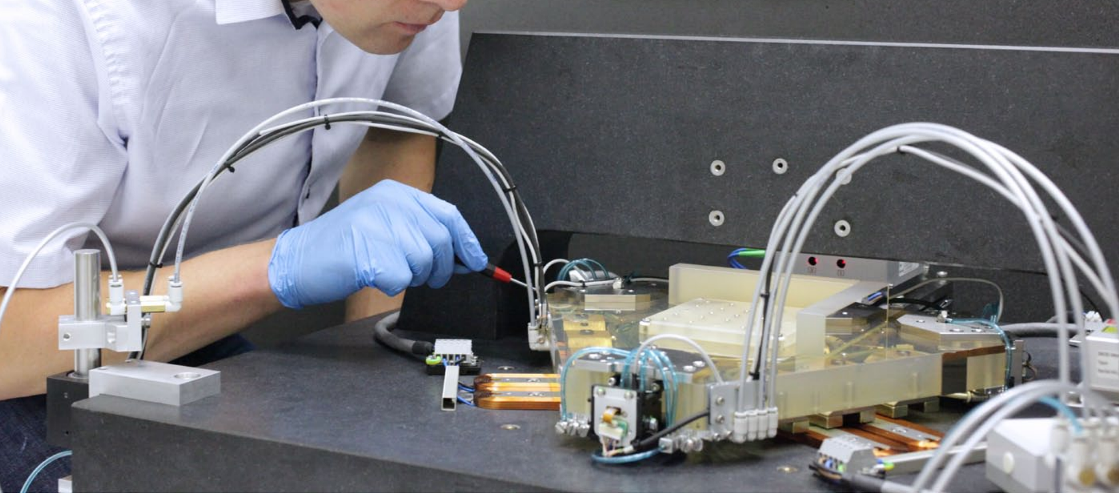
Details & video on this drive system at www.imms.de.

Internal research group for high-precision drives

We have been researching and developing high-precision drives since the foundation of IMMS. We will continue to be committed to ever more precise drives. In an internal research group, we are working on new solutions for high-precision direct drives to pave the way for new applications. This is made possible, for example, by low stray field planar motor structures, the real-time capable networking of planar direct drives and AI-based methods for novel approaches to control and regulate such drives.

INPOS –

6D integrated direct drive moving objects through nanometre spaces



Work on a 6D direct drive capable of positioning objects anywhere in an area of ∅ 100 mm while raising or lowering them through 10 mm under active control on the nanometre scale. Photo: IMMS.

Objectives and overview

Direct drives incapable of raising objects with nanometre-accuracy above large areas

Direct drives can position objects with high speed and precision, backlash-free and without any intervening gears or coupling. One of their uses is in semiconductor manufacture, for instance the manouevring of reticles. A positioning stage is usually part of the equipment for measuring and structuring substrates, wafers, reticles and the like. The slider of this stage moves objects with extreme accuracy on one plane. As it is impossible to produce stage surfaces with ultimate smoothness, there will, if only for this reason, be variations in height and some tilting of the slider during its glide over the stage surface. In addition, the dimensions of reticle-holder height and wafer or reticle thickness are not always identical. Not only this, but the manufacturing itself is carried out on different levels. Here an example is the measuring of stacked images behind a reticle and another example the structuring of wafer layers. Such layers are often as thin as a few nanometres; an entire wafer may be between 0.7 and 0.9 mm thick.

INPOS at www.imms.de.

The lifting of payloads and their safe, precise positioning have so far been possible only with great difficulty and a degree of compromise. For vertical movements, electro-dynamic actuators are preferred because they can be finely controlled. However, if they have to lift both the slider and the object on it, a huge amount of power is needed. Severe power loss is the consequence and this generates heat. Temperature increases of as little as 0.01° Kelvin will already result in a measurement error because the material of the reticle for the photolithography of the wafer expands, leading to failure of the integrated circuits that are being manufactured.

Presently available systems of wafer measurement only achieve the extremely low level of measurement uncertainty which is so much in demand today over a mere few square millimetres. Across their full area, for whole wafers with diameter 150 to 300 mm the typical measurement uncertainty is only in the ±0.5 to ±1 micrometre range.

Solution to the problem: an integrated 6DoF direct drive with pneumatic gravity compensators for the lifting

In joint work with SIOS Meßtechnik GmbH and Ilmenau University of Technology, IMMS has developed a 6-dimensional direct drive with air bearing which can move objects along three spatial axes and freely in space around these axes in an area of travel appropriate to the application: planar diameter of 100 mm, ascent or descent range of 10 mm under active control with nanometre-accuracy. Pneumatic gravity compensation assists the raising and lowering by constantly approximating to zero the power to be supplied by the vertical electromagnetic actuators. As a result there is next to no current flowing in the actuator coils, which means there is no unwanted source of heat in the measuring space to interfere with the necessary precision of measurement.

SIOS' view on the direct drive

The new drive will enable a slider to bring objects into position for sampling or processing at much greater accuracy than previously, with no Abbe error, free of contact, friction and stick-slip effect. The principle behind this drive is absolutely new in the field of six-dimensional direct drives and has been applied in no known drive system to date. Investigations have already been carried out into its scalability for other applications with a planar field diameter of 200 mm.

More on actuator systems at www.imms.de.

General construction

Unique to the new drive is the fact that the forces controlling all six degrees of freedom, i.e. the three translatory movements on the x, y and z axes and the three rotations around these axes (r_x-r_y-r_z), can be actuated with no contact and no friction on a single moveable slider.

As with many precision drives, the position coordinates are acquired using three laser interferometers distributed around the slider. When the reflecting corner of the slider moves, laser beams reflected from the plane mirror surfaces are used to measure the distances. The object is inside the corner mirror and the imaginary extensions of all laser beams along the x, y and z axes of the interferometer meet at the sampling (or processing) point, as required in Abbe's spatial comparator principle. The corner mirror and the object has to be raised or lowered as the thickness or surface profile requires, so that the sampling point on the surface of the object is always brought to the Abbe point.

The partners together have produced a basic design for the apparatus which is configured as in Figure 1. The design leaves the space above the slider free for a customer-specific measuring or manufacturing tool.

SIOS provided the leadership not only for the system architecture and the overall principle but also for design integration, construction, commissioning and characterisation. Ilmenau TU was responsible for developing and implementing the high-precision multichannel interferometer system. IMMS created the planar drive system with its lift and drive units and the open- and closed-loop control.

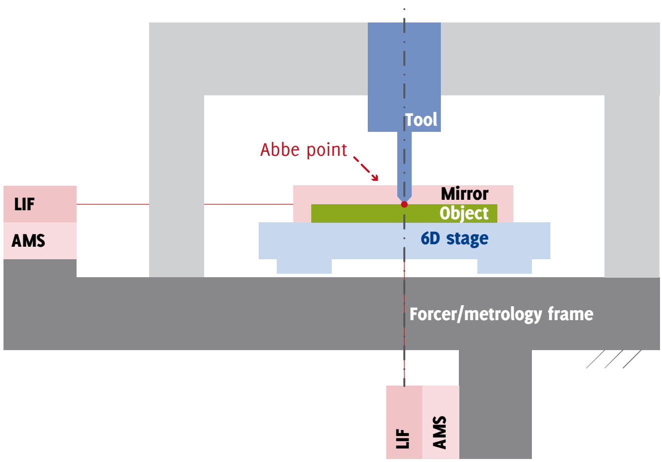


Figure 1:

Basic apparatus design

LIF = laser interferometer

AMS = angle measurement system

Diagram: IMMS.

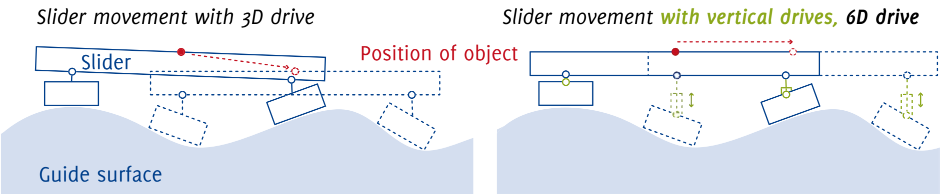


Figure 2: Uneveness of the guide area is already a source of height variation and tilting of the slider in presently available 3D drives (left) when the object glides over the area. With vertical actuators in a 6-DoF drive (right) the variations in height can be evened out and the slider positioned at the correct height. Diagram: IMMS.

IMMS' solution – extending from 3 dimensions to 6

Starting point for the planned planar drive were the integrated planar 3D direct drives and a vertical actuator, both of which systems had been developed at IMMS. Three of the vertical drives were integrated into a planar 3D drive as actuator and guide elements to compensate for irregularities in the stage surface and position the slider at the correct height, see Figure 2. IMMS' aim was to construct a genuine 6D direct-drive system which had the features described above, to conceive open and closed-loop control for the 6 degrees of freedom and then to start testing the performance achieved by this new approach.

Integrated planar 3D direct drives by IMMS as starting point

More on planar drive systems: www.imms.de.

Basically, the approach relies on the excellent positioning characteristics of an integrated planar electro-dynamic direct drive, see Figure 3. IMMS had already developed this type of aerostatic direct drive for three degrees of freedom: a planar slider with air-bearing which had bridge magnets on its underside could move in both the horizontal axes (x and y) and around its axis of rotation r_z above pairs of fixed coils as forcer. The slider elements with their great stiffness are capable of following a set route very accurately at high speed. The slider has a further significant advantage. It is passive, i.e. it functions entirely without the interference of any trailing cables for actuators and sensors. Harmful sources of heat can be kept well away from the object to be moved. These IMMS drives are already well-established commercially.[1]

Second starting point, vertical IMMS drive as actuator and guide

More on the vertical drive at www.imms.de.

IMMS and AeroLas GmbH had already developed a technical solution for a vertical actuator, see Figure 3 (r). In the new 6D direct drive this now serves instead of the three air-bearings as an actuator and guide element to take the weight of the slider with a

1 *https://alsi.asmpt.com/active-mounts/*

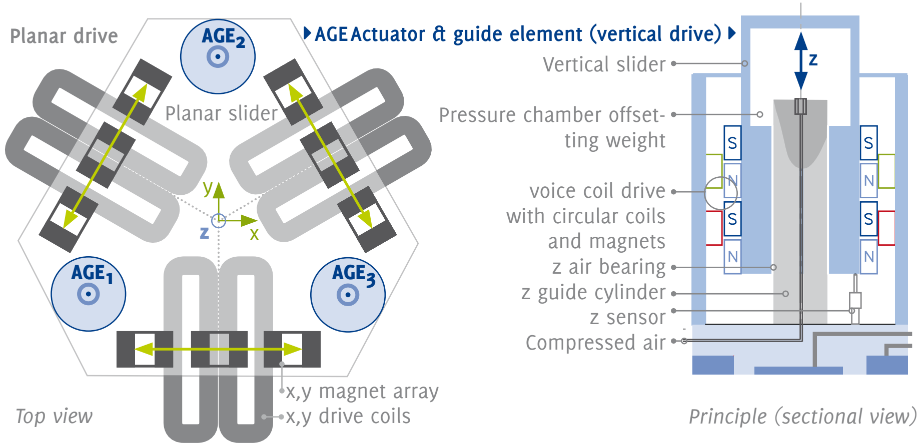


Figure 3: schematic representation of a planar drive system with 3 pairs of coils.For the 6-DoF drive, instead of the 3 air-bearings, 3 vertical drives (right) were installed. Diagram: IMMS.

very sensitively controlled pneumatic pressure chamber. The rest of the positioning of the slider which has been started by a moving coil drive then only requires a few millinewtons. As a result, any warmth from parasitics generated within the device by the drive is almost negligible. The lifting of the slider and its load, the object to be measured, consumes almost no power and at the same time permits nanometre-precise resolution of the position.

Development of the 6D planar drive system

IMMS did the dimensioning of the core components for the planar drive and the guide system in the basic layout above. Vibration in the mechanical system was a particular focus. FEM simulation enabled the drives and the mechanical components to be configured so that the weight being moved is kept to a minimum and yet at the same time excellent structural stiffness is maintained so that the eigenfrequencies are high enough to meet the extreme demands on the positioning dynamics. Figure 4 shows the result of FEM modal analysis of the final slider design with a first eigenfrequency of 291 Hz.

Services for FEM at www.imms.de.

In similar manner, IMMS also modelled the items fixed to the drive, i.e, the flat coils with holder or housing, for the purpose of using simulation to estimate the drive power and associated thermal load on the system so that the coil geometry could be optimised. Other work involved solving the coupling issues between the bridge magnets and the quartz slider; also creating a temperature control casing for the flat coils.

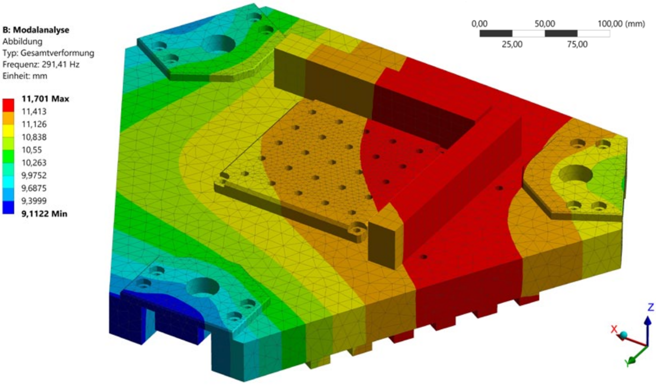


Figure 4:

One of the FEM simulations of the slider vibration behaviour with an adequate eigenfrequency of 291 Hz by way of example.

Diagram: IMMS.

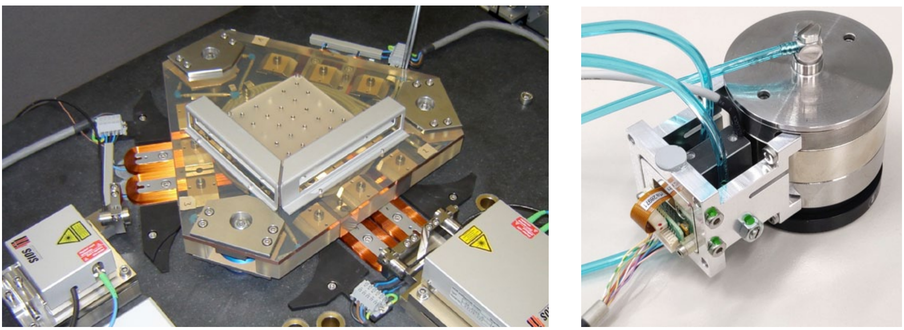
IMMS integrated the three vertical drives mechanically and pneumatically into the planar drive system and worked out an exact fit for their integration into the system's electronic control architecture. The hoses and cables are immediately alongside the slider, providing flexible transfer from slider to forcer so that travel in the working area is achieved but any parasitic forces evoked are kept tiny and, as far as possible, symmetrical while the slider is moving.

IMMS' answer – system control in 6 degrees of freedom

The drive system shown in Figure 5 was set gradually in operation with parallel, simulation-based testing of the 6D position control. Closer optimisation and fine tuning was done using parameters derived from practical situations. IMMS first established on the basis of models the physical parameters that were necessary (such as motor constants, mass ratios, transmission features for the various subsystems within the closed loop, eigenfrequencies), then verified them by experiments using the drive and to a certain extent adapted them, focussing on frequency-dependent transmission features. Fine-tuning was applied to take account of both the low dynamics of the pneumatic gravity relief in the vertical drive and the high dynamics of the

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

Figure 5: The 6-DoF positioning system created (left) with integrated vertical actuators (right). Photographs: IMMS.



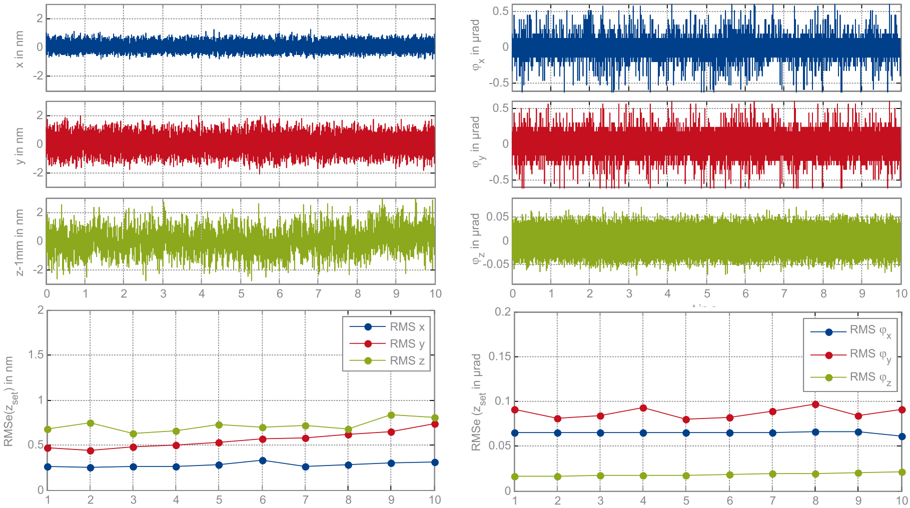


Figure 6: Time signals from the six coordinates in controlled operation (left); RMS control deviation in dependence on levitation height z_{set} (right). Graphs: IMMS.

slider actuator and achieve the best possible positioning results. IMMS developed the complex 6D closed-loop control algorithms, programmed them with Matlab/Simulink and implemented them for all the subsystems on the dSpace hardware in the control rack.

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

Outcome and future prospects

The outcome was that the desired control deviations were achieved: mere nanometres. Figure 6 shows the quality of closed-loop control attained. The time signals for controlled operation in all six degrees of freedom with a levitation height of one millimetre are shown. On the x, y and z axes, control deviations (RMS) are less than one nanometre. Further, the height-dependent changes in RMS were systematically investigated, proving that the 6D positioning system makes it possible to position the slider with nanometre accuracy anywhere in the full lift of 10 mm on the z axis. The results provide a basis for future work designing customer-specific 6D drive systems in the high-precision range.

More on actuator systems at www.imms.de.

Contact person: Dr.-Ing. Christoph Schäffel, christoph.schaeffel@imms.de

INPOS at www.imms.de.

Supported by:

Federal Ministry for Economic Affairs and Energy

ZIM Zentrales Innovationsprogramm Mittelstand

on the basis of a decision by the German Bundestag

The INPOS project has been funded by the Federal Ministry for Economic Affairs and Energy (BMWi) in response to a decision of the German Federal Parliament. The grant number is ZF4087071LT7.

RESEARCH SUBJECT

INTEGRAED SENSOR SYSTEMS FOR BIOLOGICAL ANALYSIS AND MEDICAL TECHNOLOGY

Since 2019, the SensoMem project has been developing a system that allows biochemical samples to be monitored on a laboratory scale during the reaction with the aid of sensors, thus improving the results of reactions. This is intended to avoid process repetitions. IMMS is developing a small compact wireless sensor platform for a reusable sensor unit to monitor the reactions. The picture shows initial investigations at IMMS, comparatively large standard wireless sensors with Scienova dialysers. Photograph: IMMS.

ZIM
Zentrales Innovationsprogramm Mittelstand

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

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.

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.

Internal research group on integrated system solutions for life sciences applications

We contribute know-how to integrated system solutions for life science applications that we have expanded since IMMS was founded – research and development of application-specific integrated electronic circuits (ASICs) and sensor systems, signal processing, communications and system integration. In our internal research group, we focus on transferring new sensor principles for the detection of biological and chemical features from science to the processes of Thüringen's semiconductor manufacturers and on developing a modular hardware/software platform. This platform will be used to test the functionality and performance of newly developed bioanalytical ASICs and will facilitate the rapid prototyping of application-oriented system solutions.

More on Life Sciences: www.imms.de.

Highlights of 2019 in our research on integrated sensor systems for biological analysis and medical technology

SensoMem* started: compact wireless sensor system for online monitoring of ongoing biochemical reactions in laboratories

Improved lab efficiency with online monitoring of biochemical samples

The products of biochemical reactions in the laboratory are necessary for various therapeutic approaches. Examples for such reactions are dialysis, protein synthesis or the cultivation of cells. At the moment, it is only possible to decide retrospectively from sample analysis whether the desired result has been obtained during the reaction. If that is not the case, the reactions have to be repeated, delaying the production. Since 2019, therefore, the SensoMem project has been working on developing a laboratory-scale system in which sensors monitor the probes during the reaction, thus improving the results of the reactions. Process repetitions should thus be avoided.

IMMS working on a compact, energy efficient wireless sensor platform

IMMS is developing a small compact wireless sensor platform as basis for a reusable sensor unit which will monitor the reactions. The combination of small installation space with the required long measuring time of up to several weeks as well as the integration and readout of various special sensors poses a particular challenge. The integration of all system components requires solutions that minimise the energy consumption as well as the space needed for hardware and batteries. To achieve this, we apply low-power components and design energy management strategies to enable long measurement periods. In addition, the system must be able to work reliably under different laboratory conditions and, for example, be able to transmit from metal incubators with low energy consumption.

SensoMem at www.imms.de

Contributions of the life-science partners

Our partner scienova GmbH is responsible for the selection of the sensors, the experimental setup and the data evaluation. The Fraunhofer Institute for Cell Therapy and Immunology IZI investigates biological reactions to ensure that sensors and electronics do not alter the reactions thanks to biocompatible materials, thus validates the biological compatibility of the system and studies the systems applicability in protein synthesis and cell culture.

At MEDICA 2019, IMMS showed some of the ways in which it supports partners in their applications with R&D and with support from the feasibility study through to series production.

Photograph: IMMS.

IMMS research and development for bioanalytics at MEDICA 2019

At MEDICA 2019 in Düsseldorf, IMMS presented current research and development results for bioanalytics, sharing a Thüringen booth organised by medways e.V. The solutions presented ranged from an RFID transponder chip for the flexible, battery-free operation of biosensors to a compact mobile ultrasound testing device with a smartphone-like user interface and included a microelectronic contact-imaging sensor system for the in-vitro diagnostics of breast cancer. With these and other examples, IMMS demonstrated the potential of collaboration in which IMMS has a dual role: firstly the advancement of partners' applications through R&D on electronic components and systems, and secondly provision of support from the feasibility study through to series production.

IMMS competencies at www.imms.de.

Development example: RFID transponder chip for flexible-use, battery-free operation of biosensors

An RFID transponder chip has been developed at IMMS which collects measurement data via connected individual sensors with standard interfaces, and transmits the data contact-free to any NFC-capable RFID readout unit, such as an NFC-enabled smartphone. The chip draws energy from the reader for the sensors, so batteries on the transponder side are not necessary. IMMS has developed an app for Android smartphones to read the measurement data. For demonstration purposes, a sensor transponder has been implemented that reads out ambient temperature, humidity and barometric pressure. Besides bioanalytical applications, many other sensor application scenarios are possible.

More detail in the ADMONT specialist article in this report.

The opto-electronic system presented at MEDICA 2019 is used by the partner Oncompass Medicine Hungary Ltd. for research on analytical procedures for in-vitro diagnostics of breast cancer.

The procedure is illustrated by the video of Oncompass Medicine Hungary Ltd.

Photograph: IMMS.

Development example: micro-electronic contact imaging sensor for breast cancer diagnostics in vitro

To enable the types and stages of breast cancer met in medicine to be matched to a precisely targeted therapy, it has to date been necessary in cases where the findings are ambiguous to proceed to slow, expensive, further analysis. So that in future the exact disease classification will be completed in a single stage, IMMS' partners Oncompass Medicine Hungary are currently using the optoelectronic test system developed by IMMS to investigate cell samples.

More on the optoelectronic test system at www.imms.de

Development example: compact mobile ultrasound testing device with smartphone-like user interface

Ultrasound is used not only in medicine for diagnostic purposes, but also in industry. Together with SONOTEC Ultraschallsensorik Halle GmbH, IMMS has developed a new type of digital ultrasonic testing device for industrial applications. The handheld mobile tester with a five-inch touchscreen combines innovative measurement of a wide ultrasound frequency range (from 20 to 100 kHz) and a new type of sensor detecting both structure-borne and air-borne sound, combined with smart apps that are intuitive in use. IMMS developed the digital components of the hardware as well as algorithms to enable the engineer to hear the measured values as audible output. Imms also adapted the Android operating system and supported SONOTEC in moving to mass production of the device. In this mobile system, MEDICA witnessed a demonstration of how design of bioanalytical applications, too, can arise as a complete solution in teamwork between partners.

More on the SONAPHONE at www.imms.de

INSPECT –

Proving and quantifying presence of PSA for point-of-care prostate cancer diagnosis with immunoassay on CMOS biochip

Senova and IMMS are the first to succeed in precisely quantifying PSA (prostate-specific antigen) directly with an opto-electronic CMOS biochip by measurement of light absorption. The method fully complies with "Rili-BÄK", the guidelines published by the German Medical Association (Bundesärztekammer) for quality assurance in medical laboratory tests. Photograph: IMMS.

Objectives and overview

The goal: rapid, precise testing for prostate cancer diagnosis

During diagnosis and care of prostate cancer, PSA concentration (prostate-specific antigen) is determined at all stages: early recognition,[1] exploratory investigation, treatment monitoring and follow-up care. Even a few nanograms PSA per millilitre blood (ng/ml) are an indication of whether and which further tests and treatment are needed. Higher PSA concentrations may be a sign of cancer or its return.[2] The physician takes blood and sends it away for analysis. The PSA test results usually

1 *In the future, PSA measurements could be included in the risk-adapted PSA early detection, which is currently being researched and which provides individual regular measurements based on a basic PSA value, cf. https://www.krebsinformationsdienst.de/tumorarten/prostatakrebs/psa-test-frueherkennung.php (last access 27.04.2020). A general PSA early detection is currently not recommended, cf. https://www.leitlinienprogramm-onkologie.de/fileadmin/user_upload/Downloads/Leitlinien/Prostata_5_0/LL_Prostatakarzinom_Kurzversion_5.1.pdf (last access: 27.04.2020).*

2 *Cf. on current recommendations and reference values for PSA concentrations https://www.leitlinienprogramm-onkologie.de/fileadmin/user_upload/Downloads/Patientenleitlinien/Patientenleitlinie_Prostatakrebs_1_v01-2020.pdf (last access: 27.04.2020).*

take a few days to come back.[3] Not only for PSA concentrations, science has been working on one new point-of-care (PoC) testing system after another which may obviate costly, time-consuming lab tests carried out on huge, complex apparatus and reduce to a minimum the usually very worrying wait for the patient.

In many cases, such solutions involve test strips which change colour enabling the doctor to assess concentrations in the consultation room. The colour changes vary in intensity and are caused by biochemical reaction. There has been a move in recent years towards using PoC devices with photodetectors or a camera for concentration testing.

Apparatus of this kind still labours under the disadvantage of inaccuracy in comparison with laboratory testing. In the case of PSA detection, the "Rili-BÄK" (the guidelines published by the German Medical Association (Bundesärztekammer) for quality assurance in medical laboratory tests) prescribe a lower detection limit of 0.2 ng/ml and a range up to 50 ng/ml. Confidence in the results depends on a coefficient of variation (CV) which is at most 15.5%.[4] Measurements taken with a PoC reader and PSA test strip combination developed for reference purposes in the current research project, however, failed to reach these standards.

Chip-based prototype detects and measures PSA at less than one nanogram per millilitre

In the INSPECT project, IMMS designed and developed a photometer as a portable reader in combination with a replaceable opto-electronic CMOS biochip and produced a demonstration model. Instead of the test strip employed to date in certain PoC systems with camera, the new version measures the biochemical reaction without a gap between photometer and sample, which is placed directly onto a microelectronic chip. IMMS' partner in the project, the company Senova Gesellschaft für Biowissenschaft und Technik mbH, undertook the tasks firstly of providing the chip surface with its biochemical functions using immobilised prostate-specific antibodies and secondly of using the prototype to measure samples with various PSA concentration levels. If the sample contains PSA, this is shown by biochemical reactions which darken the sample to an extent that varies with the concentration and with photometry and electronics the differences in brightness are measured. It is a world first for the Senova and IMMS partnership that the presence of PSA on a

More detail on INSPECT at www.imms.de

More on chip developments: www.imms.de.

3 *https://www.krebsinformationsdienst.de/tumorarten/prostatakrebs/psa-test-frueherkennung.php (last access: 27.04.2020)*
4 *www.bundesaerztekammer.de/rilibaek2019 (last access: 27.04.2020)*

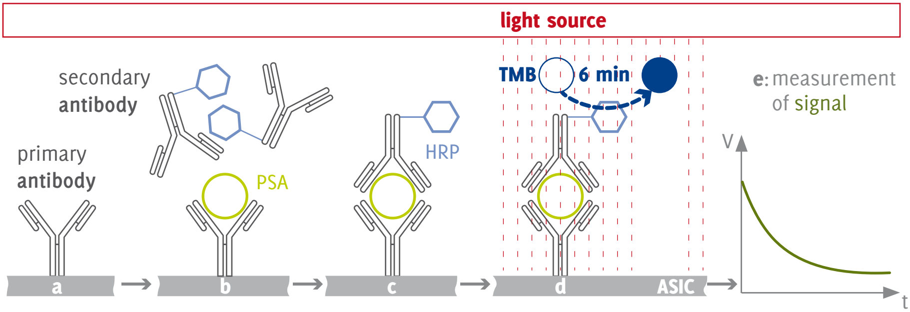


Figure 1: Diagram showing concept of detection and quantification of PSA analyte by means of immobilised primary antibodies, secondary antibodies marked with HRP (the horseradish peroxidase enzyme) and TMB (tetramethylbenzidine) substrate solution. The colour change caused by the HRP-TMB reaction alters the luminous intensity, which is what is measured by the chip. Diagram: IMMS/Senova.

CMOS biochip can be proven with a lower detection limit of 0.1 ng/ml. This degree of accuracy fulfils the requirements for clinical PSA tests set by "Rili-BÄK". The total time required for the test with the CMOS biochip is 14 minutes, there is digital output of the results and these can be processed on a computer connected to the diagnostic device.

The IMMS solution in detail

Measuring principle – PSA immunoassay on microelectronic chip

The biological and technological principle behind the new system is comparable with that of lateral flow tests, the type represented by the usual test strips. Analytes in a sample are targetted with an interaction between antibody and antigen. In the case of prostate cancer the PSA is the analyte. The primary antibodies (anti-human PSA antibodies) which would on the test strip be the "catcher" molecules are fixed on the chip surface as shown in Figure 1 (a). They catch PSA if it is present in a sample placed on the chip. To prove and quantify the presence of the PSA, secondary antibodies for PSA which are marked with HRP (the horseradish peroxidase enzyme) are also applied to the chip. These likewise attach to the PSA molecules. This sandwich made up of primary antibodies, PSA, secondary antibodies and HRP is as yet invisible. Any marked secondary antibodies which are not fixed to the chip surface are rinsed away (c). The next step is to add colourless TMB (tetramethylbenzidine) substrate solution, which reacts with the HRP and after 6 minutes renders the invisible antibody-antigen combinations visible because of a colour change to blue (d), which in turn changes the optical density sensed and evaluated by the chip (e).

The procedure is to measure luminous intensity before the reaction and after it to measure the attenuation due to the coloration.

Initial design and construction of a portable photometer

To trigger and measure the optical signals from the chip, IMMS developed a compact, portable, enclosed and light-proof readout unit which is attached to a PC via USB cable. From the computer, the software created by IMMS enables the test to be run and the results to be shown and further processed. The sample is applied direct to the chip which is on a small PCB in plug-in cartridge form in the black box. The cartridge is plugged into the device below the light source. This is an LED at a fixed distance from the chip which supplies homogenous light so that the sample is illuminated at constant intensity during the reaction.

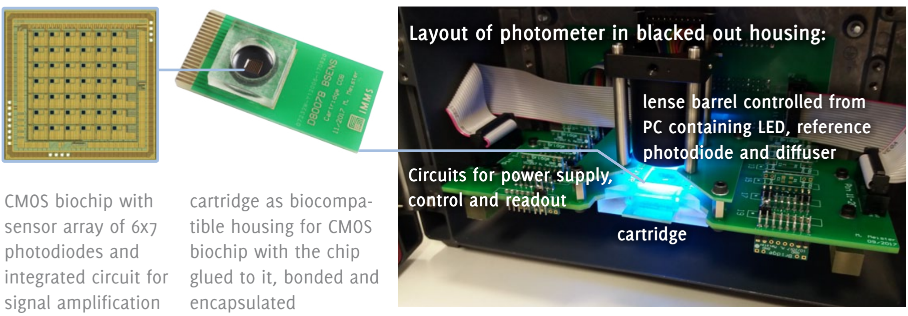
At first, the readout unit was operated with a pre-existing chip to establish requirements and contingent conditions applicable to the whole system and to provide the basis for a new dedicated ASIC. The pre-existing chip was originally developed for detecting infectious diseases, not the PSA application. It contains a matrix of 6 x 7 photodiodes, see Figure 2 (left) and is therefore relatively large for research purposes. When it was originated it was for detecting a variety of pathogens in parallel by measurement of differences in light.

More on sensor systems at www.imms.de

Article on this research chip: www.imms.de.

Photometer optimisation trials for quantifying PSA

To develop the photometer, IMMS created various experimental setups and testing systems which included the chip so that a number of features could be established: the light absorbed by samples, the linearity, sensitivity and resolution limit of the



CMOS biochip with sensor array of 6x7 photodiodes and integrated circuit for signal amplification

cartridge as biocompatible housing for CMOS biochip with the chip glued to it, bonded and encapsulated

Figure 2: The optoelectronic CMOS biochip (left) which is exchangeable because of the cartridge solution (centre) can be used in the photometer for the analysis (right). Photographs: IMMS.

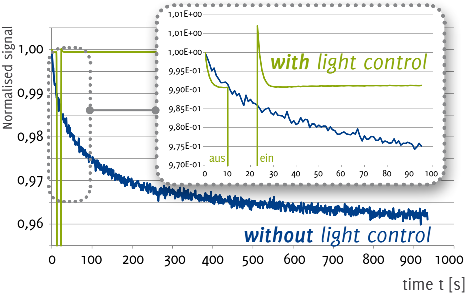


Figure 3:

Comparison of system behaviour based on the normalised photocurrent over a period of 15 minutes without (blue) and with light control using a reference photodiode in the lense barrel (green): the light source stabilises within a few seconds of being switched on or off.

Diagram: IMMS.

photometers; also to analyse influences like the rise in temperature of the electronics and light source, constancy of illumination, evaporation effects and light scattering.

As one result of the experiments, IMMS integrated illumination control into the analyser. This enabled the startup time for the whole system to be reduced from more than 15 minutes to less than one minute, see Figure 3, so that systematic measurement errors are reduced and the actual biochemical reactions are more clearly evidenced. Systematic measurement errors can arise from a temperature rise in the electronics and LED or the evaporation of liquids below an intense light.

The LED can be regulated from the GUI on the connected PC. The ASIC amplification, the choice of sensors, the calculation of the mean, the measured value per unit of time and the storing of the analysis data likewise take place on or from the PC. Various graphs are provided via the GUI for the evaluation of the control and the measurement results, see Figure 4.

More on system integration at www.imms.de

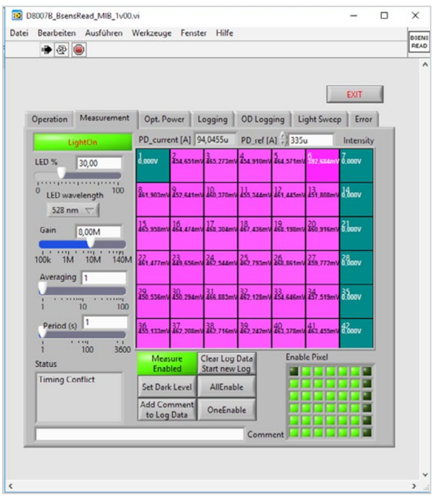


Figure 4:

Graphic user interface created by IMMS for the control of and measurement with the photometer, which is connected to a PC or laptop by USB cable. This screenshot is of the matrix for the measured values from the sensors.

Diagram: IMMS.

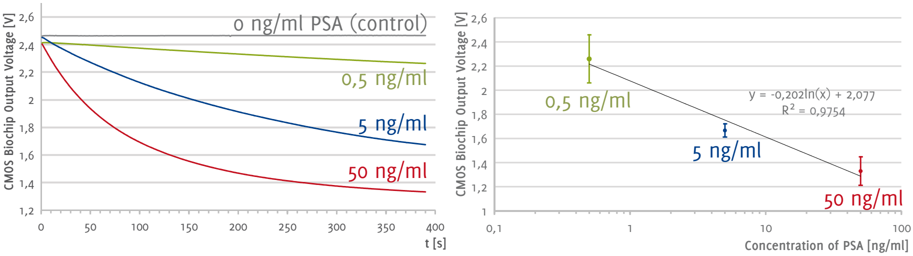


Figure 5: Left: Decreasing averaged output signals (V) from five CMOS biochips for each concentration of PSA during measurement process, which starts with addition of substrate to the immunoassay. Right: Calibration curve (logarithmic) for the PSA immunoassay with different PSA concentration levels measured after six minutes. Diagrams: IMMS.

Measuring PSA with photometer after optimisation

The optimised photometer was handed over to Senova with the cartridge units (see Figure 2) so that the measuring system could be validated for PSA. Senova provided the chip surfaces with the appropriate functions using immobilised anti-human PSA antibodies, optimised the PSA assay and carried out measurements on samples containing various PSA concentrations.

As can be seen from Figure 5, as PSA concentration in samples increases, there is a decrease in strength of the photometric signals. Five repetitions of the experiments using different CMOS biochip cartridges gave the same results. The presence of PSA was proven with a lower detection limit of 0.1 ng/ml. The figures for the coefficient of variation across the experiments were 8.8%, 3.2% and 8.9% for 0.5 ng/ml, 5 ng/ml und 50 ng/ml of PSA. This being the case, the requirements set in the "Rili-BÄK" for clinical testing are fulfilled.

Development of an opto-electronic CMOS biochip D4021A on the basis of the experiments

IMMS created the ASIC D4021A for the specific purpose following these experiments on the PSA testing system, sending it for wafer manufacturing in 2018. This chip is smaller and more affordable than that used in the initial experiments and its architecture produces even more accurate and noise-free measurements. The D4021A also includes a digital section for the initial processing of the values captured by analogue means. This simplifies the ensuing signal processing and standardised output to data processing systems. There is a further benefit in that the digitised signals are less vulnerable to external factors.

More on ASIC development at www.imms.de.

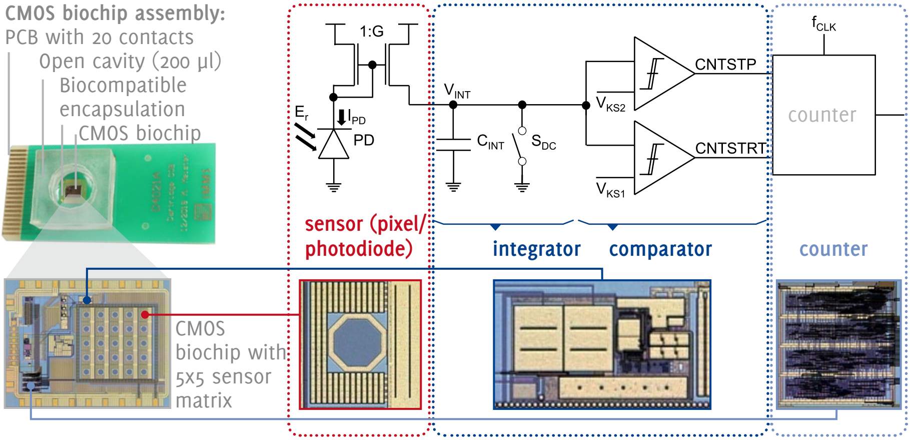


Figure 6: Photograph of the chip and circuit diagram, D4021A CMOS biochip. Photographs and diagram: IMMS.

Wide-range and low-noise signal processing with digitisation included

The D4021A CMOS biochip comprises a sensor matrix of 5 x 5 photodiodes, see Figure 6. Incident light is converted by the photodiode into a pre-defined photocurrent I_{PD} and amplified using a current mirror. The photocurrent is integrated at capacitance C_{INT}, causing the integration voltage VI_{NT} to rise. Two comparators and a signal meter then work together in digitising the signal. Two set threshold reference voltages V_{KS1} and V_{KS2} serve to enable the comparators to start and stop the meter counting as soon as the integration voltage V_{INT} has reached the appropriate threshold value, see Figure 6. CNTSTRT and CNTSTP are the start and stop signals.

The value is in indirect proportion to the luminous intensity striking the sensor. If the timing cycles counted are few in number, i.e. the threshold value is rapidly reached, the intensity is high (see Figure 7). This method of signal processing enables fluctuating photocurrents generated by the incident light to be treated almost noiselessly across a wide signal range, so that the signal-to-noise ratio is excellent.

More on ASIC development at www.imms.de.

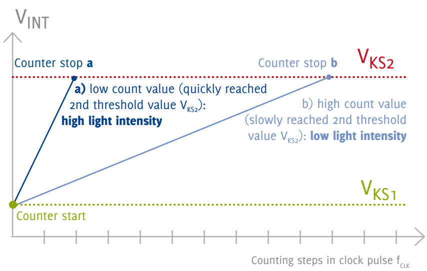


Figure 7:
Illustration of the counting principle exemplified at (a) higher and (b) lower light intensity: with timing at set frequency f_{CLK}, counting continues until the integration voltage V_{INT} reaches the second threshold value, stopping the clock. V_{KS} refers to the threshold and reference voltage 1 and 2 of the comparators. Diagram: IMMS.

Wafer testing took place on ten wafers each comprising approx. 600 of the D4021A circuits. This was to check the basic functions of contactability, operating current, test voltages and signal processing plus particular special functions. Also, various sample biocompatible cartridges containing the ASIC were designed and constructed, see Figure 8.

In early characterisation measurements using red light with the wavelength 617 nm, the ASIC produced was capable of a dynamic range of 114 dB. This means it permits signal coverage 2.5 orders of magnitude greater for optical density between 2.8 and 0.0004 than that of the chip used in the preliminary experiments. Consequently, the detection threshold is improved by a factor of 25. Further optimisation potential in this context is also available to the settings on the new ASIC as well as to the optics.

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

Summary and Outlook

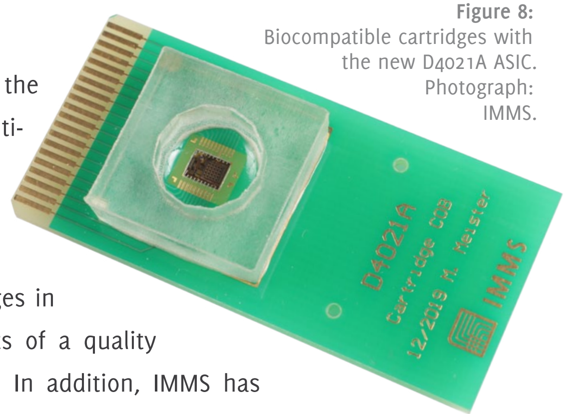


Figure 8: Biocompatible cartridges with the new D4021A ASIC. Photograph: IMMS.

As partners, Senova and IMMS are the first to succeed in precisely quantifying prostate-specific antigen by PSA immunoassay on an optoelectronic CMOS biochip exactly measuring light absorption changes in a portable unit that gives results of a quality required of medical laboratories. In addition, IMMS has concluded the development of a much more exact and tiny CMOS biochip which thus suffers much less from noise, testing it at wafer level; the Institute has also designed and constructed plug-in modules containing the new ASIC for this reader. In the INSPECT project, IMMS has reengineered the device so that it is now considerably more compact and contains upgraded LED controls so that the noise and responsiveness of the illumination unit has been improved. The IMMS internal research group on integrated system solutions for life science applications is responsible for the construction and for testing the system with the improved hardware.

Thanks to the fact that the biochemical reactions took place on the chip itself, PSA presence could be measured with no gap between the sample and the light sensor. This being the case, the CMOS biochips gave more accurate, more reliable results than do test strips. It is to be expected that the newly developed principle now successfully tried and tested on PSA will be able to improve the sensitivity of other tests. Starting here, IMMS now aims to use the results of this project to develop further PoC electronic solutions with which to serve other bioanalytical purposes or open up new ones.

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EFRE EUROPE FOR THURINGIA EUROPEAN REGIONAL DEVELOPMENT FUND
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More on Life Sciences: www.imms.de.

More detail on INSPECT at www.imms.de.

ADMONT – RFID chip supporting battery-free operation of off-the-shelf sensors for diagnostics and analytics

IMMS has developed an RFID sensor transponder IC as a bridge between NFC and I^2C, with which commercial sensors for diagnostic and analytical applications can be connected and operated without batteries. Photograph: IMMS.

Objectives and overview

Wireless sensors for future point-of-care diagnostics

In the field of personalized medical care and diagnostic tests, more and more sensors are being used today. There are, for instance, sensors which can be implanted subcutaneously to measure blood glucose concentration. Besides blood glucose meters, test strips, e.g. for pregnancy, ovulation and allergy tests, facilitate rapid analysis directly at home with a simple yes/no result (qualitative assessment). In future, digital sensors will complement today's test strips to enable quantitative assessments. This will be extended beyond what the present portfolio of test strips can do. For example, patients could be monitored after treatment of heart problems, athletes could have their lactate levels monitored, pets could be tested for disease. With modern, wireless communications and energy supply technologies such as RFID, these sensors can be read by any smartphone and the information obtained can be sent directly to the family doctor or linked to value-added services via an app. Such wireless point-of-care sensors have the characteristics of full-fledged IoT com-

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ponents which, in conjunction with Big Data and cloud-based application software, represent the most important basis for new data-driven business models. Due to their battery-free operation and the resulting resource-efficient setup, RFID sensors can be regarded as one of the most important future technologies for point-of-care diagnostics.

Flexible RFID sensor transponder chip from IMMS as a bridge between NFC and I²C sensors

IMMS has developed a battery free (passive) NFC-enabled RFID transponder chip that supports various types of commercially available digital I²C sensors with different power requirements as a flexible bridge interface, see Figure 1. It can supply a regulated voltage for external sensors of up to 2.2 V with a maximum current of 10 mA. It ensures low power consumption of the overall system and minimizes the number of external components needed to build an RFID sensor transponder. With the IMMS RFID chip, building up a wireless sensor life science application can become faster and more cost-effective.

More on chip development at www.imms.de.

The IMMS solution in detail

RFID sensor transponders are also able to receive and transmit sensor data

RFID technology

RFID, or Radio Frequency IDentification, is a well-established form of technology that works wirelessly for purposes of tracking and access control. A typical RFID system consists of at least one reader and one or more transponders. The reader communicates with the surrounding transponders via a radio frequency (RF) field, and they respond with

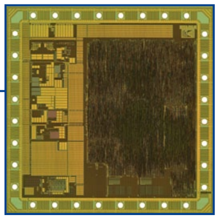

Figure 1:
left: RFID sensor transponder, illustrated here with temperature, humidity and pressure sensing;
right: RFID transponder chip. Photograph: IMMS.

their unique identification numbers. The combination of RFID with sensors to form RFID sensors is a further development of RFID technology. Its core element is an RFID sensor transponder IC – an integrated circuit that measures environmental changes, such as the ambient temperature, and transmits this information to the reader.

Near-field communications (NFC)

Near Field Communications (NFC) is an RFID-based standard for the transmission of energy and data over short distances, which has become widely used with smartphones (Device to Device Communications). Until now, this technology has been used mainly for contactless cash payments, but it is very well suited for various sensor involving personal healthcare monitoring applications. The NFC technology utilizes the same ISO protocols for communications with the transponders as HF RFID at 13.56 MHz. Every NFC-enabled smartphone thus functions as an RFID reader that supplies the sensor transponder with power, so that it can then read and transmit the sensor data without an additional battery on the transponder side. NFC can therefore open up new applications for consumers in the future and can serve as a key technology in the B2C segment.

Lack of flexible and energy-efficient transponder architectures

Dedicated RFID sensor transponder ICs, in which the sensors are integrated directly into the RFID chip, are state of the art, so that energy efficiency, functionality and sensor accuracy can be optimized within the IC [1]. However, such ICs are designed for specific applications and are therefore not flexible enough for a wide variety of application scenarios. Many commercial RFID sensors therefore combine RFID transponder ICs, microcontrollers (MCU) and stand-alone sensors, see Figure 2.

Here, it is the MCU that manages the sensor operation, acting as master in the system. The sensors and RFID IC will act as a slave. In systems like this, most of the power available from the reader is used up by the MCU, which consumes approx. 100 µA/MHz. Therefore, it is not possible to interface them with energy-hungry sensors, such as optical sensors based on photodiodes and LEDs, which are frequently used in diagnostic applications. An LED approximately requires about 3 – 5 mA for its operation.

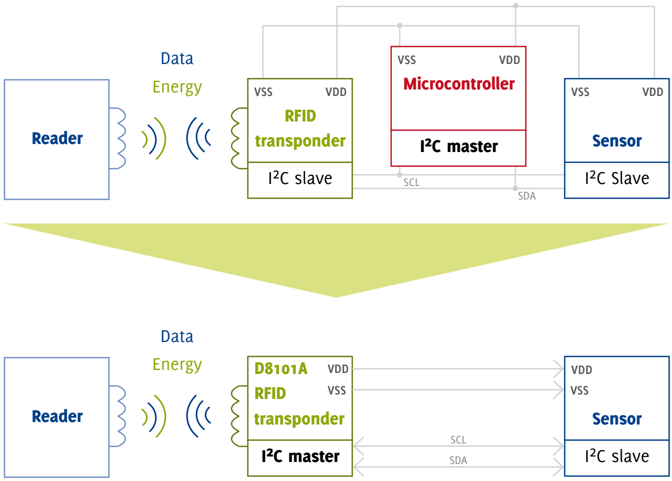

Figure 2:

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

Below: In RFID sensor systems with the new RFID transponder IC D8101A with integrated (on-chip) master, a microcontroller is no longer necessary.

Diagram: IMMS.

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

In response to this need, IMMS has developed an NFC-compatible HF RFID transponder IC that can serve as a flexible wireless bridge interface for commercially available digital I²C sensors. The chip is supplied with an on-chip I²C master and a configurable power management block which can support different types of sensors with different power requirements. It can supply a regulated voltage for external sensors up to 2.2 V at a maximum current of 10 mA [2]. The on-chip I²C master block eliminates the need for an MCU to perform simple read/write operations with sensors. This reduces the power consumption of the entire system as well as the number of external components required to build an RFID sensor transponder. Figure 3 shows the chip architecture.

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Figure 3:

Block diagram of the RFID sensor transponder IC D8101A.

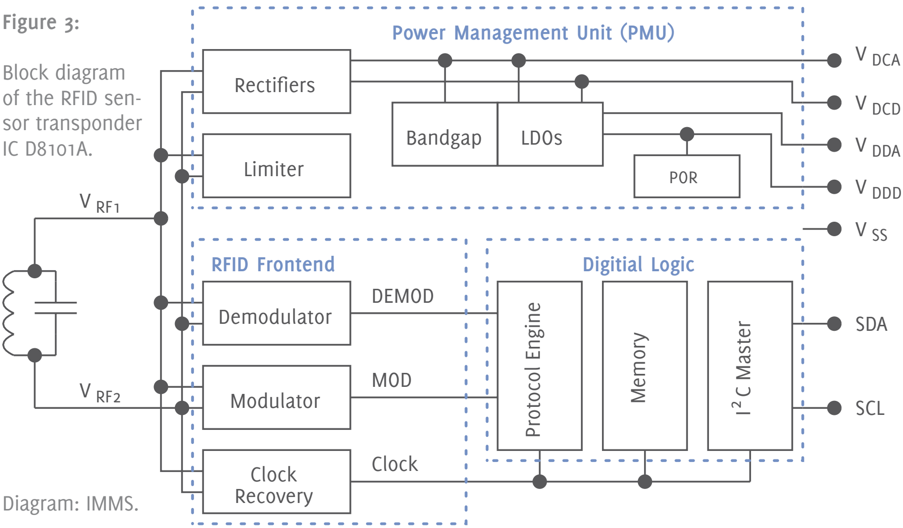


Diagram: IMMS.

When coupling an I²C master with a slave IC, pull-up resistors are required on each bi-directional line (SDA, SCL). In a conventional I²C bus system, the ohmic resistors are unfavourable for high energy consumption. To solve this problem, IMMS has also developed a latch-based ultra-low power pull-up emulator that is fully I²C standard-compatible [3]. Together with the pull-up emulator, the RFID sensor transponder IC forms an extremely energy-efficient solution for building wireless personalized health-care applications.

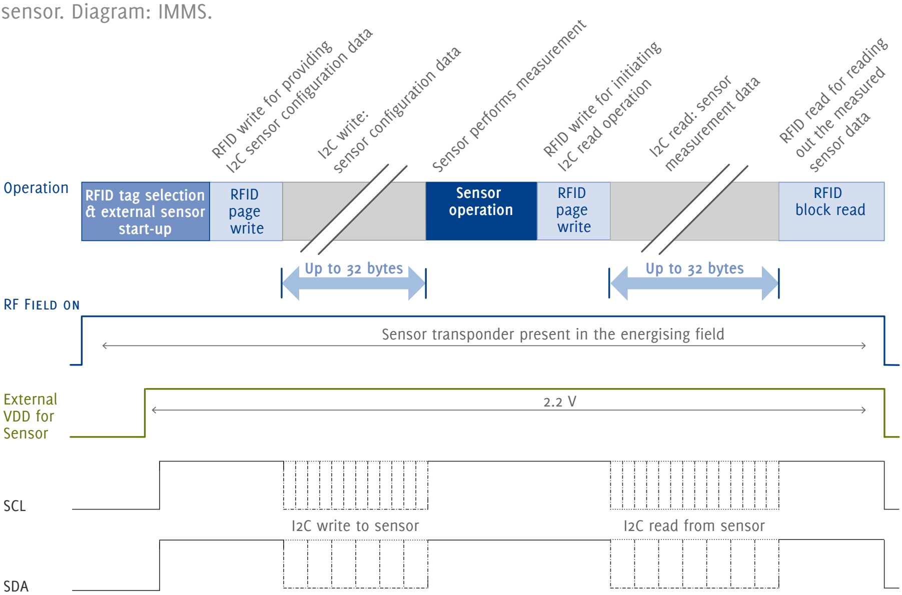
Power management and communications with I²C sensors

Unique to the developed chip is the flexible power management, with which stable communications with external I²C sensors is achieved. The chip uses an external capacitor that automatically stores energy while the transponder is in the energy field of the reader. When the required energy for system and sensor operation is charged, an internal interrupt "Power_OK" is initiated. From this point on, the operation of the connected I²C slave chips, such as sensors and external memory, can be initiated. The charging process of the external capacitor is configurable to allow different energy consumption levels of commercial sensors. Configurations can be easily programmed to the on-chip memory using standard ISO 14443 Type-A write commands. For communications with the external I²C sensors, the I²C communications informa-

More on energy efficiency: www.imms.de.

More on communications solutions at www.imms.de.

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



tion is written into the command registers in the transponder memory. The on-chip I²C master makes use of this information to initiate the I²C transactions with the external sensors. For external I²C sensors, the chip offers flexibility of operation in the following respects: multiple read and write operations; combined reading and writing (write information to start sensor operation and read back acquired data on conclusion of operation); start delay (time for start-up of sensor); delay between two consecutive I²C writes (required when writing information into a non-volatile external memory).

Monitoring of diagnostic applications in laboratories

The developed chip is not only intended for NFC-based sensor applications in consumer applications but can also be used for diagnostic laboratory applications that require permanent monitoring of environmental parameters such as temperature, humidity and pressure. Since the chip is fully compatible with the ISO 14443 Type-A protocol, it can be used with any commercially available HF RFID reader.

More on Life Sciences at www.imms.de.

Future prospects: digital value creation thanks to NFC

A major advantage of NFC-based analysis of sensors compared to conventional approaches is its compactness and flexibility: with NFC, the user can configure and read out the sensors via a smart phone app, which enables complex parameter combinations, analysis algorithms and the connection to the internet in a simple way. Instead of having to install LEDs or a display on the sensor side, the larger screen of a smartphone or tablet can be used. This increases user-friendliness and simultaneously reduces system costs. Compared to other technologies such as Bluetooth or WiFi, NFC-based sensors do not require batteries, which is a major advantage, especially compared to today's disposable electronic tests. Therefore, the presented RFID chip when intended for interfacing with commercial sensors offers for the first time a technological basis for a large number of point-of-care applications where sensor data is collected for new

More on communications solutions at www.imms.de.

Figure 5: Smartphone app developed by IMMS for reading data from the RFID sensors. Photograph: IMMS.

value creation, e.g. with individualized product recommendations, in a resource-saving way, thus paving the way for new data-driven business models in our digital world.

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[1] J. Tan, M. Sathyamurthy, A. Rolapp, J. Gamez, E. Hennig, E. Schäfer, and R. Sommer, **"A Fully Passive RFID Temperature Sensor SoC with an Accuracy of ±0.4°C (3σ) from 0°C to 125°C,"** *in IEEE Journal of Radio Frequency Identification (JRFID), vol. 3, no. 1, pp. 35-45, Mar. 2019.* **DOI: 10.1109/JRFID.2019.2896145**

[2] J. Tan, M. Sathyamurthy, A. Rolapp, J. Gamez, M. Elkharashi, B. Saft, S. Jäger, and R. Sommer, **"An RFID to I²C Bridge IC with Supply Interference Reduction for Flexible RFID Sensor Applications,"** *in IEEE International Conference on RFID 2019, Phoenix (AZ), USA, Apr. 2019.* **DOI: 10.1109/RFID.2019.8719257**

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More detail on ADMONT at www.imms.de.

RESEARCH SUBJECT CPS:

ENERGY-EFFICIENT AND ENERGY-AUTONOMOUS CYBER-PHYSICAL SYSTEMS

For their development of the SONAPHONE digital ultrasonic leak scanner, SONOTEC and IMMS earned third prize in the TÜV Süd Innovationspreis 2019 competition. The mobile testing device unites innovative sensors and software to be used intuitively in Industry 4.0 maintenance tasks. IMMS developed the digital components of the hardware and the FPGA firmware. Photograph: IMMS.

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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 detail on Industry 4.0 at www.imms.de.

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

Highlights of 2019 in our energy-efficient and energy-autonomous systems research

SONOTEC and IMMS win third prize in the 2019 TÜV SÜD Innovation competition

For their development of the SONAPHONE digital ultrasonic leak scanner, SONOTEC and IMMS earned third prize in the TÜV Süd Innovationspreis 2019 competition. The mobile testing device unites innovative sensors and software to be used intuitively in Industry 4.0 maintenance tasks.

More on the SONAPHONE at www.imms.de.

"This award gives us extraordinary pleasure. It provides an even stronger foundation for our success story in ultrasound testing and maintenance equipment. The prize gives due credit to the teamwork we achieved and will help us to continue with developing our SONAPHONE technology," said Michael Münch, SONOTEC GmbH's CEO.

Leak detection with the digital ultrasonic testing device SONAPHONE for maintenance 4.0.

The device is presented by the award winners in a video from TÜV Süd.

Photograph: SONOTEC.

Award for the SONAPHONE digital, mobile ultrasonic testing device to use in “I 4.0” maintenance

The ultrasound specialists from Halle have been developers and distributors of ultrasound testing equipment in the maintenance field for more than 25 years. Among the purposes of their products are detection of leaks in compressed air plant, condition-monitoring and inspection of electrical installations. With the SONAPHONE device, SONOTEC has revolutionised maintenance tasks and has brought the first digital, ultrasonic tester onto the market that is Android-based. The innovative smart technology relies on a modular system made up of a new type of broadband sensor, electronic components, mathematical algorithms, new measurement techniques and new software applications.

Publications & videos on the SONAPHONE at www.imms.de

The advantage is that any damage to machines, for instance in association with roller bearings and ball bearings, can be detected before it has even arisen, and the components replaced. In addition, the hand-held mobile tester has for the first time made automatic evaluation of compressed air leaks possible. The maintenance engineer has the specially developed apps to hand throughout the testing process so that consistent reports are guaranteed. Sketches on paper with their imperfections can now be replaced by using this device and its technology.

SONOTEC and IMMS worked hand in hand on the SONAPHONE

“We were only able to achieve so much innovation in the SONAPHONE by close cooperation with IMMS,” says Michael Münch. For instance, while IMMS staff were getting the digital components of the hardware and the FPGA firmware together, SONOTEC were able in parallel to develop the broadband air-borne and structure-borne sound sensors, together with the design and the apps for the device. As Professor Ralf Sommer, Scientific Managing Director at IMMS, puts it: “The SONAPHONE is proof that cooperation between SMEs and academic institutions is a real source of innovative energy”.

Technical data and product information on the SONAPHONE: www.sonotec.de

What is the TÜV Süd Innovationspreis?

This is the third time that a competition has been offered for cooperation between enterprise and academia, leading to this regional innovation prize. It is open to all lateral thinkers in Germany's SMEs who have developed a particularly creative idea, a product, an innovative process or a technological service in conjunction with a university, University of Applied Science, or research institution. The finalists share between them 50,000 euros.

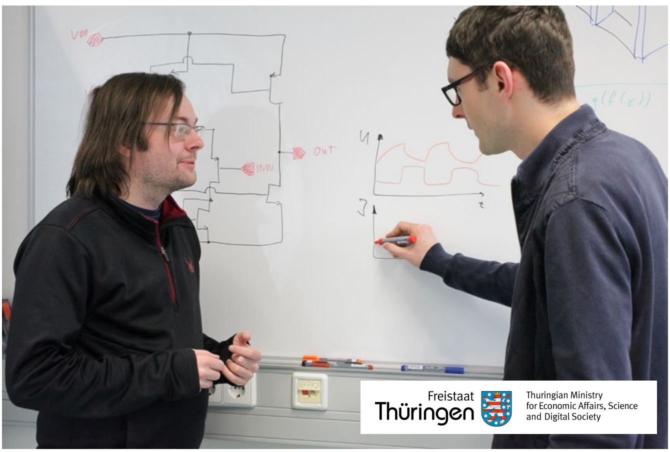
IntelligEnt* research group begins work on AI and ML for design in microelectronics

Since January 2019, under the name IntelligEnt, IMMS and the group in the Ilmenau TU Department of Computer Science and Automation concerned with Software Engineering for Safety-Critical Systems (SECSY) have been working together on assistance systems for chip designers in a two-year Thüringen project with the name "IntelligEnt – Artificial Intelligence and Machine Learning for the design and verification of complex systems". The purpose is improvement of design methodology in integrated analogue/mixed-signal systems. An advisory council accompanies the project, with members from X-FAB Semiconductor Foundries GmbH, Melexis GmbH, Micro-Sensys GmbH, Ilmsens GmbH and the CiS Forschungsinstitut für Mikrosensorik GmbH.

More detail on IntelligEnt at www.imms.de.

Designers' know-how for mixed analogue/digital systems difficult so far to automate

Crucial in the creation of microelectronic and micro-electro-mechanical systems (MEMS) is the design engineer's knowledge and experience. The development of



Since January 2019, IMMS und TU Ilmenau have been working in the Thüringen research group "IntelligEnt" with artificial intelligence methods and machine learning on assistance systems for the design of microelectronics.

Photograph: IMMS.

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

such systems has long been researched, with improvements and ever more sophisticated automatic design methods being achieved. It has to be said that the engineer's knowledge from experience is not easy to represent visually so that it can be used for automatic design as would be the case if the systems were purely digital. In consequence, systems that are analogue and complex or are mixed analogue/digital are often less than perfect or have incongruencies like poor layout or incorrect test limits which come to light only later, often not until they interact with the components they are serving. More time and money thus has to to be invested at both the design stage and that of validation of the systems after fabrication.

The aim: to use machine learning at the system design stage as a means to major reductions in cost and risk

The IntelligEnt group formed by IMMS and Ilmenau TU is, therefore, working on application-oriented machine learning concepts in the design of microelectronic devices which can be tacked on to existing methodology and tools. The aim is to make use of the huge potential of machine learning for continued practical and research progress, dramatically reducing both the costs and the risks associated with system design.

This will be possible if the incongruencies are found early and obviated to maximum effect. There are many areas in which machine learning has the edge over humans, among them being pattern recognition. If an automated design and characterisation process is integrated into the system design procedure it may, by recognising structures, reduce the total sum of data, sniff out anomalies and greatly improve the existing solution. In the IntelligEnt project, the machine learning algorithms are seen as tools with uses such as regression and classification based on deep learning methodology or for detection of outliers based on self- and semi-supervised learning.

In IntelligEnt, critical stages in the system design are being tackled

Modelling – creating models of predicted behaviour: Critical for the design quality is the creation of models of the system components and/or the IP. The idea is that integrating features like power consumption and operational areas into system level models will in the end be automated because the system is capable of learning.

Creating functions when designing analogue/mixed-signal circuits: The structure or the topology is what determines how well a mixed analogue/digital circuit performs. To get computers to optimise the structure, a procedure for structure recognition and adaptation is being developed.

More detail on IntelligEnt at www.imms.de.

Designing the chip manufacturer's construction plan at the analogue/mixed-signal circuit layout stage: Layouts that are technically correct may still have incongruencies, among them substrate coupling, field transistors and mismatch. A self-learning system should be able to evaluate new layouts by starting from existing designs and recognising potential mistakes.

Checking all steps and functions at pre-fabrication stage by simulation and verification: at each of the above stages, before the chip is fabricated, the system is checked, with the function groups increasing in size at each stage. The simulations carried out for this purpose make use of the models that have been extended by the machine learning methodology.

Checking manufactured chips with absolute thoroughness by testing and characterisation: to date, optimisation of the test procedures and the choice of critical tests for MEMS and mixed-signal systems have had to be done manually, which can mean that redundant tests are carried out. Machine learning algorithms are capable of revealing the factors which are interdependent, so that they can be taken account of. The aim is a digital platform on which the test plan can be adapted, with removal of images predefined as unsatisfactory.

More detail on IntelligEnt at www.imms.de.

Results from StadtLärm* project included in MDR-Wissen's noise study – sensors and central data turntable by IMMS

In June 2019, when the science section of MDR, a German broadcaster, called on people in Central Germany to report on noise sources, it was for the MDR Wissen noise study. MDR's appeal was its springboard for a scientifically supported, deep-probing dive into noise problems and potential solutions. Among the supporting scientists were the creators of a noise monitoring system that resulted from the StadtLärm project, concluded in 2018. StadtLärm means "CityNoise": it was a response to the noise pollution from sporting and other major events, building works or even individual moving vehicles, suffered especially by people in towns and cities.

First field test in Jena

The StadtLärm project saw the development of a full new system. It has been on field test in Jena, Germany since the spring of 2018, continuously and anonymously logging noise-related data from a wide area as detected by sensors. Noise-space models are created with the innovative software, appearing in 3D visualised form on maps of the city (in this case, Jena) or in graphs. The measured data can be correlated with specific events, such as city centre concerts for which permission has been given.

More detail on StadtLärm at www.imms.de

Work at IMMS on components for noise measurement, which were also used for the noise study by MDR Wissen. Photograph: IMMS.

ZIM Zentrales Innovationsprogramm Mittelstand

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Study of noise, Central Germany

The aim of the MDR noise study is to produce a noise map for Central Germany. Certain of the noise sources reported by those affected, including the B244 trunk road in Wernigerode and Sachsenring, a motor racing track, in Hohenstein-Ernstthal, have already been taken into the study. The monitoring systems developed in StadtLärm were installed at these locations, measurements were taken over several weeks in each case and the results were investigated with the help of Fraunhofer IDMT, which had been the initiator of the StadtLärm project, bringing IMMS on board to do the conceptual design of the system architecture and to create the basic software for the noise sensors. For the Central German noise study, IMMS provided the hardware to use at the various installation locations, gave technical instructions, helped on the installation and dismantling, and ensured the system was operating and data being acquired.

Documentation in the MDR media library

StadtLärm as novel solution for noise monitoring

The StadtLärm system enables local authorities to observe not only the level of noise but also, using a web-based application, the types of events as classified by the system, and thus to assess the source of any noise more effectively. They can refer to data gathered both in real-time and retrospectively for particular and/or longer periods, resolved in terms of time and location. In addition, the system can be used to predict future noise from noise events of the past.

More detail on StadtLärm at www.imms.de

The classification of sound events was developed by project partner Fraunhofer IDMT. The data for the system is supplied from a platform with noise sensors developed by Bischoff Elektronik GmbH, and there is a central turntable or ”data hub“ in the form of an MQTT broker. This broker forms the interface between the evaluating algorithms provided by IDMT and for the StadtLärm application created by another of the project partners, Software Service John.

An IMMS contribution: the central data turntable

As the StadtLärm partner creating the basic software platform for the noise sensors and data acquisition, also integrating the audio data processing provided by Fraunhofer IDMT, IMMS came up with the communication-via-broker solution and all the communications architecture. This involved defining the communication structures and messages, configuring and supervising the broker, and producing a central administrative component for the overall system. In addition, IMMS increased the platform's usefulness by integrating into it variable sensors for environmental conditions.

More detail on communications solutions at www.imms.de.

Retrofit automated KSS* (cooling lubricant) monitoring

In metalworking situations, cooling lubricants (KSS) are part of many manufacturing processes. Lubricoolant emulsions do not merely cool, they reduce friction, protect against corrosion, contribute to higher dimensional accuracy and improve surface quality. They are, however, prone to biological contamination, fungal or bacterial, and thus have to be kept under constant observation, with additives to restore or maintain quality. Being of considerable relevance to employees' health and safety and to the environment, they are subject to strict legislation.

KSS-Kontrolle at www.imms.de

Add-on sensors automate required KSS testing and offer new functions

In a project with the name KSS-Kontrolle, a system for use in machining has been under development since 2019 which fully automatically and without interruption captures the data for both process and environment. It thus permits correlation of the quality of the finished products with the condition of the cooling lubricant used as well as the state of the latter with environmental conditions. This new system brings high-quality automated control of KSS (previously available only in the centralised plant of major manufacturers) into the reach of SMEs, despite the fact that they mainly have decentralised machines, each with separate cooling lubrication. The previous manual checks requiring staff and time investment are automated and the digital data comes at shorter intervals, helping to improve process stability, reduce the quantity of additives needed and make it easier for companies to keep within the health, safety and environmental rules.

EFRE
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EUROPEAN REGIONAL DEVELOPMENT FUND
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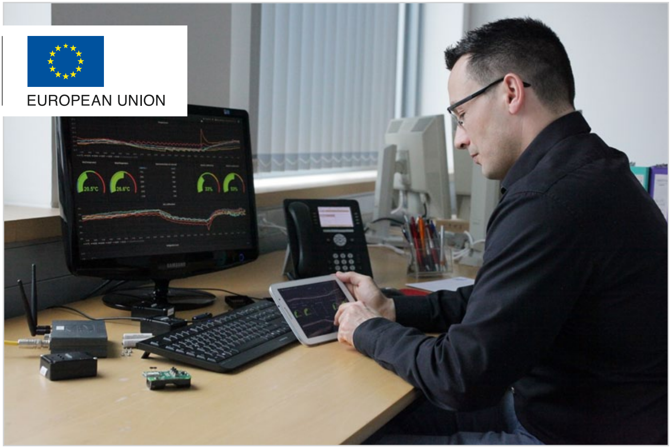


The IMMS contribution to a retrofittable system for monitoring lubricoolants comprises sensors, signal communication and a configurable software infrastructure.

Photograph: IMMS

IMMS provides the sensors and systems for acquisition, transmission, processing, visualisation and cloud storage of climate data

In the project, IMMS will incorporate wireless environmental sensor technology into the system, which will be able to detect this factor directly influencing component quality and to indicate ambient conditions relevant to deterioration of the cooling lubricant. IMMS will also use an industrial PC to aggregate the data from all sensor systems on site and transfer it to a cloud platform. The cloud implementation will be technologically compliant with Industry 4.0, providing central data storage and evaluation. Wherever possible and available, the solutions for data storage, data processing and visualisation will be open-source. To enable the whole system to be incorporated into particular projects, IMMS is also planning and implementing a means of rolling out the entire software infrastructure to benefit additional installations, with the advantage of keeping manual configuration to a minimum.

KSS-Kontrolle at www.imms.de

Gefördert durch:
Bundesministerium für Ernährung und Landwirtschaft
aufgrund eines Beschlusses des Deutschen Bundestages

ptble
Projektträger Bundesanstalt für Landwirtschaft und Ernährung

Preliminary studies with different soil moisture sensors for measuring the microclimate as well as for data collection to monitor drought stress. Photograph: IMMS.

Launch of EXPRESS* – experimental field for digitisation in agriculture

Digitisation is also becoming increasingly important in agriculture, for example to optimise the irrigation of crops during long dry periods. Many farms, however, lack the prerequisites for identifying suitable and affordable systems for them, recording their potential and generating benefits for them.

EXPRESS at www.imms.de

Regional Experimental Field EXPRESS

The basis for the interaction of existing technical infrastructures with new technologies and methods is therefore to be tested and evaluated on farms within the German experimental field EXPRESS, launched in 2019.

EXPRESS aims primarily at crop production with a special focus on special crops. Digital technologies are to be used to increase resource efficiency, support environmentally friendly production and preserve biodiversity in the long term. Innovative technologies such as sensor systems, block chain, virtual reality, field robots, and 5G applications shall help to shape new value chains and optimise production processes.

In EXPRESS, we will test potentially suitable technologies in cooperation with farmers. The results are made available to the industry. We focus on five use cases corresponding to focal areas:

- cross-scale water stress monitoring for irrigation optimisation
- automatic monitoring of abiotic key parameters, e.g. by measuring the microclimate in the crop
- food tracing via block chain

- augmented/virtual/mixed reality in agriculture
- data integration and management of highly heterogeneous data sources from various sensor systems

IMMS supports monitoring of microclimate and drought stress

IMMS is responsible for data collection and is in charge of determining the microclimate and other parameters for monitoring drought stress. Different system solution concepts for these two applications will be evaluated with agricultural enterprises. For this purpose, IMMS is testing various sensor systems available on the market for their suitability for the two use cases. This also includes an evaluation of RFID sensor technology. In addition, IMMS is equipping the experimental fields with suitable sensor technology, monitoring their operation and the transmission of data via 5G to the S2DES cloud.

IMMS develops cost-efficient autonomous sensor systems for practical use

The focus of IMMS developments is on practical, self-sufficient sensor systems. We design these systems as modularly as possible in order to later adapt them to the respective boundary conditions in an agricultural enterprise and to be able to use them there for further analyses and optimisation. The challenge here is to develop cost-effective systems that record all the necessary variables with sufficient accuracy and at the same time enable usable and, above all, useful information to be obtained with as few measuring points as possible.

EXPRESS at www.imms.de

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

Constructing demonstrators for knowhow transfer

In its role as "Migration Model Factory", in the "Mittelstand 4.0" (SME 4.0) Competence Centre Ilmenau, IMMS uses technological demonstrators and feasibility studies to show small and medium-sized enterprises how they can gradually introduce digitalisation into their practice.

More detail on the SME 4.0 project at www.imms.de

2019 saw IMMS creating the **"Retrofit"** demonstrator in conjunction with the software company Batix as part of the Retrofit M4.0 technology migration scheme. It reveals how simple it is to retrofit an ordinary power drill with various sensors. Serving as proof of concept, the retrofitted drill is a paradigm of how to bring up to scratch for digitalisation any machinery already present. AI (artificial intelligence) is applied in processing and evaluating the data that is captured in the drilling process. The result is data visualised "just in time". Retrofitting of this kind enables a machine to be meshed with the existing factory IT systems.

A further technological demonstrator of a mobile kind was made during 2019 as part of the SME 4.0 "**Sensorik-Koffer 2**" project (its name implies "sensors in a suitcase"). In it are installed sensors with commercially available SmartMesh® IP modules suitable for industrial use. These modules can automatically construct a fully meshed wireless sensor network with routing-enabled nodes. The network at present contains, as one retrofitting idea for machinery or whole shopfloors, sensors that detect ambient conditions and vibration. The system can, however, be extended at any time to include further sensors. The "Sensorik Koffer 2" is available for demonstrations to interested companies in-house at IMMS or at trade fairs and other events or for on-site test installation.

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

IMMS is a Migration Fab in the Ilmenau M4.0 competence centre supporting SMEs. In 2019, IMMS experts gave eleven workshops, six regulars' drop-in meetings or information days, and, at outside events, eight lectures. These were all funded by the German federal ministry for industry (BMWi) and free to SMEs. They reached about 540 people, many of them representing industry in the local region. Over the year as a whole, IMMS also conducted 29 information sessions with SMEs, opening up a number of collaborative projects with the Institute and other enterprises for the companies.

2019 also saw the subject of **artificial intelligence** (AI) came to greater prominence at the regular M4.0 drop-in meetings. At these events, external speakers from research and industry indicated how AI can be applied in a company or in acoustics or in the monitoring of machinery. Plans have been made to provide the scheme known as "AI trainers for SME 4.0" also in Ilmenau and at IMMS. This format focuses on digital connectivity in manufacturing and work processing for regions with a fragmented industrial structure.

The **Sensors 4.0 workshop series** for M 4.0 that had been established in 2017 continued through 2019, covering aspects of Linux-based real-time-capable sensor systems and OPC Unified Architecture (OPC UA).

All SME 4.0 events at www.imms.de.

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.

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Mittelstand-Digital

These are events in which IMMS provides company chiefs, engineers and decision-makers with practical ideas and resources to improve plant and processes by applying the technology of Industry 4.0. Using examples from practice itself, lectures are given on how machinery can be retrofitted with a mesh of wireless sensors, data from which will then help contribute to new diagnosis, maintenance and service schemes and link up with cloud-based services. Participants are taken step by step through all the stages of their own first attempts at using open-source software on universal electronics platforms for components that are Industry 4.0 compatible. They get hands-on experience of how real-time-capable solutions can be put together rapidly at a reasonable price.

Again in 2019, the **workshop series on using OPC UA in Industry 4.0 communications** saw IMMS opening up to members the details of the new industrial communications norm and many real instances of its use. On-the-spot exercises illustrated Industry 4.0 communications practice and how to get components ready to apply it.

IMMS also provided several workshops on Design Thinking and arranged drop-in meetings for regulars on subjects which included RFID in Manufacturing, Automated Testing and the Digital Twin, and Digital Tools to Keep Work Organised. At all of these, numerous external speakers gave professional input and held discussions with participants.

All SME 4.0 events at www.imms.de.

Dr. Tino Hutschenreuther (r) showing demonstration models at IMMS to Reinhard Bütikofer (l).

Photograph: ”Mittelstand 4.0-Kompetenzzentrum Ilmenau“.

Reinhard Bütikofer visits IMMS at the ”Mittelstand 4.0-Kompetenzzentrum Ilmenau“

On 13th December, 2019, the two Ilmenau partners in the M4.0 project (the Ilmenau competence centre for SMEs and Industry 4.0), Ilmenau TU and IMMS, received a visit from Reinhold Bütikofer, MEP (Green) and Ms Stella Versimer, his assistant in the Thüringen Green Party regional office which had been opened in August. They came to learn what view the competence centre takes on current Thüringen issues and collaborative structures.

Competence centre supports Thüringen SMEs with digitalisation and connectivity

More detail on the SME 4.0 project at www.imms.de

Funded by BMWi, the German federal ministry for industry, with the TU leading the consortium, the competence centre is a source of hands-on manufacturing demonstrations and theory-to-practice digitalisation scenarios. These take the form of five ”model factories“ for the benefit of participating SMEs. The visitors were given insights into the practical work of the centre. They saw successfully implemented projects and sample constructs which all demonstrate how introducing Industry 4.0 techniques and digitalisation and increasing the efficiency and flexibility of production and business chains all the way through from the drawing board to the finished product brings competitive benefit.

Examples at IMMS showing digital transformation and increased energy and resource efficiency

On the models demonstrating automated, energy-efficient start up after a pause in manufacturing and such examples as the UV-sensor-supported water disinfection unit showing economy with resources, Mr. Bütikofer said: ”Companies need to bring environmental issues into much sharper focus. They are a vital aspect as companies seek the competitive edge. This digitalised technology shows the way. This is how industry by saving resources can protect the environment while at the same time saving money."

Dignitaries Dr. Daniel Schultheiß and Ms Beate Misch visit IMMS

On May 2nd, 2019, IMMS was paid a visit by the Mayors Dr. Daniel Schultheiß (for Ilmenau and its attached communities) and Ms Beate Misch (for Ilmenau town), together with Sebastian Poppner, Ilmenau's Industrial Support Officer.

Guided tours of several labs, presentations of prototype products and demonstrations of applications devised jointly with partners in industry clearly showed how IMMS supports regional SMEs with its R&D, fulfilling its mission of connecting the analogue world to that of information technology by digital means.

The visitors saw prototype data-intensive real-time software applications currently under investigation in the Time Sensitive Networking (TSN) laboratory. A variety of sensor systems using cloud connections were also presented which are to serve industrial automation and wireless sensor networks for traffic connectivity.

In one of the experimental semiconductor labs, dignitaries got a glimpse of measurement tasks required in the development of MEMS chips. Their last destination was the lab working on high-precision drives. Here, drives were demonstrated that IMMS has engineered for the sort of positioning systems that enable products in the semiconductor and life-science fields to be fabricated with accuracy down to the last nanometre.

Dr. Daniel Schultheiß, Sebastian Poppner, Beate Misch and Prof. Dr. Ralf Sommer, Scientific Managing Director of IMMS, (f.l.t.r.) in one of the test laboratories for the microelectronic and micro-electro-mechanical systems developed at IMMS.

Photograph: IMMS.

Ko^{2}SiBus – Continuous, cost-effective signal analysis for Ethernet-based bus systems

IMMS has developed novel cost-effective methods of monitoring data lines across running industrial plant. A demonstrator maps the entire system with the complete analysis chain: Ethernet signals can thus be manipulated in a targeted manner to simulate cable faults artificially or to show the influence of such faults. Photograph: IMMS.

Motivation and overview

Until now no continuous monitoring of communication lines in interconnected machinery

The conditions and processes in machines and industrial plant are continuously monitored to enable highly automated processes in industry to run smoothly. However, what is still missing, because there has been no suitable procedure to do so, is the wiring of ethernet based communications which enables rapid, secure data exchange and links up networked industrial plant. It is only at the commissioning or during maintenance (if the machine is stopped for the purpose) that these physical connections are checked. But cables in production areas can be put under great strain by constant bending: for instance, when they are carried over drag chains. The strain can cause the data transfer quality to deteriorate and may even lead to cable breakages. With current methods, such changes in the cable properties are not at present being monitored, which makes the cables an additional weak point in any system.

More on Industry 4.0 at www.imms.de.

More on Ko^{2}SiBus at www.imms.de.

A solution for continuously monitoring communication cables to ensure trouble-free production

With a view to reducing the associated downtime and maintenance effort to a minimum, methods were designed, developed and evaluated in the Ko²SiBus project, to enable the monitoring of the signal quality in the Ethernet cable continuously and cost-effectively for a plant during its regular operation without any interruption to the actual communications. The methods conceived were implemented in the form of a prototype. Its effectiveness was proven in laboratory tests.

This should not only make it easier to plan maintenance work. The new concept should also make it possible to pass on the data from the monitoring through a unified open interface so that it can be easily integrated into customer-specific control systems,possibly as a switch extension or as a feature installed directly into the end device.

IMMS created a circuit concept and constructed a demonstrator

The role of IMMS in the continuous monitoring scheme of communication lines was to design an embedded system and develop the appropriate circuit concepts, creating a system that tracks physical signal parameters using integrated analogue and digital components and reports any deviations to a monitoring centre. The functionality was tested with a demonstrator largely built by IMMS. The demonstrator maps the entire start-to-finish system from the signal measurements through to graphical representation of the analysis and the integration possibilities. It can also be used to manipulate the Ethernet signals very specifically, for example to simulate cable faults artificially or to show the influence of such faults.

More detail on signal processing at www.imms.de.

View on the project by TURCK Electronics

The IMMS solution in detail

Preparatory work for IMMS' circuit design

With the project partners, IMMS compared and analysed possible test and inspection methods for a variety of Ethernet standards. Having identified the 100BASE-TX standard as that used in a majority of applications installed currently in machinery, see Figure 1, they focused on this for later work so as to be able to offer solutions for the most commonly used Ethernet installations first. Offenburg University of Applied Science researched the communication interfaces required for transferring analytic data to higher systems. This partner also optimised and implemented standard protocols for small, low-power microcontrollers and created the relevant control sys-

› INPOS
› INSPECT
› ADMONT
› Ko²SiBus
› AgAVE
› Dig. Engineering
› IRIS
› Contents
* Funding

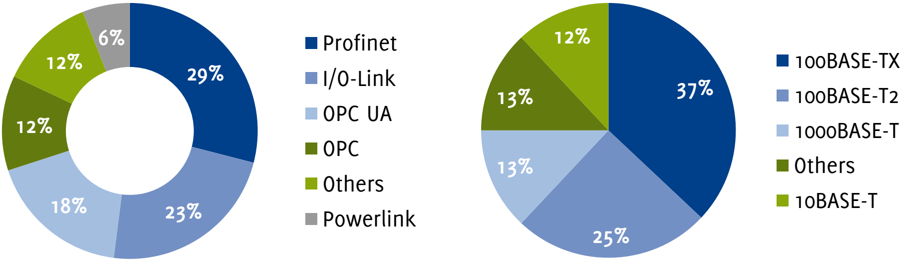


Figure 1: Standards and Ethernet modes used in industry. Source: survey by Offenburg UAS.

tems for the analytic functions. The Simple Network Management Protocol (SNMP) and the OPC Unified Architecture Protocol (OPC UA) were the protocols used for the system developed in the Ko²SiBus project.

IMMS' circuit to provide measurements on basis of undersampling

Equivalent circuits for short wires in series constitute the circuit for a cable

If a short section of wire is considered, the wire has inductance L in series with the resistance R. Together, the wires adjacent to each other and the return wire create a capacitance C. Finally, there is a very high insulation resistance G between the two wires. The short length of wire can be described approximately by an equivalent circuit which is made up of these four elements. A cable can thus be modelled as numerous such small circuits connected in series. From the discretised equivalent circuit diagram, it is clear that a cable is a cascade of second order low-pass filters.

Different Ethernet-categories – different data transmission features

The ISO/IEC 11801 norm defines the categories (cat) of twisted pair cables. Each individual category specifies certain transmission features of the data-carrying cable such as impedance, bandwidth and attenuation which derive from the primary wire parameters (L, R, C, G). In the 100BASE-TX standard, the characteristic impedance is defined as 100 Ω for all cables. Cat5 cables (belonging to category 5) or cat5e cables must have transmission bandwidth of 100 MHz, cat6 cables 250 MHz.

The Fast Ethernet 100BASE-TX standard provides a series of coding steps which are intended to counteract strong signal power dissipation and baseline wander (i.e. drift in the DC voltage) and make clock recovery possible. The multistep coding process includes 4B5B (4bit-to-5bit) coding, a scrambler, NRZI (Non-Return to Zero

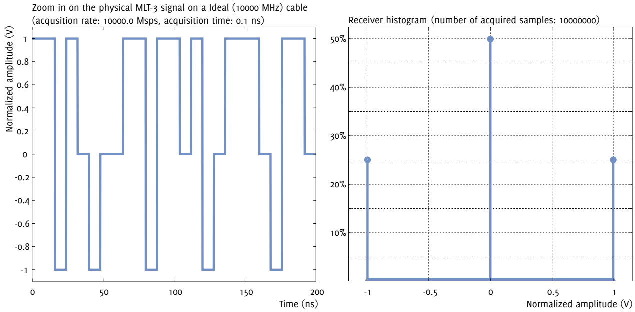


Figure 2: Idealised MLT-3 signal and histogram. The screen-shot on the left shows the sequence of an idealised MLT-3 signal. The resulting histogram shown on the right reflects the distribution of the symbols, which only extends over the three available symbols. Source: IMMS.

Inverted) coding and MLT3 (Multi Level Translation) coding. Finally the electrical signal is carried along the wire at three different levels (–1 V, 0 V, 1 V) and a symbol rate of 125 MBaud within a bandwidth of 31.25 MHz.

If the Ethernet data stream is randomly scrambled, the distribution of the signals is on average 25% at –1 V, 50% at 0 V and 25% at 1 V. Ideal distribution is shown in Figure 2. Figure 3 shows the influence of a cat5 cable on the signal shape and the frequency distribution.

More detail on signal processing at www.imms.de.

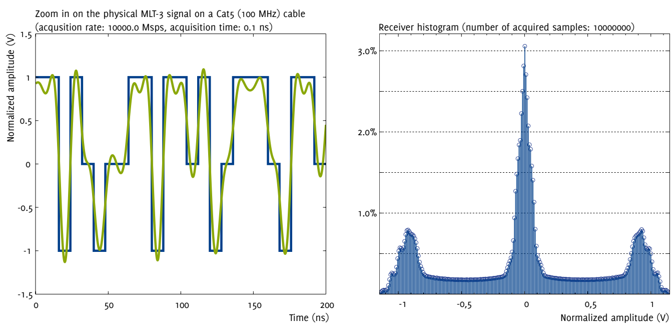
Disturbances are revealed by evaluating the frequency distribution of changed characteristics

If there have been changes in the cable, for instance because the insulation is damaged, the above mentioned primary nominal dimensions (R, L, C, G) will also change. This makes it possible to detect deviations in the transmission features: reduced bandwidth, for example. Such deviation inevitably leads to a different frequency distribution for the signals being transmitted, so that determining and evaluating the frequency distribution of the transmitted symbols or the voltage level will provide a statement on changes in the cable and enable warnings to be issued before the connection is broken.

Figure 3:

Actual MLT-3 signal and histogram. In the case of a real MLT-3 signal, the symbols are somewhat distributed but assignment is nonetheless clear.

Source: IMMS.



To establish the frequency distribution of the symbols transmitted, the signal must be sampled at at least twice the signal frequency i.e. at least at 250 MHz. This in turn makes expensive hardware components (ADC, FPGA) necessary. As an alternative approach, for a more cost-effective circuit solution, undersampling was chosen, by which the signal is sampled at a lower frequency.

Analysis and evaluation by undersampling and using four parameters

Granted, undersampling means the data transmitted cannot be restored; however, the statistical distribution can be established nonetheless. Evaluation of the undersampled Ethernet signals reveals multi-modal distribution with three modes, around the three values 1, –1 and 0.

The four following parameters were defined for determining cable quality: clarity, amplitude, asymmetry and activity. From these four parameters a good description of the distribution of the signals can be obtained. To calculate distribution, the ADC values are subdivided into 32 voltage ranges (the lines in the histogram) and 1000 readings are evaluated for each subdivision.

The **Clarity** parameter contains an estimation of how clearly the levels (–1, 0, +1) can be distinguished from each other. To calculate the Clarity, the sum of the assigned values is obtained. The lines in the histogram that have the most values are established and the neighbouring values included. Good signal transmission has high clarity, i.e. only a few samples lie between the 3 modes. A value that is too low indicates much noise or excessively high capacity values in the cable.

The **Amplitude** parameter is found from the distance between the most positive and the most negative value in the histogram. The **Asymmetry** is the deviation from ideal distribution. **Activity** shows whether active communication is happening on the cable to be monitored. In this case, the number of values in the mode with the most values is determined and this number then subtracted from 1000.

Figure 4 shows Ethernet signals measured and the distribution associated with them together with the quality parameters established. In the top line, the signals have been recorded during normal communication. In the ensuing measurements, an additional capacitance of 47pF or of 100pF was added. In each case, despite this influence, it was possible to maintain communication between the end points.

a)
b)
c)

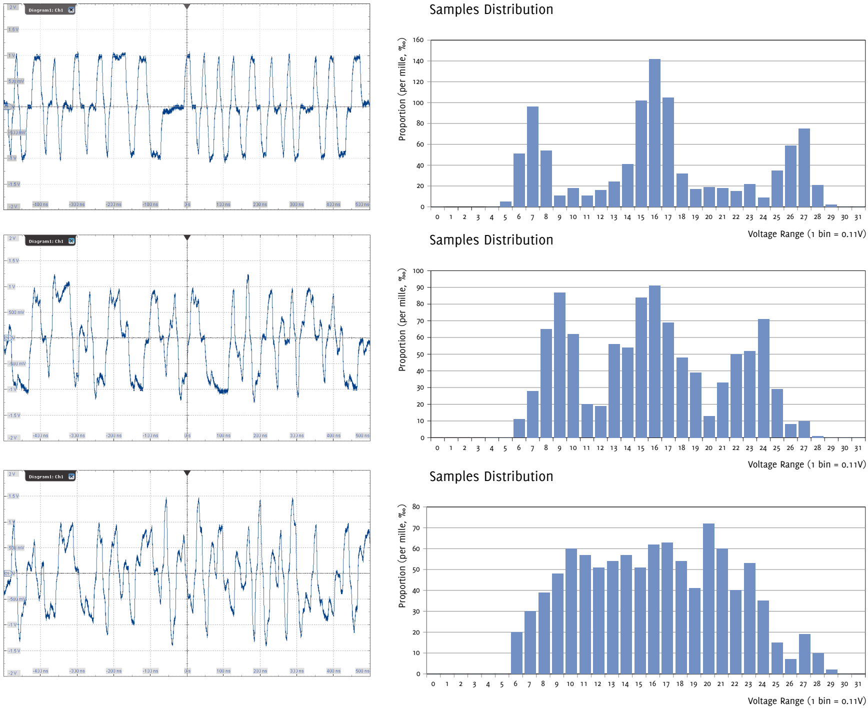


Figure 4: Comparison of Ethernet signal and associated distribution when affected by parasitics, shown under the influence of (a) normal conditions (clarity=531, asymmetry=53), (b) parasitic capacitance of 47pf (clarity=450, asymmetry=129) and (c) parasitic capacitance of 100pf (clarity=362, asymmetry=151). Source: IMMS.

System integration, prototype

The project involved designing a total system from several parts and developing it. The analogue front end created by IMMS is the foundation. It undersamples the signals in the Ethernet wires using a specially adapted sample-and-hold circuit. The target of the sampling is always the reception end. No analysis is carried out on the transmission end. Nonetheless, it is necessary keep both channels under observation while sampling, since the auto MDIX function involved means there may be crossover between receive (RX) and transmit (TX) wires. The sampled values are transferred as analogue signals to an analysis unit implemented by IMMS, where the final signal analysis and processing of the relevant values take place. The analysis unit is regulated by means of a strictly defined register set. Here the parameters can be stored for control and configuration purposes and the results of analysis can be searched. The register set is accessible from standardised interfaces such as SPI, I²C or even MDIO, which are in common use for Ethernet PHYs, simplifying any potential integration of the analysis functions.

More detail on signal processing at www.imms.de.

More on system integration at www.imms.de.

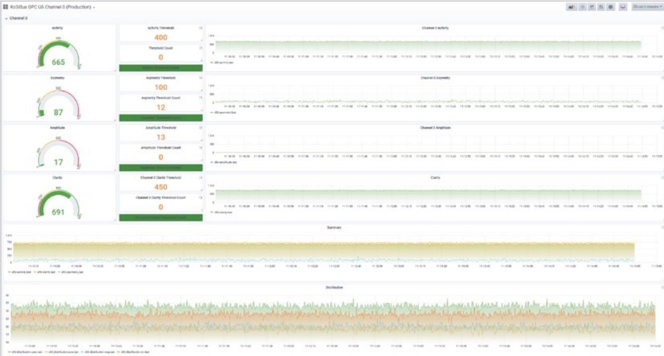


Figure 5:

Grafana dashboard for the Ko²SiBUs system. The representation shown is current measured values, also chronology of the measurements and configuration parameters.

Source: Offenburg UAS.

The interface unit developed by Offenburg University of Applied Science operates the analysis unit and configures it, also acquiring from it the analysis values before processing them and presenting them via the two protocols SNMP and OPC UA which are widely used in manufacturing and network technology. The SNMP agent can be integrated with the appropriate MIB (Management Information Base) description into any existing SNMP managers, which means it can be kept under observation. In parallel, an embedded OPC UA server is operated on the interface unit. This also gives access to the analysis and configuration values.

Demonstration version

IMMS was involved in the development of the prototype which demonstrates the entire system including the complete chain of analysis from signal measurement to presentation of the results and integration options (see Fig. 5). The prototype was extended by the addition of further technical elements to allow targeted manipulation of the Ethernet signals, representation of the measured values and interaction with the user.

The prototype consists of two mini-computers in addition to the Ko²SiBus system. They are in constant communication with each other to generate traffic. One of the mini-computers also implements the user interface. The data acquired via OPC UA or SNMP are written to an Influx-DB database via a Node-RED flow. A Grafana dashboard (see Fig. 5) can be used to access the values from this database. So that a smart phone or tablet can be easily used to access them, the mini-computer also acts as WLAN access point. A "disturbance board" has also been developed by IMMS and is inserted between the Ethernet cable where it facilitates targeted manipulation of the Ethernet signal and immediate observation on the dashboard of the effect of the manipulation.

More on system integration at www.imms.de.

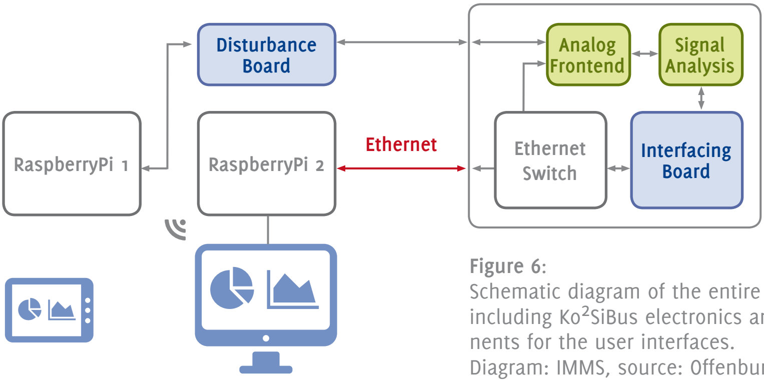


Figure 6:
Schematic diagram of the entire system including Ko^{2}SiBus electronics and the components for the user interfaces.
Diagram: IMMS, source: Offenburg UAS.

Conclusion and outlook

The methodology developed means that Ethernet cables can be monitored while in active use without there being any disruption of the actual communications. The principle has been implemented in the form of a prototype and its effectiveness shown in laboratory tests. The next steps will be to integrate the system into actual industrial scenarios and evaluate its function there. The intention is to achieve integration of the principles directly into Ethernet-based field bus devices.

More on communicatons solutions at www.imms.de.

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Industrielle Gemeinschaftsforschung

DFAM

Forschungsnetzwerk Mittelstand

The Ko^{2}SiBus project is funded through the DFAM (German research council for the application of microelectronics) via the AiF (IGF-Vorhaben 19574 BG) by the Federal Ministry for Economic Affairs and Energy (BMWi) in response to a decision of the German Federal Parliament. (AiF in English —German Federation of Industrial Research Associations; IGF — funding scheme for research serving the industrial community). The results come from work done by ivESK, the 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) as well as IMMS.

More detail on Ko^{2}SiBus at www.imms.de.

AgAVE –
Industry 4.0 communications for an assistance system, ML-based, that autonomously analyses connected production chains

Experimental setup to integrate local Industry 4.0 compliant assistance systems, which are based on machine learning (ML), into production chains. Photograph: IMMS.

Objectives and overview

The problem: errors are detected in one place but the root cause is often elsewhere

Industrial production chains are organised to operate continuously and with high throughput. Breakdowns and downtime for machinery can lead to high financial losses. It is estimated that the costs of repair and maintenance amount to 15% to 40% of industrial companies' total indirect costs.

One reason for this is that modern production chains are increasingly complex and composed of many modules or individual machines. With this structure, troubleshooting is very difficult as the location where the error is detected does not necessarily reflect the source location. Consequently, many manual, time-consuming checks are needed to find where the fault originated before resolving it. Intelligent assistance systems (assistants) can help shorten the investigation time and reduce costs.

AgAVE at www.imms.de

The solution: local and global ML-based assistants to diagnose root cause

Jointly, Fraunhofer IOSB-INA and IMMS have developed an assistance system for industrial plants. The system automatically detects risks, anomalies, and possible root causes like signs of wear and tear or sensor failures. It gives early warnings to the operator, who receives not only the details of the anomaly noted but also the suggested root cause. This requires a system working on more than one level, because each machine has access to its own data only. However, to identify the root cause of an error, data from other machines in the production chain is needed as well. Fraunhofer IOSB-INA has developed machine learning (ML) approaches by which each machine is monitored locally and global results, correlations and instructions are derived which the operator can interpret in relation to the complete chain.

The IMMS contribution: Industry 4.0 communications for the different diagnostic assistants

Data has to be exchanged between both monitoring levels. To enable this, we at IMMS developed appropriate communications systems conforming to Industry 4.0 protocols. The systems ensure reliable communication between the local assistants (at machine level) and the global assistants (at the higher analysis level). To achieve this, we defined mechanisms not only to convert data into relevant information but also to interact automatically with further modules in the processing chain. Without such communications, no analysis of the full process is possible. Using Industry 4.0 compliant protocols, ensures that the concept is applicable to any processing chain which applies these standards.

Together the partners implemented the system principles in an application-oriented demonstrator system, comprising communications and analysis components as well as sensor integration. With it, we have shown how the new ML-based assistance system is able to learn decision rules, recognize causal correlation, and identify potential error root causes within a distributed processing chain. It is installed in a production chain for packaging material which is part of the SmartFactoryOWL lab.

We have thus been able to demonstrate that novel applications for automation purposes are possible with using Industry 4.0 communications. The real-life example proves how this communications type opens up the full potential of the novel ML-based methods and the corresponding algorithms for operators of processing chains.

Fraunhofer ISOB-INA's view on the project

More on communicatons solutions at www.imms.de.

(M-)Learning how the processing chain behaves

When there is a fault, successful diagnosis requires precise knowledge of each single state that the processing chain as a whole is able to assume. There are several methods in machine learning which allow the behavior or states of machines to be captured and then represented in models.

However, because processing chains are modular, a fault or its root cause cannot often be detected locally at a machine. This detection requires a global perspective. Therefore, the AgAVE assistant system consists of one global and many local diagnostic assistants to enable it to meet the challenge of global root cause analysis. While local assistants are directly in or at the modules or machines they are monitoring, the global assistant is located at a higher level.

The machine data, the lowest level of information, is transferred to the corresponding local modules, which check the data for local correlations within it. It is here that various machine learning methods, including Support Vector Machines or Neural Networks are employed by Fraunhofer ISOB-INA. The assistants then send the result of their local analysis to the global higher-level learning layer, which generates a structure from this output which is capable of human interpretation. Here the methodology is rule-based, as with CBR (case based reasoning).

This split of the diagnostic assistants into local low-level and global high-level learning is typical of actual production chains. The low-level diagnostic assistants are sited close to the modules or single machines to be monitored, while the high-level diagnostic assistant has an overview of the complete processing chain and can recognise causal relationships between individual plant modules. As input data depending on the actual application is needed to enable the machine learning method in question to manage individual analysis tasks, the data from single machines or machinery modules is supplied to local assistants and their analysis goes to the global assistant.

› INPOS
› INSPECT
› ADMONT
› Ko²SiBus
› AgAVE
› Dig. Engineering
› IRIS
› Contents
* Funding

We evaluated different ways of getting the local and global assistants into communication with each other and of integrating them automatically into industrial communications environments. We focused for this on communications conforming to Industry 4.0, in order to design a system with high interoperability in the future.

Asset Administration Shell (AAS) with RAMI 4.0, OPC UA and Discovery Service enabling the data exchange

The local assistants process the scalar outputs of the different modules or single machines. The global assistant collects their results so that it can use decision rules to inform itself about the behaviour of the production chain. This hierarchical, algorithm-based structure requires careful and reliable management of the collected machine data. The data exchange between local and global assistants is therefore managed with concepts and protocols according to the specifications of the Industry 4.0 platform RAMI 4.0, i.e. the details and data for each assistant are organised in an Asset Administration Shell for each assistant which conforms to the structure defined by the Industry 4.0 platform. The diagnostic assistants communicate via the OPC UA client/server communications scheme, an Industry 4.0 compliant protocol for communication between machines. Besides these fundamental mechanisms, a Discovery Service has also been integrated into the system. This service helps the information from individual assistants to be found so that it can be incorporated automatically into the higher-level system. In total, these features allow flexible configuration of the assistant system.

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Asset Administration Shell transforms diagnostic assistants into Industry 4.0 components

The Industry 4.0 communications technology enables not only exchange of analysis data between assistants but also (by means of appropriate OPC UA semantic content) the exchange of metadata like details of the algorithm applied, the data type or the units of measure of the transferred data. Using the AAS also ensures that each diagnostic assistant is an Industry 4.0 component. The structure of the AAS is compliant with both the results from the open source project "openAAS" and the specifications of the Industry 4.0 platform. The system is thus compatible with any other system using an AAS on these principles.

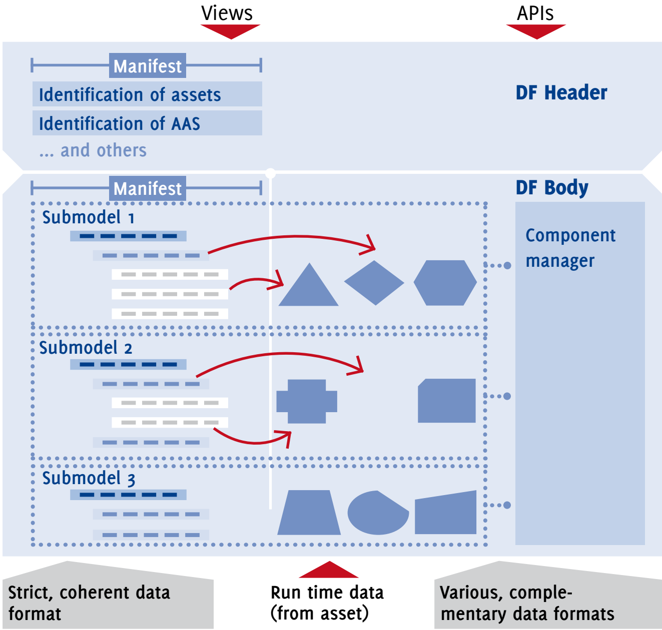

Figure 1:

General structure of the asset administrative shell.

Diagram: IMMS, source: Fraunhofer IOSB-INA.

Structure of the Industry 4.0 Asset Administration Shell for diagnostic assistants

Figure 1 shows the general structure of an Asset Administration Shell conforming to Industry 4.0. It basically consists of a header and a body part. The header contains all organisational features of the AAS and of the relevant asset, i.e. the physical or logical object which has a certain value for the organisation. Thus the AAS always has access to further details of the asset linked to it. For example, it is possible for other details besides those identifying the asset to be contained in the shell, even details like container size for parts input. The general AAS for diagnostic assistants is built upon this structure.

IMMS has adapted it to meet the demands of the two-level (local and global) assistants. What has resulted is an asset shell in which an OPC UA Companion Specification for the diagnostic assistants is implemented. The basic model has been extended by additional parameters which are relevant not only for all assistants in the AgAVE scheme but for assistants in general. To simplify the creation of the appropriate AAS, its structure is defined according to its OPC UA type, permitting simple and flexible case-by-case implementation of the concept for a variety of specific assistant systems.

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Structure

Figure 2 shows the implemented structure of the AAS implemented by IMMS. As described before, the organizational information are stored as header. The header consists of the following elements: "AAS-ID", "Asset" (Asset ID and Asset Description), "Manufacturer ID", and "Serial number". "AAS-ID" identifies the AAS itself and assigned to the corresponding real-world object of value via the object "Asset". Filling both objects results in a connection of the AAS to the module. The other elements allow a more precise description of the asset.

Information that is required to perform the individual analysis tasks are stored in the body-section. We structured the body with elements "Algorithm", "Inputs", and "Outputs". "Algorithm" collects further elements, detailing the employed analysis algorithm. "Inputs" structures all input parameters of the algorithm. The corresponding elements store the parameter values i.e. machine data. "Outputs" describes the structure of the analysis results of the assistant on the corresponding learning level. These results are accessible for further processing at different levels.

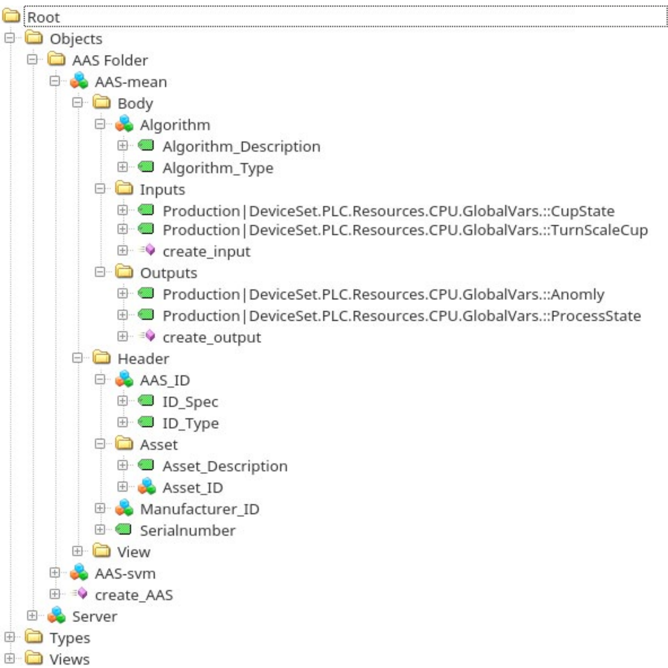

Figure 2:

Structure of the Asset Administration Shell for a diagnostic assistant.

Source: IMMS.

Communications

The communication between the different learning levels and between the individual local diagnostic assistants and the modules they are monitoring takes place on the client-server principle with a request/response pattern. Each local assistant consists of a client component to request data from the server located at or in the machine module and a server component to pass data to the global assistant. The server on the module is effectively a field gateway that stores the sensor values from the machinery in OPC UA variables, enabling selective requests for specific values to be made by the client. The client has to be within the same network but not physically close to the module being monitored.

Integration

If a complete processing chain with multiple modules or machines is to be covered, every module must be integrated into the assistant system. To reduce the resulting integration effort, a Local Discovery Server (LDS) is employed. All local assistants register themselves on this server and are accessible thereafter via the LDS. The only thing the clients absolutely need to know is the endpoint address of the LDS. Using the services of the LDS simplifies the integration of further modules. At the same time, searches can be made with it to establish the names and characteristics of modules already available.

Future prospects

In AgAVE we installed the assistant system at a demo processing chain within the Industry 4.0 model plant "SmartFactoryOWL" of the Fraunhofer IOSB-INA in Lemgo and tested it. As hardware base for the local assistants, Raspberry Pi boards were used. They run the asset administrative shell implemented by IMMS and the analysis algorithms developed by Fraunhofer ISOB-INA. The assistants communicate via a local network using OPC UA. Tests on this demo processing chain showed that the AgAVE system is able to learn decision rules to identify causal associations across the distributed processing chain, and thus to provide a selection of possible root causes in the event that defects appear.[1]

1 *vgl. http://publica.fraunhofer.de/documents/N-540915.html*

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AgAVE at www.imms.de.

However, this analysis is not yet possible other than offline. It can be run in parallel to the active process, analyzing machine data, detecting anomalies, and proposing solutions for troubleshooting or failure avoidance but does not (yet) actively interact with the manufacturing processes to control or configure the processing chain. Also, despite the distribution of the analysis onto local and global assistants, there is sometimes transport of sensor data over long distances across the network to the local assistants, causing delays. The focus of future work will be interactive analyses, requirement-oriented configuration and real-time communications.

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Supported by:

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Industrielle Gemeinschaftsforschung

on the basis of a decision by the German Bundestag

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Digital Engineering for planning and revitalisation of city districts – use of sensors **to monitor buildings**

One Digital Engineering research group task was testing connected wireless sensors to monitor the civil engineering variables of a school in Weimar. Photograph: Marco Götze, IMMS.

Objectives and overview

Computer-assisted construction and renovation a requirement of growing towns and cities

As people continue to flock to live in cities, buildings shoot up ever higher and closer together and in certain situations with intermingling of residential estates and industrial areas. To speed up the highly efficient planning and execution of complex new and renovated urban buildings, the ”Digital Engineering for Planning and Revitalisation Processes of Urban Neighbourhoods“ research group has been working on innovative computer-assisted techniques, which will help digitalise (i.e., automatically capture, process, store, visualise and validate) data from buildings, entire districts and areas of land. The methodology developed enables a consistent basis for planning to be found and both the current state of the buildings and the effect of new works to be evaluated. The research group, led by the Bauhaus-Universität Weimar, has relied on technology from a number of disciplines. For instance, drones were used to help capture the geometrical and thermographic data of existing buildings.

More on Digital Engineering at www.imms.de.

At the same time, use was made of innovative, automatic image analysis to recognise building damage and to generate three-dimensional building, district or terrain models, to draw up maps of damage identified, and to analyse energy aspects.

IMMS focus on wireless, meshed sensor networks for monitoring physical building characteristics

IMMS brought to bear its know-how in the field of wireless sensors for the purpose of widespread continuous, long-term monitoring of features of individual buildings or whole neighbourhoods like surface temperature, heat flow and wind activity. From the sensor signals, buildings or building categories can be assessed. Construction measures can be simulated, together with their potential effects on heating and ventilation or energy efficiency. Certain types of building structure, terrain forms and sizes presented special challenges to the architecture of the sensor network.

One aspect of the IMMS research was to see how far it is possible to use meshed networks as a complement to conventional, often expensive civil engineering survey methods. Surveyors can only measure at particular spots for limited periods. The meshes consist in reasonably priced self-connecting sensor nodes which, being compact and battery-powered, can in theory be installed and removed absolutely anywhere without requiring infrastructure modification. As they communicate from "facade to facade", an entire building complex can give up its data so that one step has already been taken in the monitoring of whole districts. Long-term monitoring in combination with numerous measuring points also provides a comprehensive database for research purposes. One focus could be the identification of interesting parts of a building for further, closer measurements.

IMMS has tested networked sensors on buildings. The hardware (see Fig.1) is weather-proof, independent of any infrastructure and reasonably priced and the software has been created by IMMS. The data collected has already been used for thermal-energetic simulations of physical buildings, has helped in a number of drone flights for thermography and has been integrated into BIM, a system of metadata modelling for construction purposes. Thus, features of buildings or the building fabric itself can be monitored and options for new construction or refurbishment better compared and planned. For example, long-term recording of the effective heat conduction from the interior to the exterior and vice versa will support model-based decisions, perhaps whether merely to change the heating regime or to install facade insulation along entire streets.

More on communicatons solutions at www.imms.de.

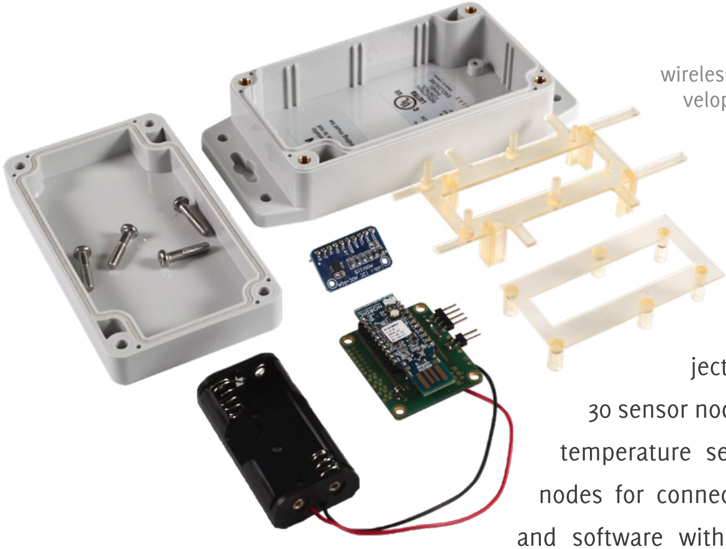


Figure 1: wireless sensor nodes as developed, components and complete assembly. Photograph: IMMS.

Available for future research projects in addition are 30 sensor nodes equipped with temperature sensors, four basic nodes for connection to gateways, and software with appropriate configuration that has already been implemented for the gateway and server systems.

More on communicatons solutions at www.imms.de.

The IMMS solution in detail

Constraints on wireless meshed sensor networks when measuring physical building characteristics

For wireless sensor networks on and in buildings, the difficulty lies in actual physical restrictions on radio communication which are attributable to the building design and difficult to predict, such as reinforced concrete, metal armatures, furniture and furnishings. Different types of radio technology perform differently under these conditions even when they are operating in the same frequency band. The reasons lie in variations in technology-dependent transmission power, reception sensitivity, modulation methods and routing protocols.

At an early stage, the research group selected the Weimar school ”Schule an der Hart“ to be a single, unified reference object for the assorted investigations and technology evaluations on the part of all the disciplines involved. As a building it was in need of renovation, made of reinforced concrete slabs with unfavourable structural physics.

The wireless sensor network which IMMS initially installed at this school was developed from one which had been originated for other applications in various preliminary projects. This network was first employed over long periods at measuring points distributed over the building to collect early data for the project partners' investigations and to work out what is practically necessary for the radio communication involved in the monitoring of buildings. In a second step, the requirements were taken account of in the creation of a sensor network platform designed specifically for the application.

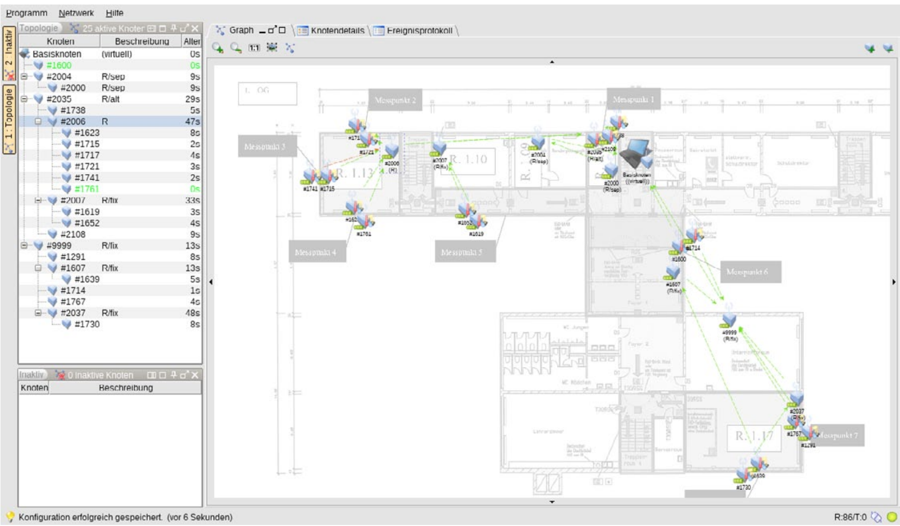
Collection of data and evaluation with available non-application-specific sensor network

First components and initial measurements

From the beginning of 2018, IMMS deployed an energy-autonomous sensor network solution developed by IMMS itself on one floor of the school building. It was a wireless mesh solution called BASe-Net, operating at 2.4 GHz and with a proprietary application protocol ConSAS built on top of the TinyOS operating system. The temperature gradient across external walls, an interesting aspect of building physics, was recorded at a total of eight measuring points, each with two sensors mounted opposite each other on the inside and outside of the facade. Several router nodes forwarded the data, increasing the range and improving the robustness of the radio communication under what were difficult conditions. With the technology used, these routers were not capable of operating autonomously as did the sensor nodes, but were supplied with mains power, as they have to receive data continuously.

Inside and outside, the surface and ambient temperatures were recorded; inside, the relative humidity was also recorded, together with illuminance in two spectral bands. In coordination with the Chair of Building Physics at the Bauhaus-Universität

Figure 2: measurement points on and in reference building, WSN topology. Diagram: IMMS.



More detail on sensor systems: www.imms.de.

More detail on communicatons solutions at www.imms.de.

Weimar, IMMS also integrated a highly accurate temperature sensor (Texas Instruments TMP116) into the pre-existing sensor solution.

The data was transported with the standard transmission protocol IEEE 802.15.4 via the wireless sensor mesh to a central gateway which collected the data and transferred it to a database at IMMS. The gateway provided was also based on pre-existing hardware and software. For lack of a locally available network infrastructure, the remote connection was by cellular radio.

Evaluation of the pre-existing sensor network

Over the long term, the reference building presented difficulties for the technology employed. There were times when communication broke down both within the sensor network and on the gateway's cellular link, limiting steady data acquisition. This was countered in the gateway with software adaptations such as data buffering, repeated transmissions and other measures to improve the robustness. Additional router nodes were not always able to solve the transmission problems caused by the reinforced concrete since the building had hardly enough power sockets for the routers and they were rarely at suitable locations. Consequently, important goals for an application-specific solution were the greater flexibility and robustness that would come with battery-powered and thus freely placeable routers.

In addition, in view of the fact that data acquisition would take place using a variety of means and technology, there was an incentive to replace the proprietary data management of the pre-existing system with standardised solutions. Standardised protocols and formats make integration easier, both into higher-level systems and with other systems. Unified data storage with appropriate semantics allows uniform access to data collected from different sources.

More on communicatons solutions at www.imms.de.

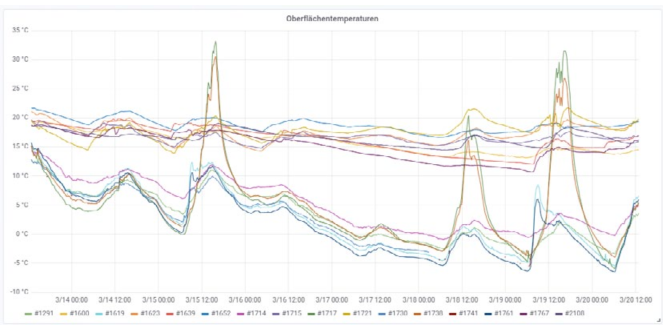


Figure 3:

sample graph of one week's surface temperature measurements for reference building in March 2018.

Diagram: IMMS.

Creation of a new platform specifically designed for the application

The sensor network platform which was created relies on more up-to-date and less expensive hardware with more robust communication and higher energy efficiency. Its communications and data provision are consistently based on standard protocols. The hardware side is based on the System-on-Chip Nordic Semiconductor nRF52840 with multi-protocol transceiver. OpenWSN, an alternative open-source operating system for sensor networks, was ported to the platform, to which are connected a remote temperature sensor and a heat flow measurement plate.

The protocols used in the internal communications of the network are 6LoWPAN (IPv6 for short-range radio networks) on the transport layer and CoAP on the application layer. A gateway collects the data in the sensor network and delivers it to a SensorThings API server, through which the measurements and metadata like size, position and references to details can be retrieved. The SensorThings API standard aims to provide an open and consistent framework for connecting sensors, data and applications over the Internet. Specifically, it addresses the interoperability of syntax and semantics, i.e. interoperability of data formats and data content and their meaning, so that even data from other systems can be aggregated on the server and made similarly accessible. Likewise, generic solutions from third-party providers can be used for visualising and processing the data.

More detail on sensor systems: www.imms.de.

Development of application-specific software for the sensor nodes

OpenWSN implements the IEEE 802.15.4e TSCH Time Slotted Channel Hopping mode of medium access control, which has energy advantages and enables battery-powered routers to be employed. This being the case, IMMS has developed software for the application that implements essential features of the protocol CoAP (Constrained Application Protocol RFC 7252) established for the Internet of Things, also its extensions RFC 7641 (Observing Resources) and CoRE Resource Directory (Draft). Sensors can thus be specifically queried with little communication effort and measured values with a configurable measuring interval can be subscribed to by the gateway, which can also automatically register sensor nodes and their resources. To estimate energy consumption, runtime and communications, simulations were carried out.

More on communicatons solutions at www.imms.de.

Development of application-specific software for the gateways

For the gateway software (paired with HARTING's MICA hardware), IMMS developed an application-specific software named coapconn. With this, the sensor network is integrated via CoAP and connected "upwards" via another standardised protocol

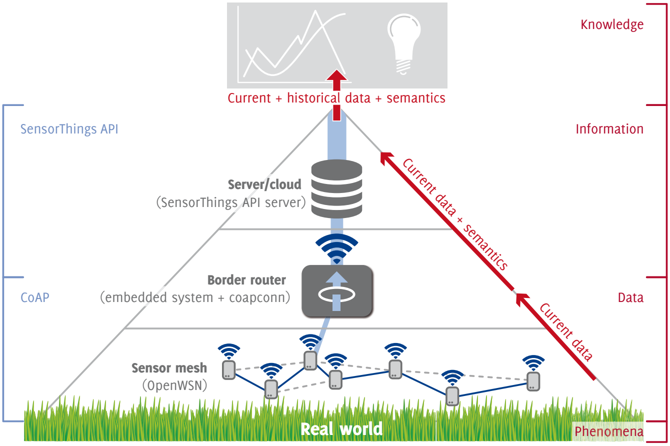


Figure 4:

Overall system architecture (logical view).

Diagram: IMMS.

from the IoT field, the OGC SensorThings API (application programming interface) to a SensorThings API server. The server forms a repository based on a comprehensive semantic data model for IoT "things" (i.e. sensors, data and metadata on sensor components, physical quantities, units, etc.). The repository enables uniform access to different types of solutions (Fig. 4). The server used was Fraunhofer IOSB's open source FROST-Server. Data can be visualised on the basis described – for example, with the open source solution Grafana. Also, coapconn implements various mechanisms to improve the robustness, such as timeouts in the communication with the sensor nodes or buffering of interactions with the server.

More detail on communicatons solutions at www.imms.de.

Testing and adjusting the platform designed for the application

Initial tests with the new platform revealed limited stability when networks were larger, especially if communication connections were poor, which necessitated extensive iterative debugging at the operating system level and testing at IMMS. By the end of the project, a test network had been installed at IMMS in Ilmenau in a constellation of sensor nodes comparable to that in the school in Weimar. It was operated for the last two months of the project. Communications between two building facades were also investigated using battery-powered routers, which demonstrated the plausibility of cross-building networks as a step on the way to data acquisition across whole neighbourhoods.

Future prospects

The Bauhaus-Universität Weimar is using the solar radiation, indoor temperature, ambient air temperature and indoor and outdoor surface temperature measurements recorded by the sensor network for purposes of validation and calibration. The sensor network offers the advantages of relatively large spatial coverage and an almost unlimited choice for positioning the sensors within the reference building. One of its uses is to validate on the basis of actual interior temperature the numerical models employed in thermal-energetic simulation of the reference building, enabling simulations with high spatial resolution based on multi-zone models to be validated and, if necessary, unerringly modified. Another is that the quantitative thermograms recorded during the drone flights are calibrated using the exterior surface temperature measurements provided by the sensor network. Sensor network data on ambient air temperature and solar radiation are serving as indicators of environmental influences that may affect the accuracy of the thermograms, causing errors.

More on communicatons solutions at www.imms.de.

The results of the research project are a significant basis for further research work of a highly practical kind to take place in the Regional Growth Core "smood – smart neighbourhood", which was started in June 2019 and is funded by the BMBF (Federal German Ministry of Education and Research). In it, specialised solutions are being developed for the planning, energy supply and operation of residential neighbourhoods already in existence.

IMMS is making use of the sensor platform developed in the research group for further work, consisting as it does of energy-efficient robust hardware and a communications solution with standardized protocols and formats up to cloud level. Thanks to these features, the platform can be easily integrated into other systems and data from different sources can be accessed uniformly. For example, an adapted version of the platform is being used in the EXPRESS* project on experimental fields for the agricultural industry.

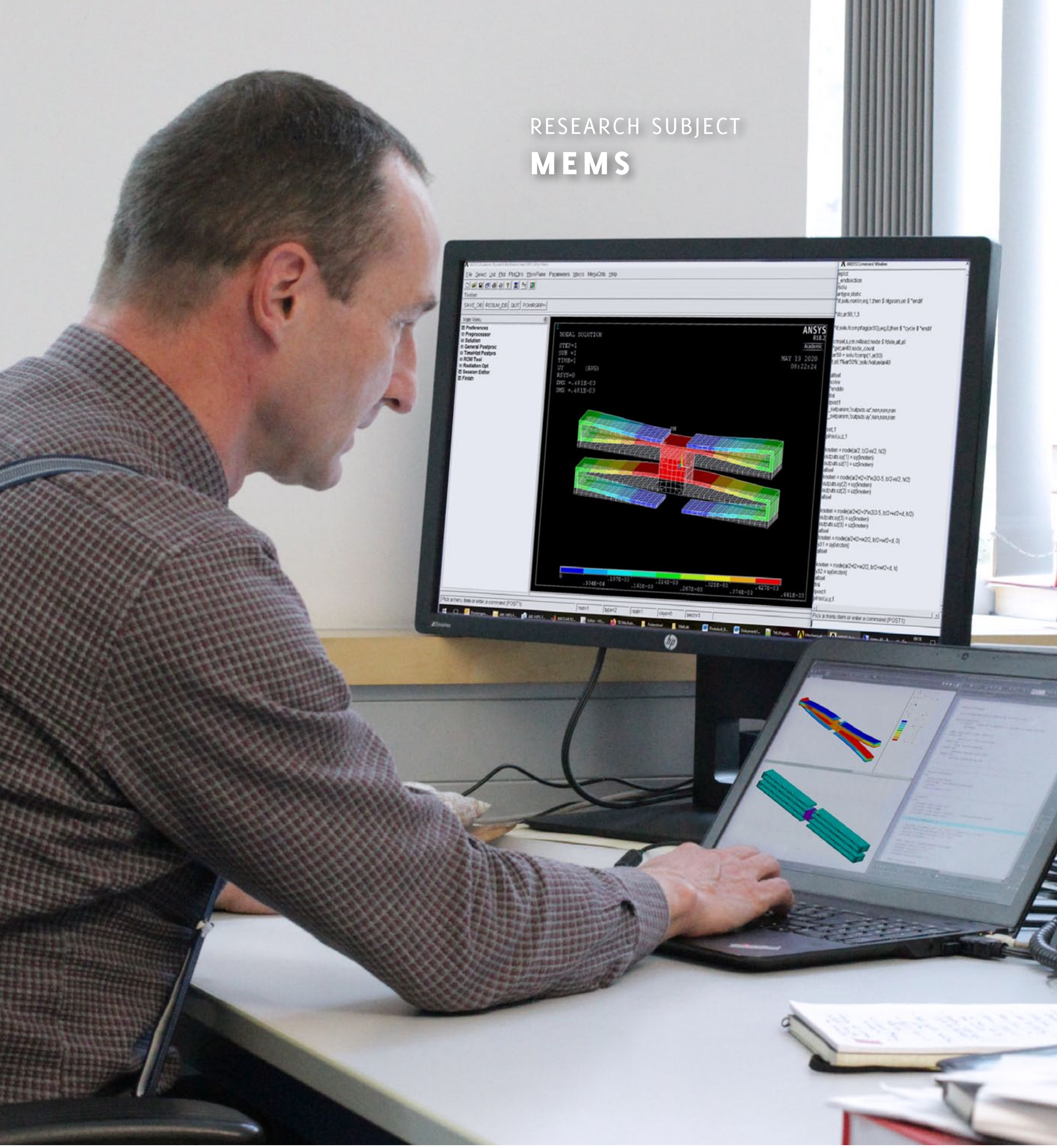
EXPRESS at www.imms.de.

Contact person: Dipl.-Inf. Marco Götze, marco.goetze@imms.de

Supported by the Thüringen government with a grant from the European Social Fund. The research group "Digital Engineering for Planning and Revitalization Processes of Urban Neighbourhoods" was funded with reference 2016 FGR 0026.

More on Digital Engineering at www.imms.de.

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



In the Regional Growth Core HIPS, IMMS supports the development of innovative, robust and highly integrated SiCer sensors with a systematic design procedure for the system design including the creation of a design library, with simulations and with the development of miniaturised processing circuits for the SiCer sensors. Photograph: IMMS.

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WACHSTUMSKERNE UNTERNEHMEN REGION Die BMBF-Innovationsinitiative Neue Länder

IMMS is supported in the Regional Growth Core HIPS within the framework of the "Unternehmen Region" initiative by the Federal Ministry of Education and Research (BMBF) in the joint projects 1 and 2 under the references 03WKDG01E and 03WKDG02H.

Research subject **Micro-electro-mechanical systems (MEMS)**

› INPOS
› INSPECT
› ADMONT
› Ko²SiBus
› AgAVE
› Dig. Engineering
› IRIS
› Contents
* Funding

Extending only over an area of a few square millimetres, MEMS (micro-electro-mechanical 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 2019 in our MEMS research: the Regional Growth Core HIPS* starts to develop new types of robust, compact SiCer sensors

With the goal of developing innovative, significantly more compact sensors to detect and quantify several physical and chemical characteristics which can be used in aggressive media or harsh environments, Ilmenau TU and the Fraunhofer IKTS have been researching and creating bonded layered substrates with the name SiCer. The technology enables hybrid microsystems to be created by the bonding of silicon (Si) and ceramics (Cer) at wafer level. The SiCer substrate unites the advantages of two types of successful technology and can be integrated into the fabrication process for MEMS.

HIPS at www.imms.de.

Twelve industrial companies and seven research institutes in Thüringen have been collaborating on building a technology platform for SiCer since 2019. The scheme is enabling innovative, robust, highly integrated SiCer high-performance sensors to be developed for liquids and gases with a view to later market launch by the collaborators.

Systematic design procedure for SiCer sensor systems

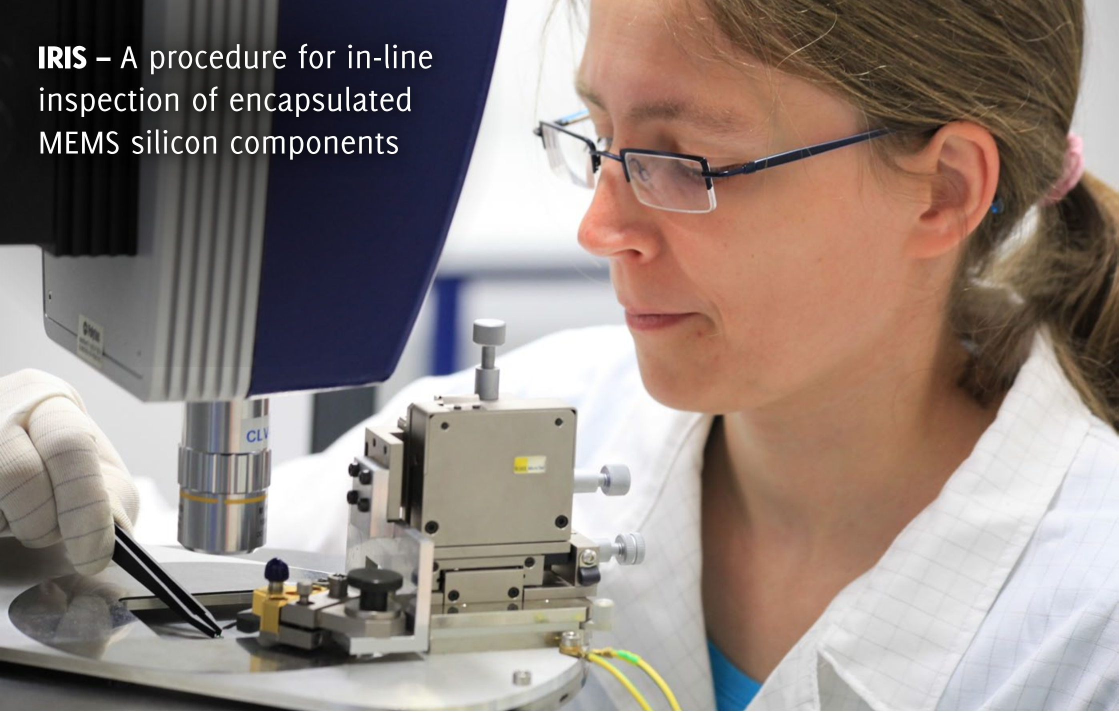
IMMS is working on new sorts of functional structures for micromechanical sensor and actuator elements, aiming to develop in collaboration with the various partners a systematic design procedure for SiCer sensor systems, including the appropriate design rules. For an assortment of structure and prototype elements, the component and system models are being developed, simulated and tested in partners' demonstrator versions. The design library elements are part of a model library. They will later serve the design of further innovative multisensor applications.

Processing circuits for infinitesimal sensor signals and metrological evaluation

At IMMS, a further focus is the development of miniaturised processing circuits for partners' SiCer sensors. This work involves specific electronics matched to the technology used and adapted to analogue capture of the sometimes infinitesimal sensor signals. The IMMS' tasks include not only design and construction of the electronics but also metrological evaluation and optimisation as well as field testing.

HIPS at www.imms.de.

IRIS – A procedure for in-line inspection of encapsulated MEMS silicon components



Vibrometric inspection of encapsulated MEMS structures. Photograph: IMMS.

Objectives and overview

No possibility to date of optical quality inspection of encapsulated MEMS during manufacture

Micro-electro-mechanical systems (MEMS) are driving innovation in many use scenarios and they generate world-wide turnover in the tens of millions of euros. MEMS are a combination in a single component of micromechanical sensors and actuators with control electronics, all on an area of only a few square millimetres. In cars they appear as airbag sensors and ESC sensors and are the smart-making element of the smartphone, acting as they do to detect orientation and acceleration, provide microphones, filter high frequencies, sense pressure and focus the camera.

Micromechanical structures can be fabricated like silicon microelectronic chips but are as a rule already protected from a variety of outside influences by encapsulation at the wafer level. However, the MEMS structures enclosed in this way could not up to now be optically inspected using conventional methods during production under the real conditions of encapsulation. The encapsulation procedure undertaken in vacuum or an inert gas ambience can, however, cause stress in the material with errors as a consequence. A MEMS manufacturer offering early recognition of any deviations at wafer level during manufacture, followed by clarification and rapid correction, would have a vital competitive advantage. It must be remembered that up to 95% of the fabrication costs arise after the wafer is divided into single microsystems and is then built up and bonded to achieve the packaged sales-ready system.

New measurement technology from partners inspects MEMS through the capsule

This situation has led to the IRIS project, in which a consortium of MEMS and metrology manufacturers together with research institutes have produced an optical means of analysing encapsulated silicon MEMS during fabrication using an innovative infrared technique. Thanks to the measuring techniques developed by one of the partners, Polytec GmbH, MEMS structures within their capsules can now be checked after an error-prone stage in the process. In the infrared wavelength between 1100 and 1700 nm, silicon is transparent, facilitating optical inspection if the measurements are taken in this range. Polytec has also achieved a first in enabling use of a laser Doppler vibrometer to measure oscillations in encapsulated microsystems stimulated optically by laser pulses.

Vibrometers have been in use for many years in the quality testing of MEMS, but only so far for exposed structures. A laser focussed on the surface to be measured enables the vibrometers to determine frequencies and amplitudes of mechanical oscillations. Inspection of the material properties and behaviour and thus the quality of MEMS structures is done by making them vibrate and analysing with the aid of the Doppler effect the frequencies in the laser beams emitted and reflected which are characteristic of each MEMS structure.

The new measuring technique now allows sensor properties in encapsulated MEMS to be detected in a very short time by vibrometry so that characterisation can take place.

IMMS developed measurement procedures at wafer level and means of determining cavity internal pressure

This new measurement technique has been used for experiments in stimulating vibration dynamically of encapsulated MEMS structures at wafer level, which is necessary if inspecting with vibrometry during the process. IMMS has come up with an indirect measurement method to determine the pressure inside the capsule (the cavity-internal pressure) and thus to provide fabricators with a significant key quality indicator and, besides, an automatic analysis of any stress in the material. Furthermore, IMMS has developed measuring procedures for in-line process monitoring

IRIS at www.imms.de

More MEMS projects at www.imms.de.

and has implemented a post-processing tool to be used for the characterisation of sensors on wafer level or of sensors as separated dies.

The IMMS solution in detail

Checking of MEMS using vibrometry for indirect identification of parameters

Already some years ago, IMMS had developed a means of identifying errors and general parameters in MEMS without capsules. This has been constantly refined over the years. This indirect method makes use of the values found vibrometrically for the eigenfrequencies of MEMS. FE simulations then assist in describing the functional association between the frequency responses measured for the MEMS structures and the parameters of interest, such as the material tension in thin-membrane-based sensors or the membrane thickness in pressure sensors. Thanks to the new measurement technology, IMMS has now been able to extend this technique for the characterisation of encapsulated MEMS. Figure 1 shows the logical structure for identifying parameters. The input parameters of the identification tool serve firstly as measurement data and secondly as simulation data. They can be found for simple structures such as beams by means of analytic equations. As a rule, however, FEM (finite element modelling) is used for the purpose. Polynomial approximation is applied to the numerical data in the identification tool in order to determine the sensor parameters from the eigenfrequency values by means of optimisation functions.

More on this method (PDF): www.imms.de

Services for FEM at www.imms.de.

Stimulating oscillation of MEMS

Different excitation for active and passive MEMS

So that frequency responses from MEMS can be checked by vibrometry, the eigenfrequencies of the structures must be stimulated. Depending on the type of excitation, MEMS can thus be divided into the active and the passive type. In the case of

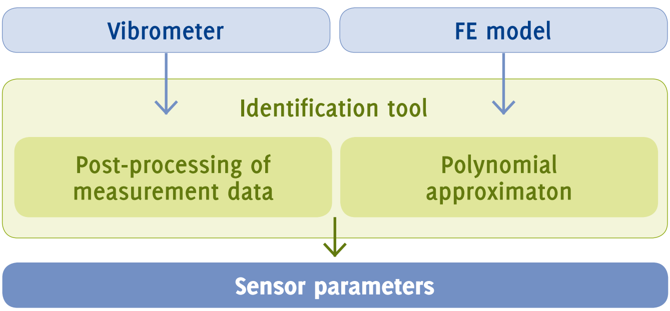


Figure 1:

Logical structure of parameter identification to determine cavity pressure.

Diagram: IMMS.

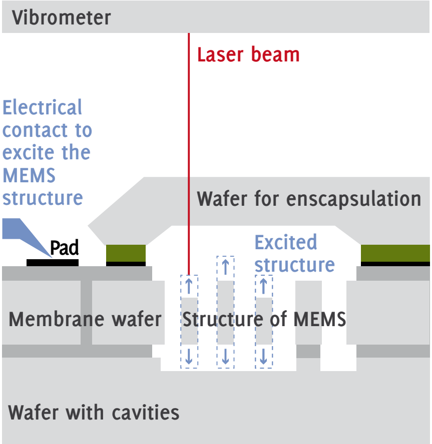


Figure 2:

Example of an encapsulated MEMS structure at wafer level, here an acceleration sensor in X-FAB's XMB10 technology. Encapsulation is achieved with the aid of an additional wafer which is bonded to the wafer with the MEMS structures on it.

The functional elements of *active* MEMS structures can be excited by electrical contact. The oscillations can thus be used to support vibrometric measurement.

Diagram: IMMS, Based on: X-FAB illustration.

MEMS with active excitation (these include inertial sensors or resonators), existing functional elements can be used electrically to start the MEMS vibrating, see Fig. 2. In contrast, membrane-based MEMS (which include pressure sensors) have no functional elements with which to start vibration. In their case, if the MEMS is not in a capsule, the vibration in the structures is stimulated electrostatically, i.e. passively, using an electrode situated approx 20 micrometres (µm) above and parallel to the membrane surface.

Thermal stimulation of oscillation in passive encapsulated MEMS

When MEMS are encapsulated, electrostatic stimulation is prevented by the existence of the encapsulation material. IMMS has, therefore, investigated the extent to which oscillations of passive encapsulated MEMS can be thermally stimulated to produce measurable amplitudes in the range of a few picometres (pm) using integrated resistances for the heating. These enable measurable oscillations to be generated but are dependent on such membrane features as thickness and suspension. While it has been possible to show vibration amplitudes in the pm range for membranes with soft suspension such as infra-red sensors, the much stiffer pressure sensors with typical membrane thickness in the 10 µm range cannot be stimulated to oscillate measurably by heating elements.

Extension of indirect MEMS parameter identification to include cavity pressure and quality

To enable MEMS structures to operate mechanically as desired, a specific quality factor requires an application-specific pressure inside the capsule, known as the cavity pressure. IMMS has, thanks to the new measurement techniques, extended its procedure for indirect parameter identification to include the parameters of cavity pressure and quality factor.

These two parameters are optically determined for encapsulated MEMS with the aid of vibrometry. In the identification tool, they are calculated from the half width (meaning the full width of the curve at half the height reached by its maximum and designated FWHM) of the frequency peaks measured on the one hand and of the FE simulation of the damping on the other. To do this, the frequency response function FRF as measured is compared with the theoretical FRF calculated by modelling, i.e. with a Lorentz function which is used in physics when resonance is described, see also Figure 4. The models provide theoretical frequency responses which are to be expected in the case of a certain cavity pressure or quality factor.

Services for FEM at www.imms.de.

The accuracy in the estimation of the quality factor is dependent on its level. The higher the quality factor, the fewer the frequency lines determining the eigenfrequency in the FRF measured, which, in turn brings with it greater numerical uncertainty. For the uncertainty to be classified, the procedure implemented provides for left- and right-sided regression of the Lorentz function around a frequency peak. Ideally, both the quality factor values found should be identical, though this almost never happens in practice. On the basis of evaluation of the experimental data, a criterion for vibrometrically determinable cavity pressure has been defined as a deviation of 10% between the two quality factor levels found. By this method, the cavity pressure of encapsulated sensors can be indirectly determined by vibrometry in respect of quality factor levels Q = 10,000, i.e. in respect of systems with comparatively low damping. The statement has been proved by measurements on inertial sensors with cavity pressures between 0.005 and 0.45 bar.

More on the development of tests at www.imms.de.

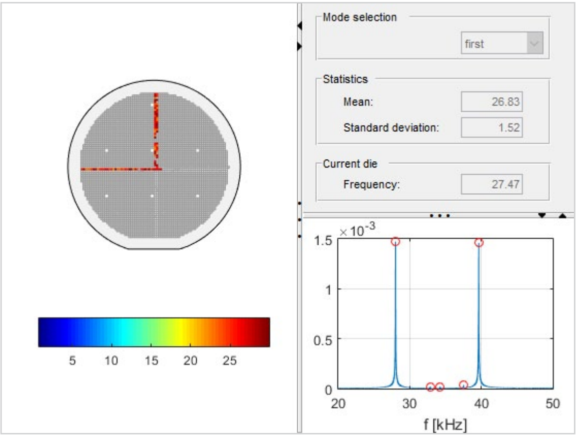


Figure 3:

GUI for post-processing of measurements.

Source: IMMS.

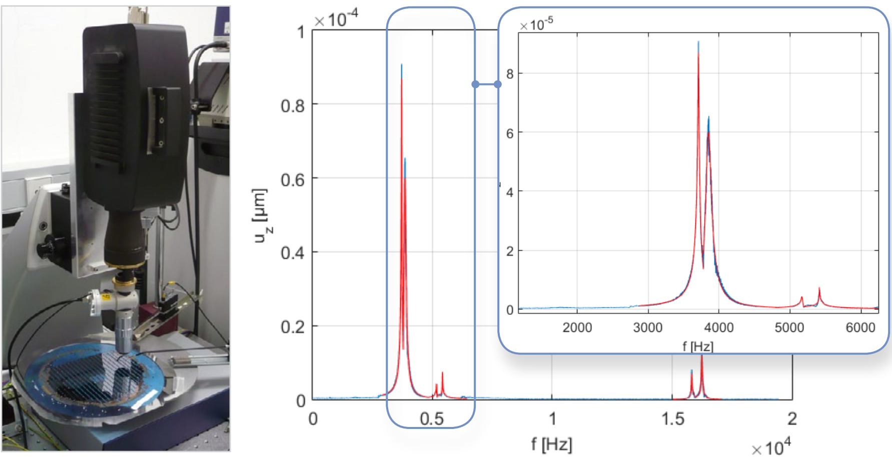
Development of a post-processing tool for wafer-level testing of MEMS structures

IMMS has developed a post processing tool and implemented it in Matlab for various classes. The tool imports the measured data from a wafer prober system and exports the results as a wafer map or an Excel file, see Figure 3. Besides detecting frequency peaks and modes automatically from the FRF measurements, the post-processor has interfaces to integrate it with existing software for the characterisation or monitoring of process parameters.

Detection of frequency peaks

To allow the parameters to be identified, frequency peaks have to be detected in the measured FRF. The FRFs of MEMS can be characterised according to noise level, amplitude ratio between the highest and lowest frequency peak (depending on the

Figure 4: left: setup of the innovative vibrometer used in measuring encapsulated MEMS structures: right: FRF measured by this means with twin peaks and the fitted Lorentz function. Photograph, graphs: IMMS.



More on the development of tests at www.imms.de.

Pre-processing	. Local estimation of **noise level** . Determination of **envelope curves** . Iterative addition of **peaks** as long as they are above the noise level
Parameter regression	**Non-linear minimal squares procedure** to determine the Lorentz function parameters (width or quality), based on the starting values in the Preprocessing

Figure 5:

Peak detection algorithm.

Diagram: IMMS.

application and the type of stimulus up to a factor of 100) and according to the distance between peaks close together (twin peaks). Twin peaks will appear for instance in nominally symmetrical sensor structures such as quadratic membranes because of process-dependent geometrical tolerances or asymmetrical mechanical stress. The challenge for automatic detection of frequency peaks is that the FRFs belonging to the different sensor types can differ vastly in respect of the three classification criteria. Absolute criteria such as minimum amplitude values cannot, therefore, be used for peak detection.

The peak detection is carried out in a two-stage algorithm developed by IMMS as is shown in Figure 5. In the first step, initial values are determined for the ensuing non-linear regression of the peak parameters of the Lorentz function

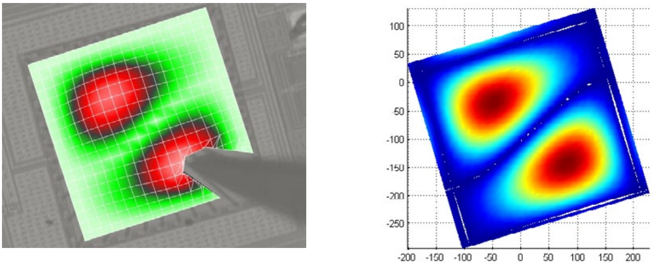
$$L(x) = A\,\frac{1}{1 + \left(\frac{x - x_0}{x_h}\right)^c}$$

with peak amplitude A, position of peak x_0, FWHM x_h and regression exponent c. In the second step there follows a non-linear regression of the peak parameters. To keep the time taken for processing of a frequency response measured below that of the measuring time of one second, a number of time-consuming functions were implemented in C++ and integrated into the tool.

Detection of frequency modes

Knowing the eigenfrequency values is a necessary, but not always sufficient, pre-condition for the identification of the parameters. For instance, mechanical stresses can cause a shift in the order of the frequency modes. Typically, the allocation of the oscillation modes to the frequency values takes place within the characterisation as here, in contrast to the production test, the measuring time is less important. Defining a measurement grid with a number of measuring points helps in the evaluation of the oscillation modes.

More on the development of tests at www.imms.de.



Figures 6:

Measured (left) and assigned (right) vibration modes.

Source: IMMS.

IMMS has implemented two different algorithms. If there are no simulation data available or the simulated vibration mode because of its complexity is not easy to describe with one of the basis functions, the order of the vibration mode can be determined from detection of the nodes and antinodes. In simple geometrical structures such as membranes, the modes measured can be described by a non-linear LSQ regression of the parameters of the basis function and allocated to the simulated modes (see Figure 6).

More on the development of tests at www.imms.de.

Future prospects

The overall outcome of the IRIS project is a wafer testing procedure suitable for use in fabrication, by means of which encapsulated sensors can be investigated using vibrometric measurement of out-of-plane oscillations, and peaks in the measured frequency responses measured can be automatically detected and evaluated. The procedure thus makes it possible to carry out in-line monitoring of cavity pressure in inertial sensors for example and to detect mechanical stress which may have been imprinted on the MEMS structures by the encapsulation stage itself. Both represent a significant improvement on the measuring methods previously available for monitoring MEMS during manufacture. The project partners are already in conversation with MEMS manufacturers on the subject of how the new methods can be actually integrated into fabrication.

IRIS at www.imms.de.

More MEMS projects at www.imms.de.

Contact person: Dipl.-Ing. Steffen Michael, steffen.michael@imms.de

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The IRIS project was funded by the BMBF (German Ministry of Education and Research) under the reference 13N13565.

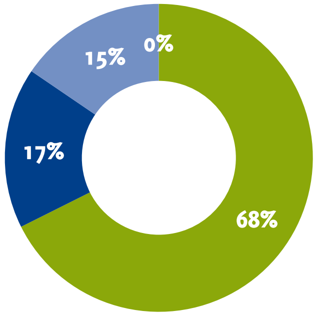
PROOF THROUGH FACTS AND FIGURES

Measurements in the clean room measuring lab at the Erfurt section of the Institute. Photograph: IMMS.

Facts and Figures in 2019

At the end of the business year 2019, there were 71 members of staff at IMMS.[1] Of these, 48 were research scientists and 11 were students occupied in research and development. Our scientific staff were thus around 83 % of our full complement.

Staff structure



Scientists | administration/apprentice students | other assistants

Over the 2019 business year, a total of 27 students of both sexes were given supervision at IMMS in practical research; three were writing their BSc and three their MSc dissertations. Eight members of staff were pursuing doctoral studies at a university.

It is our highly committed and qualified staff members who are the backbone of the continued successful growth of IMMS. We were able to attract new young scientists of both genders to IMMS in 2019. Even without counting student helpers, there were eight nationalities represented at IMMS in 2019, reinforcing the international exchange of ideas to the benefit of R&D at IMMS.

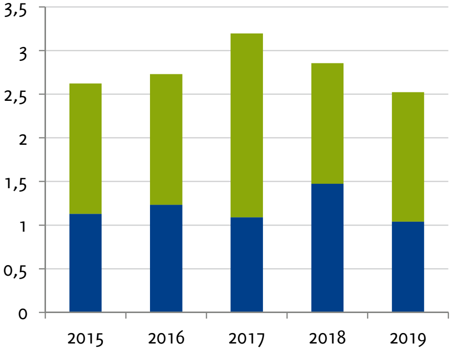
2019 did not see the same high level of earnings from third-party commissions as had been achieved the previous year. This is reflected particularly in the income from industrial projects, which did not rise to the previous year's high figure. The general worsening of the overall economic climate had its effect. On the other hand, the income from publicly funded projects again rose.

The drop in third party earnings was also to be seen in the project revenues, down by about 11% on the previous year's figure. Countering the development of earnings from industrial projects, the revenues from industrial projects exceeded that of the previous year by around 12%. The arrival of payments in 2019 for projects concluded

1 *As the staffing figures given are actual numbers for 31.12.2019 without calculation of FTE, only limited comparison with those in earlier annual reports is possible.*

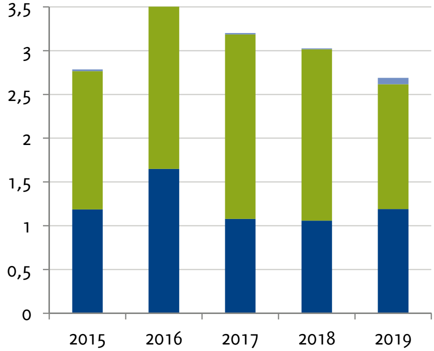
Project **earnings**

Industrial projects / funded projects
in million €



Project **revenues**

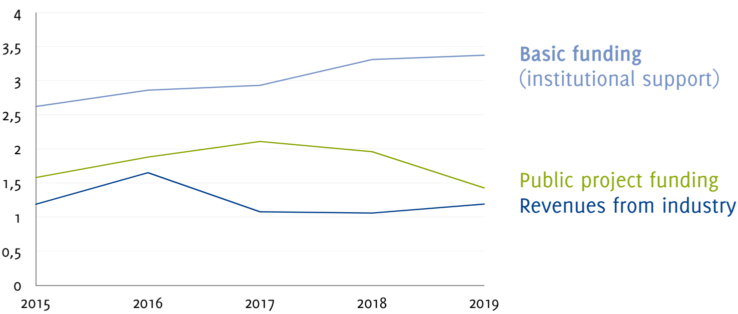
Industrial projects / funded projects / others
in million €



at the end of 2018 had an effect here. The actual revenues flowing from publicly funded projects remained below that of the previous year. Eight publicly funded projects were started in 2019 and 16 previously started projects continued.

The main financial pillar supporting IMMS is the institutional support of the Thüringen government. As before, it is the prerequisite to the application-relevant, future-oriented research done by IMMS which is a support to small and medium-sized Thüringen enterprises in particular. The internal research groups with their institutional funding are enabling IMMS to concentrate on particular research subjects whatever the current position concerning public tenders. They thus contribute significantly to IMMS' strategic success and consequently to its future.

Pillars of financial support
in million €



More detail on funding at www.imms.de.

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[+] since 01 February 2019 / [++] to 31 January 2019

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

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

10 Jan 2019 – Stammtisch "Arbeitswelt 4.0" (Regulars' table on Work 4.0 of the SME 4.0 Competence Centre Ilmenau (M4.0)), IMMS Ilmenau

15 Feb 2019 – Information event for the SCHULEWIRTSCHAFT Thüringen Initiative, IMMS Ilmenau

21 Feb 2019 – 9th Workshop "Sensorik 4.0" (M4.0 Workshop Sensors 4.0): Linux-basierte echtzeitfähige Sensorsysteme, IMMS Ilmenau

26 Feb 2019 – edaBarCamp: may the 4th be with you!, X-FAB Global Services GmbH Erfurt

28 Feb 2019 – Workshop "Design Thinking", IMMS Ilmenau

14 Mar 2019 – Stammtisch "Sensorik 4.0" (M4.0 regulars' table on Sensors 4.0): RFID in der Produktion, microsensys GmbH Erfurt

04 Apr 2019 – Stammtisch "Industrie 4.0" (M4.0 regulars' table on Industry 4.0): Testautomation und Digitaler Zwilling, IMMS Ilmenau

09 Apr 2019 – User Group Meeting "Einsatz künstlicher Intelligenz in meinem Unternehmen" (AI in enterprises), IMMS Ilmenau

09 Apr 2019 – Information event for the Thüringer Ernährungsnetzwerk, IMMS Ilmenau

Current events at www.imms.de.

08 May 2019 – Information event for the Mittelstandsvereinigung pro Südthüringen e.V., IMMS Ilmenau

11 May 2019 – Lange Nacht der Technik 2019 (Long night of technology) IMMS Ilmenau

23 May 2019 – Workshop ”Hands On – Industrie-4.0-konforme Kommunikation – OPC UA“, (using OPC UA in Industry 4.0 communications) IMMS Ilmenau

28 May 2019 – EMC Seminar, IMMS Ilmenau

02 Jul 2019 – User Group Meeting ”Wie geht es meiner Maschine?“ (machinery condition), TGZ Ilmenau

04 Jul 2019 – Stammtisch ”Arbeitswelten 4.0“ (M4.0 regulars' table on Work 4.0): Digitale Tools für die effektive Arbeitsorganisation, IBYKUS AG Erfurt

22 Aug 2019 – Workshop ”Design Thinking“, IMMS Ilmenau

27 Aug 2019 – User Group Meeting ”Datensicherheit in der Cloud“ (Data security in the cloud), IMMS Ilmenau

01 Oct 2019 – Stammtisch ”Unternehmen wachsen“: (M4.0 regulars' table) Digitalisierung der Produktion für effizientes Wachstum, TGZ Ilmenau

05 Nov 2019 – EMC Seminar, IMMS Ilmenau

08 Nov 2019 – Lange Nacht der Wissenschaften (Long Night of the Sciences): IMMS Erfurt

03 Dec 2019 – Information event for the Mittelstandsvereinigung pro Südthüringen e.V., IMMS Ilmenau

13 Dec 2019 – Information event for Reinhard Bütikofer, MEP (Green), IMMS Ilmenau

Trade fairs/Exhibitions

05 Mar 2019 – VDMA-Informationstag 2019 (info day), *exhibition booth, demo,* Frankfurt am Main

28 Mar 2019 – IT Leistungsschau 2019 (IT exibition), *exhibition booth*, Erfurt

01 Apr 2019 – Hannover Messe 2019 (trade fair), *demo*

10 Sep 2019 – Saalfelder Technologiedialog 2019 (technology dialogue), *exhibition booth, demonstrator,* Bildungszentrum Saalfeld GmbH

24 Sep 2019 – elmug4future 2019, Technology conference on Condition, Health and Quality Monitoring – Sensors, Methods and Applications, *2 lectures, 2 demos*, Erfurt

13 Nov 2019 – InnoCON Thüringen 2019 (exhibition and conference) *lecture, specialist poster, exhibition booth, demo,* Erfurt

18 Nov 2019 – MEDICA 2019, *5 demos, Thüringen joint booth*, Düsseldorf Trade Fair

27 Nov 2019 – Transfertag an der TU Ilmenau (transfer day at Ilmenau TU) *lecture, exhibition booth, 3 demos,* Ilmenau TU

Current events at www.imms.de.

Conferences with contributions by IMMS – an overview

23 Jan 2019 – Science meets Industry in Silicon Saxony, *lecture*, Fraunhofer IWU, Chemnitz

19 Feb 2019 – Industrie-Innovations-Dialog (dialogue on industry and innovation), *lecture*, IHI Arnstadt

19 Feb 2019 – ICAART 2019, 11th International Conference on Agents and Artificial Intelligence, *co-author lecture*, Praha, Czech Republic

24 Feb 2019 – TuZ 2019, 31th GI/GMM/ITG Workshop on Test methods and reliability of circuits, *lecture*, Prien am Chiemsee

26 Feb 2019 – embedded world 2019 (trade fair), *lecture*, Nürnberg

18 Mar 2019 – DAGA 2019, 45th Annual Conference for Acoustics, *lecture*, Rostock

20 Mar 2019 – Wirtschaftsabend (business evening), Bad Kissingen, *lecture*

02 Apr 2019 – IEEE RFID 2019, 13th Annual IEEE International Conference on RFID "The premier conference for the latest discoveries in technical RFID research", *lecture*, Phoenix, Arizona, USA

15 Apr 2019 – IEEE WF-IoT 2019, IEEE 5th World Forum on Internet of Things, *lecture*, Limerick, Ireland

24 Apr 2019 – DDECS 2019, IEEE Symposium on Design and Diagnostics of Electronic Circuits and Systems, *lecture*, Cluj-Napoca, Romania

07 May 2019 – BioCHIP 2019, Berlin International Forum on Biochips and Biochip Solutions, *lecture*, Berlin

24 May 2019 – Thüringer Digitalfestival 2019: KI-Forum (digital festival: AI forum), *specialist poster*, Erfurt

27 May 2019 – WFCS 2019, 15th IEEE International Workshop on Factory Communication Systems, *lecture*, Sundsvall, Sweden

19 Jun 2019 – Workshop "Digitale Services als Grundlage neuer Geschäftsmodelle" des Thüringer ClusterManagements, *lecture*, DAKO GmbH Jena

25 Jun 2019 – 20. GMA/ITG Fachtagung Sensoren und Messsysteme 2019 (symposium on sensors and measuring systems), *lecture*, Nürnberg

26 Jun 2019 – Rudolstädter Kunststofftage (symposium on plastics), Workshop "Erste Schritte in eine digitalisierte Wirtschaft", *lecture*, TITK Rudolstadt

07 Jul 2019 – ICSV26, 26th International Congress on Sound and Vibration, *specialist poster*, Montréal, Canada

Current events at www.imms.de.

08 Jul 2019 – **HiTEN 2019**, International Conference and Exhibition on High Temperature Electronics Network, *lecture*, St. Anne's College in the University of Oxford, United Kingdom

15 Jul 2019 – **SMACD 2019**, International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design, *5 lectures*, Lausanne, Schweiz

15 Jul 2019 – **PRIME 2019**, 15th Conference on PhD Research in Microelectronics and Electronics, *lecture (Silver Leaf Award)*, Lausanne, Schweiz

20 Aug 2019 – **Unternehmerworkshop** der GFE "Optimieren sie ihre Prozesse" (workshop for entrepreneurs), *lecture*, Schmalkalden

29 Aug 2019 – **ISEF 2019**, 19th edition of International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering, *lecture*, Nancy, France

04 Sep 2019 – **IFAC 2019**, The International Federation of Automatic Control, Invited Session "Precision scanning systems in metrology and manufacturing", *lecture*, Wien, Austria

18 Sep 2019 – **IDAACS 2019**, 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, *lecture*, Metz, France

24 Sep 2019 – **elmug4future 2019**, Technology conference on Condition, Health and Quality Monitoring – Sensors, Methods and Applications, *2 lectures, 2 Demos*, Erfurt

09 Oct 2019 – **Vortragsveranstaltung** der Initiative "Zukunft.Coburg.Digital" zu Retrofit (lecture event on retrofit), *lecture*, Coburg

17 Oct 2019 – **Tech Biz Day with X-FAB** – From Innovation to Medical Electronics, *lecture*, Hotel NH Lyon Airport, France

25 Oct 2019 – **DCASE 2019**, Detection and Classification of Acoustic Scenes and Events, *Co-author lecture*, New York City, USA

13 Nov 2019 – **InnoCON Thüringen 2019** (exhibition and conference) *lecture, specialist poster, exhibition booth, demo*, Erfurt

26 Nov 2019 – **TELFOR 2019**, 27th Telecommunications Forum TELFOR 2019, *lecture*, Sava Center, Belgrade, Serbia

26 Nov 2019 – **Vortragsveranstaltung** "Ressourceneffizienz vor Ort" (lecture event on resource efficiency), Thüringer Energie- und GreenTech-Agentur (ThEGA), *2 lectures*, IHK Südthüringen, Suhl

27 Nov 2019 – **Transfertag an der TU Ilmenau** (transfer day at Ilmenau TU), *lecture, exhibition booth, 3 demos*, Ilmenau TU

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› Contents
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Urban Noise Monitoring in the StadtLärm Project – a Field Report, Jakob Abeßer[1]. Marco Götze[2]. Tobias Clauß[1]. Dominik Zapf[1]. Christian Kühn[1]. Hanna Lukashevich[1]. Stephanie Kühnlenz[3]. Stylianos Mimilakis[1]. *Detection and Classification of Acoustic Scenes and Events (DCASE) 2019, 25 – 26 October 2019, New York City, USA,* **DOI: doi.org/10.33682/s9w3-5341.** [1]Fraunhofer Institute for Digital Media Technology (IDMT), Ilmenau, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [3]Software-Service John GmbH, Ilmenau, Germany.

Silicon-Ceramic Composite Substrate: A Promising RF Platform for Heterogeneous Integration, Michael Fischer[1]. Sebastian Gropp[1]. Johannes Stegner[1]. Astrid Frank[2]. Martin Hoffmann[1]. Jens Mueller[1]. *in IEEE Microwave Magazine, vol. 20, no. 10, pp. 28 – 43, Oct. 2019.* **DOI: doi.org/10.1109/MMM.2019.2928675.** [1]IMN MacroNano, Technische Universität Ilmenau, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Enhancing RF Bulk Acoustic Wave Devices: Multiphysical Modeling and Performance, Vikrant Chauhan[1]. Christian Huck[2]. Astrid Frank[3]. Wolfgang Akstaller[1]. Robert Weigel[1]. Amelie Hagelauer[1]. *in IEEE Microwave Magazine, vol. 20, no. 10, pp. 56 – 70, Oct. 2019.* **DOI: doi.org/10.1109/MMM.2019.2928677.** [1]Institute for Electronics Engineering, University of Erlangen-Nuremberg, Germany. [2]Institute of Physics, University of Augsburg, Germany. [3]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

A Cost-Efficient and Continuous Ethernet Cable Diagnosis Technique based on Undersampling, Ahmed Yahia Kallel[1]. Sebastian Uziel[2]. Manuel Schappacher[3]. Axel Sikora[3]. Thomas Keutel[1]. Olfa Kanoun[1]. *10th IEEE International Conference on*

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Integrated Planar 6-DOF Nanopositioning System, Stephan Gorges[1]. Steffen Hesse[1]. Christoph Schäffel[1]. I. Ortlepp[2]. E. Manske[2]. E. Langlotz[2]. D. Dontsov[3]. *11th IFAC Symposium on Nonlinear Control Systems (NOLCOS 2019), 4 – 6 September 2019, Vienna, Austria , IFAC-PapersOnLine, Volume 52, Issue 15, 2019, Pages 313 – 318, ISSN 2405-8963,* **DOI: doi.org/10.1016/j.ifacol.2019.11.693.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Technische Universität Ilmenau, 98693 Ilmenau, Germany. [3]SIOS Meßtechnik GmbH, 98693 Ilmenau, Germany.

Design of a Test Station for Magnetoelectric Sensor Development, Maximilian Krey[1]. Hannes Toepfer[1]. Roman Paris[2]. Thomas Froehlich[3]. *19th edition of International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering (ISEF 2019), 29 – 31 August 2019, Nancy, France, pp. 1 – 2,* **DOI: doi.org/10.1109/ISEF45929.2019.9097048.** [1]Technische Universität Ilmenau, Advanced Electromagnetics Group, Ilmenau, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [3]Technische Universität Ilmenau, Process Measurement Technology Group, Ilmenau, Germany.

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Analysis and Optimization of Power Supply Rejection for Power Management Unit Design in RFID Sensor applications, Jun Tan[1]. Ralf Sommer[1]. *16th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), Lausanne, Switzerland, 15 – 18 July 2019, pp. 181 – 184.* **DOI: doi.org/10.1109/SMACD.2019.8795258.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

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The sound of ultrasound, Nicki Bader[1]. Peter Holstein[1]. Hans-Joachim Münch[1]. Sebastian Uziel[2]. Tino Hutschenreuther[2]. Steffen Seitz[1]. *26th International Congress on Sound and Vibration (ICSV26), 7 – 11 July 2019, Montréal, Canada, ISBN: 9781510892699.* [1]SONOTEC Ultraschallsensorik Halle GmbH, 06112 Halle, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

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A modular application specific active test environment for high-temperature wafer-test up to 300 °C, Michael MEISTER[1]. Marco REINHARD[1]. *International Conference and Exhibition on High Temperature Electronics Network (HiTEN 2019), 8 – 10 July 2019, St. Anne's College in the University of Oxford, Oxford, United Kingdom,* **DOI: doi.org/10.4071/2380-4491.2019.HiTen.000122.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

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From Constraints to Tape-Out: Towards a Continuous AMS Design Flow, Andreas KRINKE[1]. Tilman HORST[1]. Georg GLÄSER[2]. Martin GRABMANN[2]. Tobias MARKUS[3]. Benjamin PRAUTSCH[4]. Uwe HATNIK[4]. Jens LIENIG[1]. *A. Krinke et al., 2019 IEEE 22nd International Symposium on Design and Diagnostics of Electronic Circuits & Systems (DDECS), Cluj-Napoca, Romania, 24 – 26 April 2019,* pp. 1 – 10. **DOI: doi.org/10.1109/DDECS.2019.8724669.** [1]Technische Universität Dresden, Institute of Electromechanical and Electronic Design, Dresden, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [3]Heidelberg University, ZITI, Computer Architecture Group, Heidelberg, Germany. [4]Division Engineering of Adaptive Systems, Fraunhofer IIS/EAS, Institute for Integrated Circuits, Dresden, Germany.

A Case Study on Energy Overhead of Different IoT Network Stacks, Silvia KRUG[1,2]. Irida SHALLARI[1]. Mattias O'NILS[1]. *IEEE 5th World Forum on Internet of Things, 15 – 17 April 2019, Limerick, Ireland, 2019 IEEE 5th World Forum on Internet of Things (WF-IoT), pp. 528 – 529.* **DOI: doi.org/10.1109/WF-IoT.2019.8767284.** [1]Department of Electronics Design, Mid Sweden University, Sundsvall, Sweden. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

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Oral presentations and specialist posters

Überwachung von Druckluftanlagen zum Einsparen von Ressourcen, Sebastian Uziel[1]. *Veranstaltungsreihe Ressourceneffizienz vor Ort – Digitalisierung & Ressourceneffizienz, 26. November 2019, Industrie- und Handelskammer Südthüringen, Suhl.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

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La petite puce – Customized Chip Design for optical and wireless Sensors, Peggy REICH[1]. *Tech Biz Day – From Innovation to Medical Electronics, 17 October 2019, Lyon, France.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Herausforderungen im Entwurf von Mixed-Signal Systemen, Georg GLÄSER[1]. *VDE Vortragsreihe „Aktuelle Herausforderungen der Elektrischen Energietechnik", 14. Oktober, TU Ilmenau, Ilmenau.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

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RFID-basierte Sensorlösungen für den industriellen Einsatz, Eric SCHÄFER[1]. *Erste Schritte in eine digitalisierte Wirtschaft, Rudolstädter Kunststofftage, 26. Juni 2019, Thüringisches Institut für Textil- und Kunststoff-Forschung e.V., Rudolstadt.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

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Abbreviations

5G *Fifth generation mobile radio standard*
6LoWPAN *IPv6 over Low power Wireless Personal Area Network*

ADC *Analog-to-Digital-Converter*
AI *Artificial Intelligence*
API *Application Programming Interface*
ASIC *Application-specific Integrated Circuit*

B2C *Business-to-Consumer*

CMOS *Complementary metal–oxide Semiconductor*
CoAP *Constrained Application Protocol for IoT*
CP(P)S *Cyber-physical (production) system*

EDA *Electronic Design Automation*
EMC *Electromagnetic compatibility*

FEM *Finite element method*
FPGA *Field Programmable Gate Array*
FRF *Frequency Response Function*

GUI *Graphical User Interface*
HRP *Horseradish peroxidase*

I²C *Inter-Integrated Circuit*
I4.0 *Industry 4.0*
IC *Integrated Circuit*
IEEE *Institute of Electrical and Electronics Engineers*
IoT *Internet of Things*
ISO *International Organization for Standardization*

MCU *Microcontroller Unit*
MDI *Medium Dependent Interface*
MDIO *Management Data Input/Output*
MEMS *Micro-electro-mechanical system*
MIB *Management Information Base,*
ML *Machine learning*
MQTT *Message Queuing Telemetry Transport*

NFC *Near Field Communications*

OEM *Original Equipment Manufacturer*
OPC UA *Open Platform Communications Unified Architecture*

PHY *Physical Layer*
POCT *Point-of-care testing system*
PSA *Prostate-specific antigen*

RF *Radio frequency*
RFID *Radio-Frequency Identification*
RMS *Root Mean Square*

S2DES *Smart sensor-based Digital Ecosystem Services*
SCL *Serial Clock*
SDA *Serial Data*
SiCer *Silicon (Si) ceramic (Cer) composite substrate*
SME *Small and medium-sized enterprises*
SNMP *Simple Network Management Protocol*
SPI *Serial Peripheral Interface*

TMB *Tetramethylbenzidine substrate solution*
TSCH *Time Synchronized Channel Hopping*
TSN *Time-sensitive Networking*

WSN *Wireless Sensor Network*

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