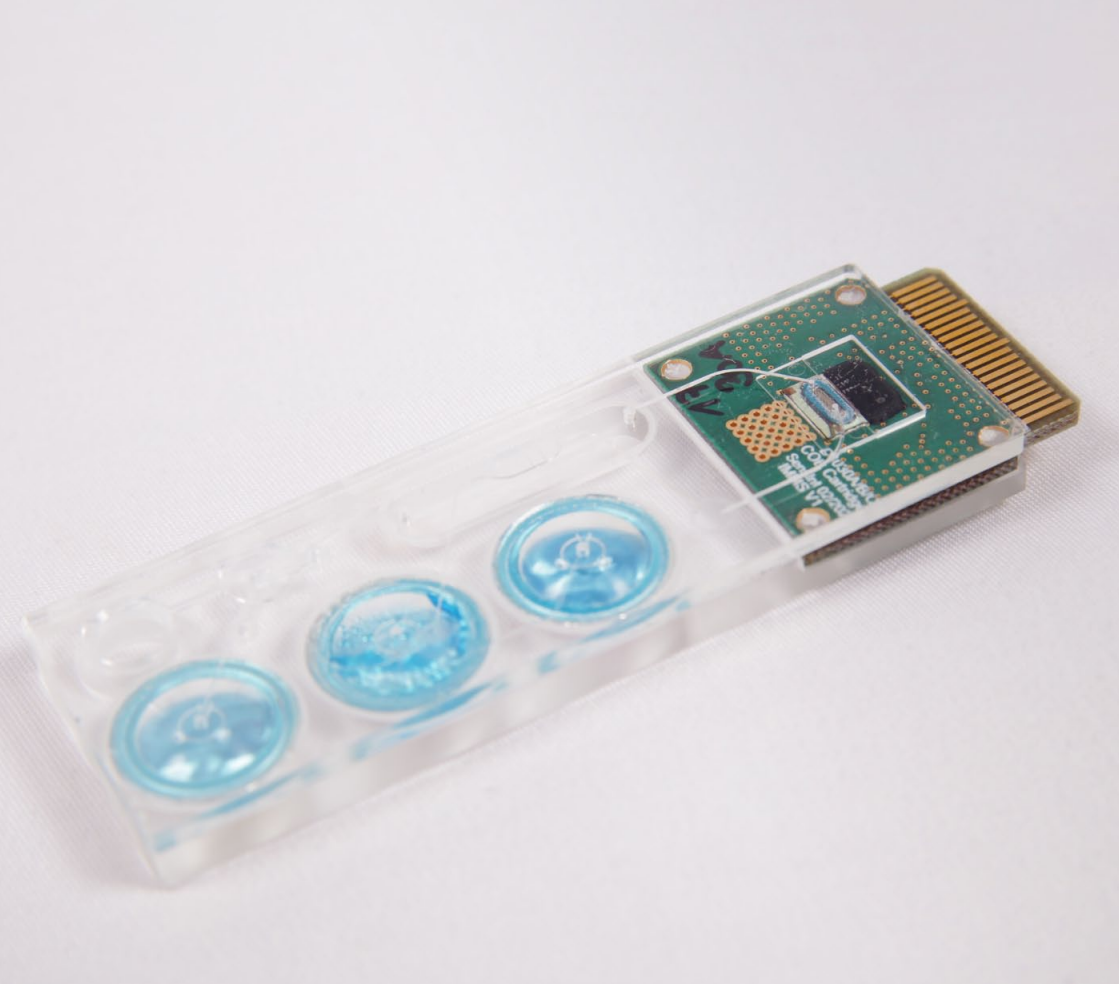


IMMS

ANNUAL REPORT

2023

Contents

www.imms.de/annualreports

Cover photo: CMOS image sensor for time-resolved fluorescence measurement developed in the SensInt* project at IMMS, which can be integrated directly into microfluidic cartridges for point-of-care devices for fast, patient-centred diagnostics using 3D screen printing. Photograph: IMMS.

Foreword

Martin Eberhardt and Ralf Sommer. Photograph: IMMS.

Dear readers,

In 2023, **IMMS** was comprehensively **evaluated** on behalf of the German Land of Thüringen by the Scientific Commission of the Land of Niedersachsen and its appointed experts. The strategic orientation and development, research and transfer activities, organisation, equipment, teaching, cooperation and public relations work were all put to the test. The role of IMMS as an active, flexible, fast and equal partner for SMEs in the region was emphasised by the evaluation committee as essential and the course we have set for ourselves with our strategy was considered consistent and meaningful. To strengthen this focus, the commission has drawn up recommendations for the growth and further development of IMMS. After evaluating the recommendations from 2024 together with the TMWWDG Ministry, these will be concretised for implementation.

2023 was also characterised by increased **recruiting activities**: We travelled to more careers fairs, joined forces with Thuringian universities to expand the Long Nights of the Sciences in Ilmenau and Erfurt to include offers for study orientation and internship searches, provided a careers playlist with student video interviews on our YouTube channel and set up an online application platform.

www.imms.de/jobs

To our great delight, our employees received **awards** such as the Silicon Science Award and the iENA silver medal in 2023, and a dissertation developed from IMMS research projects was successfully defended.

The year 2023 was used intensively to achieve important **milestones in R&D projects** and industry contracts in our three research fields. This report highlights a selection of these. Among other things, we have realised a miniaturised CMOS ISFET sensor and highly sensitive SPAD-based image sensors for in-vitro diagnostics, developed intelligent communications solutions for monitoring particulate matter and road lamp defects and created virtual safety zones for truck cranes, supported research for a novel technology platform with a graphene-based field-effect transistor for in-vitro multi-parameter analysis with the development of miniaturised measurement technology, implemented a compact mixed-signal test system for characterising semiconductor memories and found new ways for unconventional, lateral measurements with laser focus sensors for nanopositioning systems.

We would like to **thank** our employees for all these and other solutions, for their expertise and personal skills and for their commitment. They are the ones who also promote young talent and are involved in associations, clusters and committees. The basis for this is the institutional funding from the Land of Thüringen. On behalf of the IMMS team, we would like to express our sincere thanks for this. We would like to thank all our research partners for inspiring our research and development, which we translate into application-oriented solutions for industry.

We would also like to thank all those who encourage us and shape the future with us and thank them for their commitment and trust. In this report, you can find out what we have achieved in some of our joint projects. We would like to develop further ideas with you.

We look forward to continuing to work and to exploring new paths together and we hope you enjoy reading this report.

Ralf Sommer
Scientific Managing Director

Martin Eberhardt
Financial Managing Director

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. In 2023, IMMS again worked on scientific projects and issues with numerous departments in the fields of electrical engineering and information technology, mechanical engineering, computer science and automation as well as mathematics. In parallel, IMMS is strongly networked with industry. To develop internationally successful innovations for health, the environment and industry, IMMS is integrated into regional and national innovation networks as well as industrial clusters. The use and bundling of technological competences and the development of joint market strategies provide valuable practical impetus for the research activities of the Institute and the Ilmenau TU.

Selection of joint projects

Quantum Hub Thüringen*: For quantum technology from Thüringen, IMMS is researching CMOS-based single-photon detectors

IMMS, Ilmenau TU and nine other Thuringian partners are researching quantum technologies that can far surpass the performance of conventional systems and enable disruptive applications. IMMS is researching the use of single-photon detectors (SPAD), which are manufactured in a standard semiconductor technology (CMOS). They are used to convert single photons into electrical signals and allow operation at room temperature without large and complex cooling systems.

www.imms.de/qhub

thurAI*: Smart city sensor technology and methods to intelligently process data in the network for AI evaluations

In the thurAI project, Ilmenau TU, University of Jena and IMMS are working on current solutions in the three areas of smart city, healthcare and medical technology as well as production and quality assurance. IMMS and Ilmenau TU will implement a "LivingLab" in Ilmenau for the smart city topic together with the city. The core of this is data that is needed for a wide variety of AI-based services in the smart city context. On the one hand, IMMS will select and test sensor technology for recording various parameters. On the other hand, it is about providing "smart data" through suitable pre-processing mechanisms at the sensor node itself or in the downstream network for the facilitated application of AI algorithms.

www.imms.de/thurAI

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

Until 2026, 13 doctoral students, including one at IMMS, are working on solutions for tip- and laser-based 3D nanofabrication in extended macroscopic workspaces in the NanoFab research training group 2182 funded by the DFG. They are supervised by professors and scientific staff of Ilmenau TU and IMMS under the direction of the Institute for Process Measurement and Sensor Technology of the Faculty of Mechanical Engineering. IMMS is developing solutions for a drive system that will enable multi-axis highly dynamic machining of objects with nanometre precision.

www.imms.de/nanofab

IMMS as "Smart Sensor Systems Model Factory" in the „Mittelstand-Digital Innovation Hub Ilmenau"*

As the "Smart Sensor Systems Model Factory", IMMS provides impetus for the introduction of Industry 4.0 technology for the improvement of machinery 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 compatible to Industry 4.0 is a powerful means of achieving real-time-capable innovation fast and affordably.

www.imms.de/md

InSignA* high-performance centre

The aim of the 'InSignA' high-performance centre in Ilmenau is to strengthen the regional economy by accelerating technology transfer. Regional value creation networks in the future-oriented transfer areas of signalling analysis and assistance systems in production, energy supply and robotics are to be developed and established. To this end, Fraunhofer institutions in and around Ilmenau, the research profile lines at Ilmenau TU and other research institutions are pooling their expertise.

www.imms.de/insigna

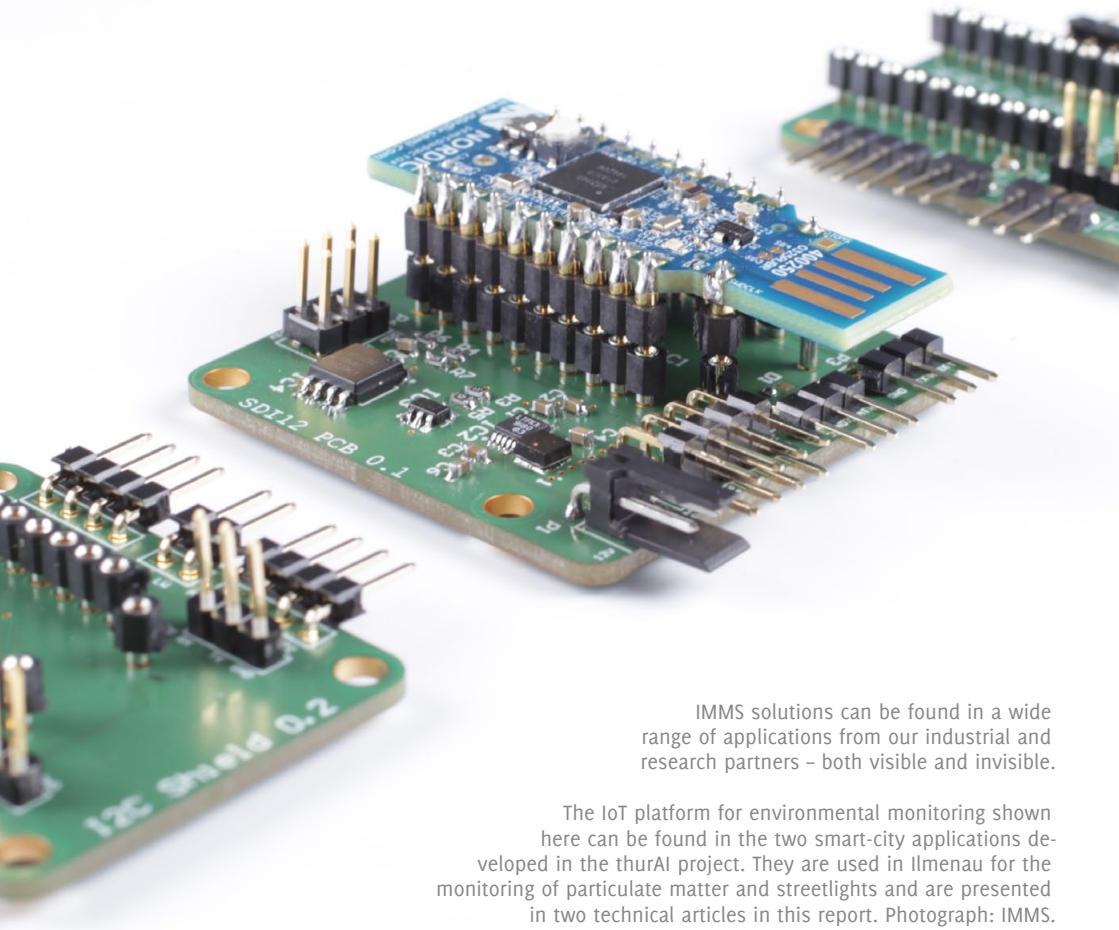
Joint encouragement of young academics

IMMS not only complements teaching at Ilmenau TU with extensive practical offers. In addition, Prof. Sommer and Prof. Töpfer are involved with courses in basic education and in the master's programme. IMMS promotes the motivation and training of students through its practical and industry-related offers, among other things, through numerous topics for internships.

www.imms.de/students

VOICES
FROM INDUSTRY AND ACADEMIA

All references: **www.imms.de/ref**



IMMS solutions can be found in a wide range of applications from our industrial and research partners – both visible and invisible.

The IoT platform for environmental monitoring shown here can be found in the two smart-city applications developed in the thurAI project. They are used in Ilmenau for the monitoring of particulate matter and streetlights and are presented in two technical articles in this report. Photograph: IMMS.

The thurAI research project is funded by the German Land of Thüringen via the Thüringer Aufbaubank under the reference 2021 FGI 0008.

Dr. Markus Lapczyna, Eppendorf

”We are committed to providing reliable solutions of the highest quality for handling valuable samples in life science research. Liquid handling is a core process in virtually every life-science laboratory. That is why it is a core area at Eppendorf. Our absolutely reliable devices and materials have become indispensable in laboratories. Whether it is a new technology or the further development of an existing product – every detail is considered with the needs of the user in mind. To this end, we are in close contact with our customers and are therefore familiar with their daily problems.

We called in the expertise of IMMS for a product maintenance project for a drive and measurement system. IMMS quickly gained a deep understanding of the system and was therefore able to identify and thoroughly analyse various influencing factors. This made it possible to identify potential for further optimisation of the drive unit. In further investigations, an approach for calibrating one of these disturbance variables was developed. We expect this to result in even greater accuracy for our controller, which can be utilised for further developments. The results speak for themselves and we are also completely satisfied with the way we worked together. We look forward to the next topics!“

www.imms.de/ref

eppendorf

www.eppendorf.de

Dr. Daniel Schultheiß, mayor of the city of Ilmenau.

Photograph: ©SVI.

Dr. Daniel Schultheiß, city of Ilmenau

"Ilmenau is a modern, innovative and liveable medium-sized centre with special dynamics. With the only technical university in the Land of Thüringen, the Goethe and university city is home to science and research and is highly attractive to younger people and families as well as innovative, technology-orientated companies and research institutes. With this in mind, the city decided several years ago to embark on the path to becoming a smart city. Only recently, these endeavours culminated in the smart city mission statement 'Ilmenau – smart city powered by its own resources'.

The smart city projects, which were implemented in the urban real-world laboratory together with the Institute of Microelectronics and Mechatronics Systems, are also part of these activities. After an initial needs analysis, three applications for the use of intelligent sensor systems were finally identified that simplify real municipal tasks.

One project uses sensors to monitor the function of the streetlights in the Jesuborn district of Ilmenau. This means that the lighting network can be permanently checked for functionality without the need for inspection trips and defects can be fixed promptly. The solution developed in the project consists of energy self-sufficient sensor nodes that can be retrofitted to any lighting columns.

A second project measures the air quality in three touristic districts by recording particulate matter in four granule sizes using an optical sensor. The IMMS team developed a system that uses inexpensive sensor technology to continuously moni-

tor particulate matter at various locations in each district to detect the causes of variations in particulate matter pollution and, if necessary, take countermeasures at an early stage. The processed measurement data is made available to the tourism administration in real time graphically and online.

The third project focusses on noise emissions. Our local authority is regularly confronted with compliance with the statutory limits and requirements. Traditionally, noise pollution is recorded on site in random samples using qualified measurement technology in accordance with the relevant legal standards. However, conventional measurement technology is expensive, requires specialised personnel and is only intended for selective monitoring. In contrast, systems such as those developed by IMMS in the preliminary 'StadtLärm' project can provide conclusions from continuous, area-wide monitoring. The noise monitoring system permanently records noise data over a large area using distributed sensors and is intended to provide the municipal authorities with the level and type of noise events. The information is helpful for future urban planning and traffic decisions as well as safety-related considerations and measures.

Throughout the entire duration of the project, I have always perceived IMMS as a competent, innovative and solution-orientated partner that dealt very flexibly and pragmatically with the multiple challenges of using modern measurement technology in a topographically and climatically demanding environment. As the city administration, we also value the personal collaboration with the institute's employees, who always find solutions through pleasant dialogue. Ultimately, these three practical examples illustrate the successful transfer of scientific endeavour to everyday use. This is why the sensors deployed will remain in use beyond the end of the project period and thus offer added value not only for the municipal administration, but also for the citizens of Ilmenau.

On behalf of the city administration of Ilmenau, I would like to thank the Institute of Microelectronics and Mechatronics Systems for the pleasant cooperation and look forward to many more joint projects. Thank you very much!"

ENCOURAGEMENT OF YOUNG ACADEMICS

All information on our study-related offers:

www.imms.de/students

Encouragement of young academics

It is one of our highest priorities to bring on the new blood in science. We are active in pursuit of this goal, inspiring and supporting undergraduate and master's students of the engineering sciences in particular by supervising internships and dissertations for BSc and MSc. The fact that we network so closely with industry provides the new generation of scientists with the opportunity to work on subjects of practical relevance where the results really matter. Thus, we impart theoretic in-depth knowledge of methods for an early combination with a practical implementation in applications. For fundamental education purposes various lectures and seminars are hold by IMMS staff at Ilmenau TU. Moreover, we offer training courses and guided tours of the establishment. School pupils, too, are given insight into our work by means of events and internships or by having their coursework supervised by professionals of the institute.

For example, we accompany offers for the Summer University of the Ilmenau TU and regularly organise BarCamps on the topic of electronic design automation. Students also take part in these interactive and open research meetings. Our internationally competitive industrial-standard infrastructure for design support and laboratory technology for electronic and mechatronic systems is also available for student research work.

www.imms.de/barcamp

Increased presence at careers fairs

In 2023, IMMS drew attention to its high-quality and committed promotion of young talent at three careers fairs – in June at Schmalkalden University of Applied Sciences, in October at inova in Ilmenau and in November at the 'Praxis trifft Campus' company contact fair at Ernst Abbe University of Applied Sciences in Jena. Students from disciplines such as biomedical engineering, electrical engineering, computer science,

IMMS team at the career fair at Schmalkalden University of Applied Sciences in June 2023. Photo: IMMS.

mechanical engineering, mechatronics and related degree programmes found out about offers for internships, bachelor's and master's theses and student assistant jobs as well as other opportunities for starting a career at the institute, e.g. a flexible combination of a master's degree and a part-time position. The long-term practical training that accompanies the degree programme with challenging topics, individual support and industrial-standard equipment prepares students for a career start in industry and application-oriented research. The aim is to strengthen companies in the region by promoting young talent at IMMS.

Video interviews with students at IMMS

In 2023, IMMS published six video interviews with students who talk about their topics for research and development and their mentorship and support provided by IMMS. In this way, they have been able to share some of their practical experiences at IMMS with others, which will help them during their studies and afterwards: good supervision, application of theory in practice, implementation of their own projects as coursework, professional development and plenty of experience from everyday R&D work. Three of the students have remained at IMMS after successfully completing their degrees, and one is currently working part-time alongside his master's programme.

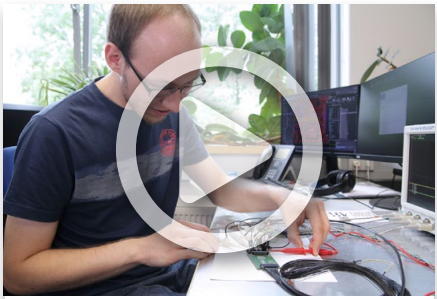
www.imms.de/students

Vincent: https://youtu.be/gZIzTS08RSk

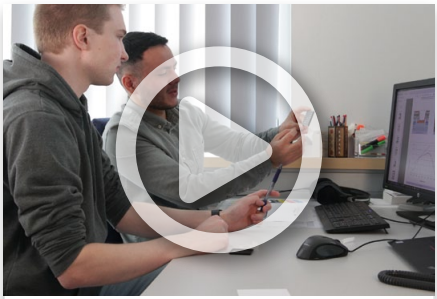
Marie: https://youtu.be/lzw58lLs3xQ

Nikita: https://youtu.be/jXxSGT1f00g

Laetitia: https://youtu.be/jBxdaxkwqwQ



Markus: https://youtu.be/-YZsnXmJ3Dg



Ilmurat: https://youtu.be/7zTNJQzHCZI

A few clicks to an internship – application platform launched

With the switch to the new application platform for regular vacancies in autumn 2023, IMMS has also transferred all topics for student offers to the new system. This means that students can not only quickly filter all topics for internships, bachelor's or master's theses or part-time jobs according to their interests, they can also apply online with just a few clicks under www.imms.de/students.

www.imms.de/students

Science nights – also for career guidance

IMMS used the Long Nights of the Sciences in Erfurt on 23 June and in Ilmenau on 1 July to provide information about its offers to promote young talent and to get even the little ones interested in technical content through hands-on activities with a fun factor. As part of the Erfurt Research and Industry Centre (FiZ), IMMS played a key role in coordinating the event for the Erfurt Science Night with partners in south-east Erfurt. The Ilmenau TU, the Ernst Abbe University of Applied Sciences in Jena, the Schmalkalden University of Applied Sciences and the Nordhausen Univer-

One of the hands-on offers at the Long Night of the Sciences.

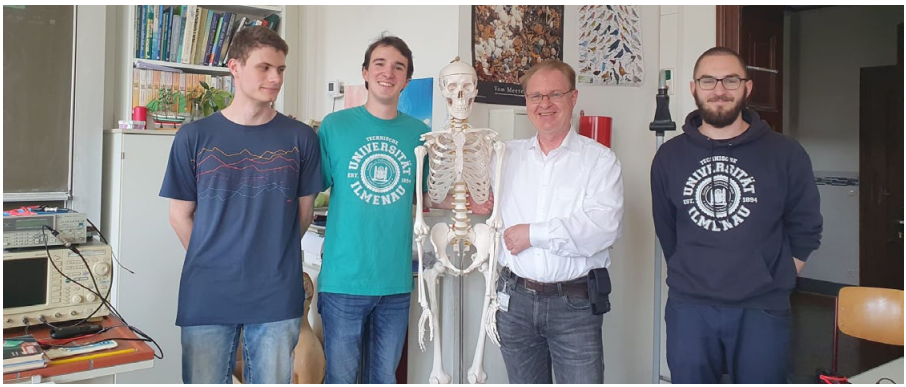
Photograph: IMMS.

https://youtu.be/vISCoSH7Qis

sity of Applied Sciences were thus won to present their study programmes at the Long Night of Science in addition to the diverse insights into research, development and production at the Erfurt South-East location as a possible future place of work for school pupils in Erfurt. The information booths of the four universities were located at the FiZ members: CiS Forschungsinstitut für Mikrosensorik GmbH, Fraunhofer Centre for Microelectronic and Optical Systems for Biomedicine MEOS, IMMS, Melexis Erfurt GmbH and X-FAB Global Services GmbH. According to the FiZ members, there were significantly more guests than usual and the overall programme was well attended.

Summer course at the Ilmenau School Research Centre

From 3 – 5 July 2023, pupils from a 6th grade took part in a workshop for a practical introduction to circuit technology during the project week at the Goethe School in Ilmenau shortly before the summer holidays. The workshop was one of the activities organised by the Student Research Centre at Ilmenau TU to arouse the curiosity of children and young people for mathematics, computer science, natural sciences and technology (STEM). It was supervised by Prof Dr Ralf Sommer, Scientific Director of IMMS and Head of the Department of Electronic Circuits and Systems at Ilmenau University of Technology, and four of his electrical engineering and information technology students.



Marius Schmidt, Richard Richter, Prof. Ralf Sommer, and Lukas Haubensack in the workshop on electronic circuit technology during the project week at the Goethe School in Ilmenau. Photograph: Ina Totzke, Goetheschule Ilmenau.

One of the many Girls' Day activities at IMMS on 27 April 2023. Photograph: IMMS.

Girls' Day at IMMS

On 27 April 2023, 15 girls from grades 5 to 8 came to IMMS for Girls' Day to find out what everyday life as an engineer is like, to take a close look at chip structures, to solder their own torch, to conduct experiments on vibrations and a mini motor, to solve lots of puzzles and to try their hand at programming. There were exciting programming tasks to solve on the OpenRoberta platform with the Calliope mini system: making LED writing work, switching on light by movement or getting a very precise picture of the environment with sensors. The day was organised by engineers from IMMS with student support and was prepared hand in hand with the offerings from Ilmenau University of Technology and Fraunhofer IDMT and announced as a joint campus offering.

Ilmurat Bazarov, M.Sc., scientist at IMMS

"From the beginning of my journey at IMMS, it has been a narrative of evolution, both professionally and personally. It all began as master thesis student, jumping into the intricate world of AI implementation within the microchip industry. Those formative student days not only shaped my goals but also instilled in me a sense of belonging, and I knew I wanted to continue my journey with this innovative company. My time as a student there was formative, shaping my goals and leading me to continue my journey at this company. Now, in the SD department, I am focused on industrial process optimisation, where we are actively binding AI to impact Industry 4.0.

At IMMS, what energises me most is the tangible impact our work has on society. The bridge between research and industry is where our efforts truly shine, as we directly contribute to real-world solutions that enhance efficiency, productivity, and sustainability. This alignment of innovation with practical application resonates deeply with me, driving my passion to make a meaningful difference. Take, for instance, our ongoing project to develop AI-based control systems for resource-efficient process optimisation in industrial production. By leveraging cutting-edge machine learning algorithms, we are not only streamlining production processes for maximum efficiency but also reducing resource consumption and promoting

www.imms.de/embeddedai

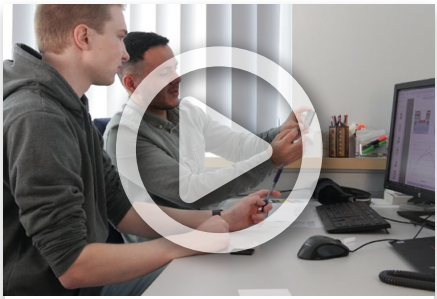
www.imms.de/immsvoices

Ilmurat Bazarov, M.Sc., scientist in the System Design department at IMMS.

Photograph: IMMS.

sustainability. This dual emphasis on productivity and sustainability underscores our dedication to responsible innovation.

My time at IMMS has been instrumental in shaping me into a result-oriented researcher. I have had the privilege of learning from the best and working on cutting-edge applications of AI in industrial scenarios. The company has provided me with a unique platform to grow as an engineer-scientist, allowing me to straddle the edge of academia and industry. I have learned a great deal about the importance of collaboration, innovation, and creativity, and I am grateful for the opportunities I have had to develop my skills and expertise. What I appreciate most is the dynamic and supportive environment. My colleagues have been an invaluable source of support, always open to new ideas, willing to lend a helping hand, and encouraging personal growth. The company has also become a melting pot of languages and cultures, offering a rich exchange of ideas and perspectives. This diversity has not only broadened my professional horizons but also enriched my personal life.“



Ilmurat: https://youtu.be/7zTNJQzHCZI

Ilmurat Bazarov (right), M.Sc., scientist in the System Design department, during his time as a master's student at IMMS with his mentor Florian Kögler. He also talks about this time in a video interview under https://youtu.be/7zTNJQzHCZI.

Photograph: IMMS.

www.imms.de/immsvoices

Vincent Haude, B.Sc., master's student and scientist in the Industrial Electronics and Measurement Technology department at IMMS.

Photograph: IMMS.

Vincent Haude, B.Sc., master's student and scientist at IMMS

"Prof. Sommer drew my attention to IMMS during my undergraduate studies in electrical engineering and information technology at the Ilmenau TU. This was followed by a two-year student assistant position in the department of industrial electronics and measurement technology in Ilmenau. During this position, I was able to gain valuable practical knowledge, which helped me to understand the theoretical knowledge from my studies and link it to practice. I was also taught how to use a wide range of measuring equipment, which is only taught to a limited extent during my studies and was very useful to me during some of my practical courses at the TU.

After my student assistant position, I moved to the IMMS branch in Erfurt in 2022 to complete my mandatory internship there. As part of this, I developed a probe card for the final test of a sensor IC. The challenge here was to develop a contact arrangement that could reliably accommodate the small pitch and small size of the contacts. When developing this probe card, I particularly benefited from the various 3D printing technologies available at IMMS. My bachelor's thesis in 2023 directly followed on from the internship. As part of this thesis, I developed circuit topologies that make it possible to pulse LEDs in the nanosecond range. Such short pulses are required for the technology of time-resolved fluorescence in medical diagnostics. When carrying out my measurements, it was necessary to measure photons in the nanosecond range. I benefited from the state-of-the-art measuring equipment at IMMS. For the research on the topic of my thesis, it was necessary for me to deal with different

Vincent: https://youtu.be/gZIzTS08RSk

Vincent Haude (links), B.Sc., scientist in the Industrial Electronics and Measurement Technology department, during his time as student assistant at IMMS with his mentor Tom Reinhold. He also talks about this time in a video interview under https://youtu.be/gZIzTS08RSk. Photograph: IMMS.

areas of science such as solid state physics, optoelectronics and electrical engineering to understand LEDs and to work on the topic as well as possible. The deep understanding of my colleagues at IMMS, who were able to categorise and answer every question, no matter how complicated, helped me here. At the end of my work, I had developed circuit topologies that make it possible to use time-resolved fluorescence measurement in devices in a cost-effective and space-saving way. To pursue the results of my bachelor's thesis further, I was employed as a part-time research assistant at IMMS after completing my bachelor's degree. I particularly like the fact that I can combine my studies with this part-time position. This allows me to gain valuable practical experience in working on research projects during my master's degree, which will make it easier for me to start my career after graduation.

I really appreciate the working atmosphere at IMMS. The team is very open-minded and every door is always open to ask questions or contribute ideas. I really appreciate the open discussions and the dialogue with colleagues, even during lunch breaks. There is also a monthly exchange between the different departments as part of the institute colloquium. At these meetings, the research focuses of the individual departments are presented so that everyone can look beyond their own specialist area.

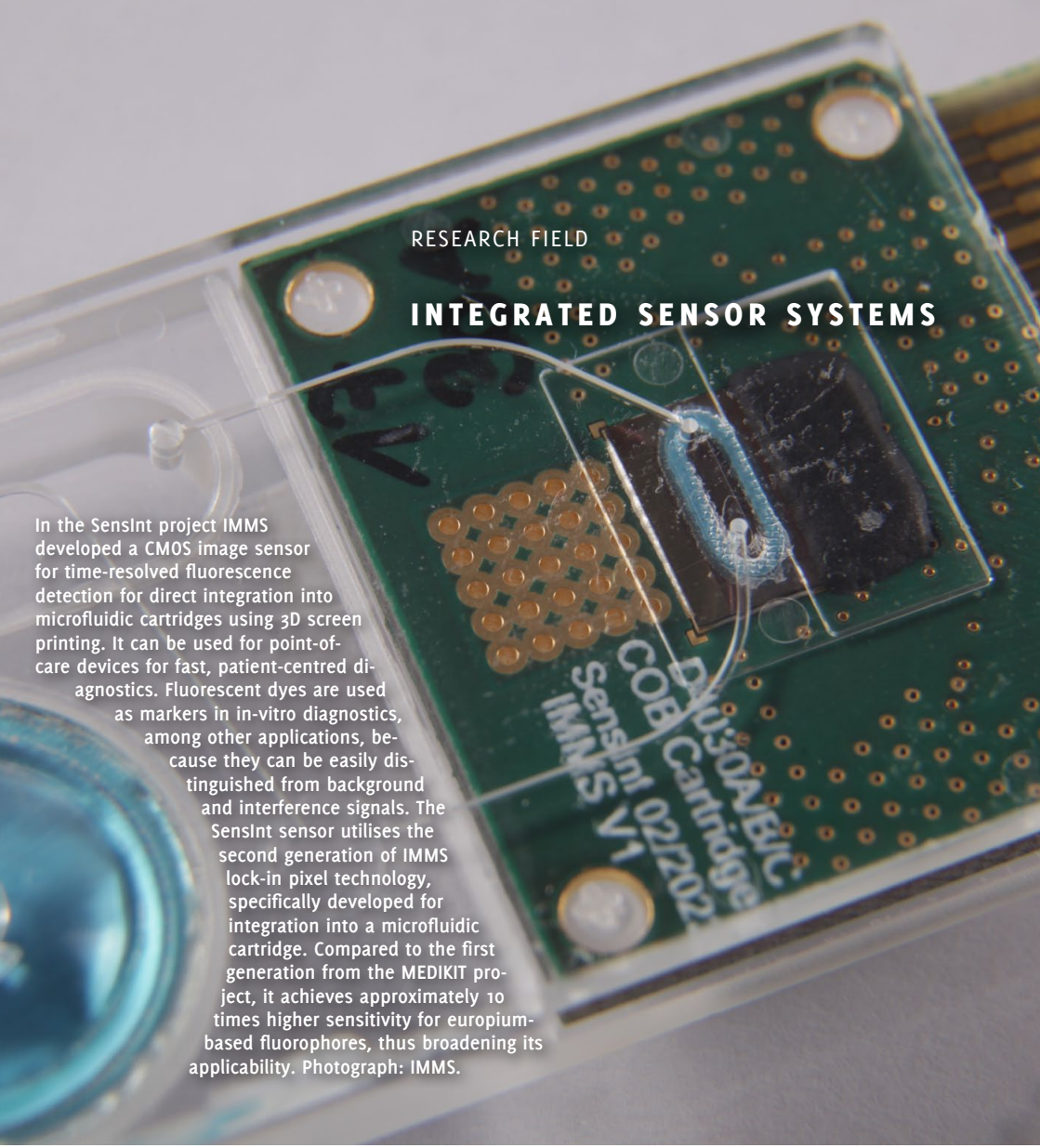
www.imms.de/immsvoices

I also appreciate the wide range of tasks and work experience, internship and thesis topics at IMMS. In the three years that I have been working at IMMS, I took the chance to work on many different topics and deal with 3D design, PCB conception, design and construction, measurement and characterisation of circuits as well as many other activities."

www.imms.de/students

RESEARCH FIELD

INTEGRATED SENSOR SYSTEMS



In the SensInt project IMMS developed a CMOS image sensor for time-resolved fluorescence detection for direct integration into microfluidic cartridges using 3D screen printing. It can be used for point-of-care devices for fast, patient-centred diagnostics. Fluorescent dyes are used as markers in in-vitro diagnostics, among other applications, because they can be easily distinguished from background and interference signals. The SensInt sensor utilises the second generation of IMMS lock-in pixel technology, specifically developed for integration into a microfluidic cartridge. Compared to the first generation from the MEDIKIT project, it achieves approximately 10 times higher sensitivity for europium-based fluorophores, thus broadening its applicability. Photograph: IMMS.

REACT-EU – Als Teil der Reaktion der Union auf die COVID-19-Pandemie finanziert.
EFRE
EUROPA FÜR THÜRINGEN
EUROPÄISCHER FONDS FÜR REGIONALE ENTWICKLUNG
EUROPÄISCHE UNION

The SensInt project was funded as part of the European Union's response to the COVID-19 pandemic through the European Regional Development Fund (ERDF-OP 2014 – 2022) under the reference 2021 FE 9072.

Research field: **Integrated sensor systems**

In the research field “Integrated sensor systems”, we investigate miniaturised systems manufactured in semiconductor technology consisting of microelectronic and/or microelectromechanical components for sensors applications, as well as methods to design these highly complex systems efficiently and safely.

Integrated sensor systems connect the analogue with the digital world:

Electrical, mechanical and optical parameters can be directly detected, amplified, digitised and transmitted on these silicon chips with an edge length of just a few millimetres. They are mobile, energy-efficient, precise and powerful and therefore represent the key technology for the Internet-of-Things (IoT). Functionalised chip surfaces can be used to measure additional physical as well as chemical and biological parameters. With integrated sensor systems, structural sizes in the µm range can be achieved and thus properties can also be detected on a molecular scale, such as in the sequencing of DNA.

www.imms.de/sensor-ics

Goal: new applications through functional integration and miniaturisation

We aim to pioneer new applications through functional integration and miniaturisation. In the field of **CMOS-based biosensors**, we are researching CMOS-integrated transducers and their interaction with biological receptors. In the area of **ULP sensor systems**, we are reducing the energy demand of integrated sensor systems through intelligent power management and ultra-low power (ULP) circuit technology. Our intensive research into **AI-based design and test automation** enables our partners and us to automate the development of highly complex integrated sensor systems and make them safer.

www.imms.de/biosensors

www.imms.de/ulp

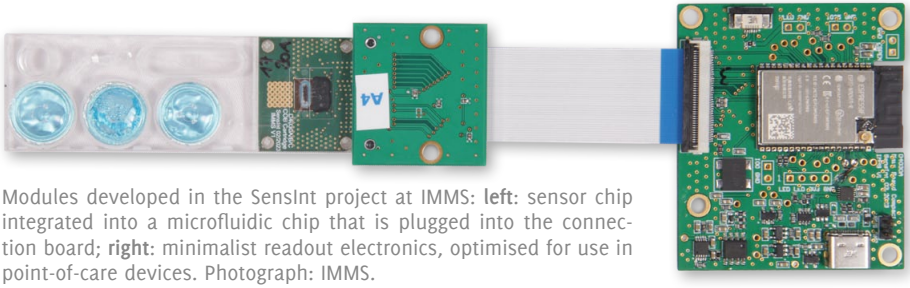
www.imms.de/aidesigntest

Research with commercial technology for industrial exploitation

The goal of our research is always industrial exploitation. We therefore focus on system design with commercial semiconductor technology. Large quantities can be used here to achieve competitive and cost-effective solutions. In addition, IP protection and trustworthiness are strengthened.

Integrated sensor systems are incorporated into solutions for all target markets of IMMS. In the lead applications of **sensor systems for in-vitro diagnostics** and **RFID sensor technology**, we focus on the use of integrated sensor systems in life sciences as well as in automation technology and Industry 4.0 target markets.

www.imms.de/ivd



Modules developed in the SensInt project at IMMS: **left**: sensor chip integrated into a microfluidic chip that is plugged into the connection board; **right**: minimalist readout electronics, optimised for use in point-of-care devices. Photograph: IMMS.

Highlights of 2023 in our research on integrated sensor systems

Project completion SensInt*: CMOS image sensor for time-resolved fluorescence detection for direct integration into microfluidic cartridges using 3D screen printing

In the SensInt project, a CMOS image sensor for time-resolved fluorescence measurement was developed at IMMS. This sensor can be directly integrated into microfluidic cartridges for point-of-care devices using 3D screen printing, enabling rapid, patient-near diagnostics. **Fluorescent dyes** are used as markers in in-vitro diagnostics, among other applications, because they can be easily distinguished from background and interference signals. Many diagnostic questions require quantitative statements about concentrations and ratios rather than simple yes/no statements provided by strip tests. Common combinations of mobile reader systems and strip tests with classic dye particles like gold are not sensitive enough for this purpose. New combinations with fluorescent dyes such as europium offer much higher readout sensitivities. An imager developed in the previous MEDIKIT project already provided the sensitivity required for the diagnosis of cancer and heart diseases. The lock-in principle of the chip eliminates the need for complex optical filters.

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The SensInt sensor utilises the **second generation** of IMMS **lock-in pixel technology**, specifically developed for integration into a microfluidic cartridge. Compared to the first generation from the MEDIKIT project, it achieves approximately 10 times higher sensitivity for europium-based fluorophores, thus broadening its applicability. The demand for point-of-care solutions and dense testing regimes has grown significantly, not only due to the SARS-CoV-2 pandemic. Microfluidics has established itself as the key technology in this field for years, enabling highly accurate results on a molecular biological basis, such as PCR. To make such systems smaller, more portable, and potentially more affordable, sensors for detection are increasingly being integrated into microfluidic cartridges.

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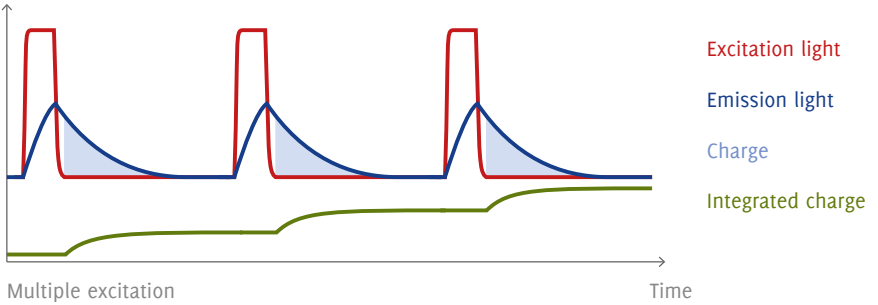


In the SensInt chip, lock-in pixel technology has been implemented to eliminate the need for optical filters to block out the excitation light: As soon as the excitation light has faded, the emitted fluorescent light is measured until this has also faded. This can be repeated several times. The fluorescence emission light is accumulated cycle by cycle, which amplifies the output signal. Diagram: IMMS.

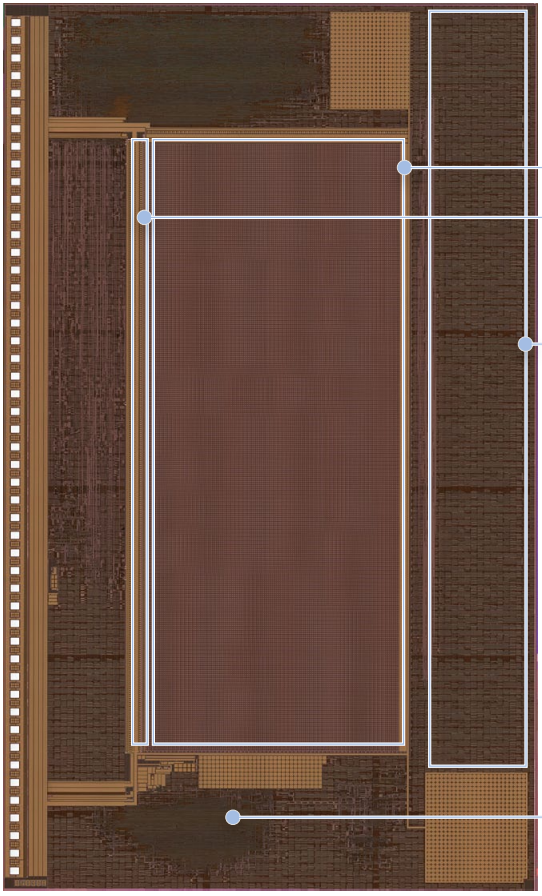
In both chips, the fluorescent dye is optically excited by a light source and the emitted photons are detected by the chip. Time-resolved fluorescence measurement involves measuring this emission after the excitation light has decayed and accumulating it over several illumination cycles. This allows even very weak fluorescence to be quantitatively detected, thus achieving higher sensor sensitivities.

The focus of the new chip generation was also on increasing the degree of integration and simplifying the required external hardware. The chip now includes an SRAM as image memory and features a QSPI interface in addition to an I²C interface.

Video explaining the lock-in principle, which eliminates the need for expensive optical filters for both chips. Source: IMMS.

https://youtu.be/pEXdMNZZkPA

For the application, the collaboration with industry partners aimed to enable seamless integration of the image sensor into the fluidic cartridges, accelerating and making the production of point-of-care tests more cost-effective. The sensor layout is specifically optimised for applying a silicone seal through the 3D screen printing process of our project partner Axenoll. The project partner Microfluidic ChipShop integrated the sensor into a microfluidic cartridge, enabling real-time PCR to be performed directly over the sensor's image field.



Features of the SensInt chip:

- Lock-in pixel with dppda photodiodes
  .Pixel size of 15 µm x 15 µm
  .Image field size of 128 rows x 310 columns
- Row-wise single-slope ADC: advanced features to improve accuracy like ramp buffer and bias sampling
- 82kB SRAM allows to buffer a full image
- Freely configurable image capturing via programmable sequencer
- Easy interfacing via I^2C & QSPI
- Centreed pixel array for maximum fluidic seal area
- XS018 CMOS technology
- Total chip size of 6800 µm x 4075 µm

Photograph: IMMS.

Georg Gläser (right) and Univ.-Prof. Dr.-Ing. Ralf Sommer (left), doctoral supervisor, scientific managing director of IMMS and professor at Ilmenau TU, after the disputation on 14 June 2023. Photograph: IMMS.

Dissertation on new methods for automation in integrated circuit design

Reliable and faster chip designs through invasive and parametric simulation methods

Georg Gläser, specialist for the integration of AI methods in design automation at IMMS, successfully defended his dissertation "Invasive and Parametric Simulation Methods for Integrated Circuit Analysis" in Ilmenau on 14 June 2023. His work, which was created at IMMS, addresses the fundamental problem in the design of analogue and mixed analogue-digital integrated circuits: These chips, which are part of every smartphone or enable IoT applications, are partly designed manually – despite Electronic Design Automation (EDA) – and then simulated. Causes of errors are searched for and eliminated on the basis of experience before the expensive and time-consuming semiconductor production starts. The aim of Georg Gläser's methods is to support this error search with innovative EDA methods. The main idea of his work is to use automated model refinements for the development of integrated circuits to include and understand problematic effects. This is achieved through targeted changes in parameters and structures, which can be used to find previously unknown information about an integrated circuit, combine it and use it to improve the circuit design. All methods were tested in chip developments at IMMS. The results are used and followed up in various research and industry-driven chip design projects and are the basis for the AI-based design and test automation researched at IMMS.

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Simulation and verification of analogue and analogue-digital integrated circuits shaped by empirical knowledge

"In chip design, problems often come to light very late – for example, during the layout, which is the construction plan that is developed for production in the end. Then, in extreme cases, you suddenly realise that, for example, lines are too close together and can impair performance through crosstalk or even destroy a chip in interaction with other effects," explains Georg Gläser. It takes a lot of time to go through the causes of errors from the individual transistor, of which there can be millions in a circuit, to the complex overall system design level by design level, because all these levels have to be described in detail with models and simulated, Georg Gläser continues. "The main problem, however, is that the models have not been able to show many effects so far. This is because people often work with simplified macro models that usually do not represent noise, parasitic couplings or unfavourable effects of deeper design levels." So far, only experience has helped. Moreover, existing methods usually start at only one design level. In addition, the systems and hence the necessary simulations are becoming more and more complex, as more and more functionality and thus circuit elements are to be put on ever smaller chip areas.

Methods provide more knowledge about the circuit and reduce design costs

On the one hand, the methods make it possible to integrate interference effects into the models to map them in more complex simulation scenarios. On the other hand, the methods provide insights into areas in which the models, circuits and systems work and where they do not. In addition, the methods make it possible to estimate design uncertainties at an early stage and to reduce iterations in the design and thereby decrease costs. For example, one method, the symmetry search for parasitic elements, delivered 223 possible problem areas as a result for a contact image sensor chip development at IMMS after only 6 hours of computing time, which would otherwise have had to be found by hand. Another method for identifying problematic couplings in the layout was already successfully used by industrial partners of IMMS before the dissertation was published.

The dissertation presents five methods that can be used at each design level or at the transition to the next. This is a clear advantage compared to other contributions, which are usually limited to one level in the design process. Some of the new methods are described here as examples.

Invasive analysis for early detection of previously unconsidered effects

Using an invasive analysis, system models can be dynamically adapted in the work to gain insights into possible or existing disturbing influences, such as coupling of lines. The framework developed for this with several 10,000 lines of code is suitable for very complex systems and can analyse the programme code of behavioural models, adapt the models accordingly and address the simulator. For example, parasitic elements are inserted or removed in this way, or test and observation modules are added.

Parasitic symmetry analysis and acceptance regions

Many problems are often only visible in the layout, e.g. when couplings occur due to closely spaced lines and thus enable signal paths that result in undesired effects. Up to now, troubleshooting after the layout is done by trial and error with many manual simulations to find out where the error comes from, sometimes also with statistical methods. A systematic approach for the analysis of mixed-signal systems before layout was missing.

The starting point of the new approach of symmetry analysis is that symmetry is a core concept in circuit design itself. The idea behind this is to find interfering operating conditions that are symmetrical, therefore neutralise each other and can thus be eliminated from further troubleshooting, similar to headphones with Active Noise Cancelling, which can cancel out noise with exactly opposite signals of the same strength so that they are no longer perceived as annoying.

To be able to map and analyse these interference variables, which are not present in the circuit diagram, the method of acceptance regions is used. With it, symmetries can be made visible and derived as a basis for the search algorithm. Behind this are complex algorithms that examine all possible symmetry pairs with maximum values. The method classifies the parameter space into segments that show where the system works and where it does not. The advantage of the method is that the layout does not have to be known.

Georg Gläser and members of the examination committee after the disputation on his dissertation "Invasive and Parametric Simulation Methods for Integrated Circuit Analysis" on 14 June 2023: f.l.t.r.: Dr.-Ing. Dirk Nuernbergk, Georg Gläser, Univ.-Prof. Dr.- Ing. Ralf Sommer, Prof. Dr.-Ing. Eckhard Hennig, Univ.-Prof. Dr.-Ing. habil. Hannes Töpfer, Univ.-Prof. Dr.-Ing. Giovanni Del Galdo. In the foreground: the graduation cap with AI-based audio output as idea generation assistance system. Photograph: IMMS.

Basis for research into AI-based design and test automation at IMMS

When Georg Gläser was honoured with the EDA Achievement Award by the eda-centrum long before he submitted his dissertation, it was already confirmed that his work is an important contribution on the way to further design automation of analogue and mixed-signal circuits, opens up new optimisation potential in circuit design and significantly expands the state of the art in EDA. Prof. Dr.-Ing. Ralf Sommer fully shares this assessment. As Georg Gläser's doctoral supervisor, scientific director of IMMS and Head of the Department of Electronic Circuits and Systems at the Faculty of Electrical Engineering and Information Technology at Technische Universität Ilmenau, he adds: "With his methods, Georg Gläser has also set the course for research on AI-based design and test automation at IMMS, which he has decisively shaped and for which he has systematically built up a team of experts in recent years to further advance the topic." Under his leadership, research groups and projects were also acquired and worked on to expand know-how in this area. On this basis, a range of services for the methodological support of industrial customers was established. In addition, he has initiated further dissertations in this field in his team, which are very promising, Sommer continues. "We are curious to see what the future entails. Georg Gläser has made a great contribution, of which we are very proud."

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The inventors Benjamin Saft (left) and Georg Gläser (right), IMMS, received a silver medal in the competition of the inventors' fair iENA 2023.

Photograph: IMMS.

iENA silver medal for latch-based active ultra-low-power pull-up emulator

Energy efficiency for serial inter-chip communications with commercial wireless sensors

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IMMS was honoured with a silver medal on 12 December 2020 in the competition of the iENA inventors' fair for the Thuringian award event of the PATON – Patent Centre of the Land of Thüringen at Technische Universität Ilmenau for their development "Circuit configuration to provide the charging energy for a level change on a signal bus, method for the calibration and signal transmission system". At the end of October, PATON submitted the work to the competition at the iENA in Nürnberg on behalf of the inventors Georg Gläser and Benjamin Saft. The latch-based active ultra-low-power pull-up emulator makes it easier to use commercial sensors for new applications: Active wireless sensors, such as Zigbee sensors, can be used by battery for longer. Passive wireless sensors without their own battery supply, e.g. RFID sensors, can work with a greater range. The circuit is generally suitable for different bus systems and any signal frequencies. No adaptations are required for conventional system components connected to the bus. The circuit can therefore be easily integrated into conventional bus systems.

Conventional communications for ultra-low-power applications unfavourable in terms of energy consumption

Standardised communications protocols between different electronic chips are a basic requirement for the design of modern electronic systems. Established protocols,

which are supported by most commercial chips, are often associated with relatively high energy requirements during communications.

Signal transmission between electronic system components is often handled via a serial signal bus. Various communications protocols are used, such as SMBus, I²C, 1-wire or SPI. Many of these protocols require pull-up resistors that create a defined high level on the signal bus, which can be pulled to low level for signalling. The continuous current flow via the pull-up resistors contributes significantly to energy consumption when such signal buses are used in ultra-low-power and battery-operated systems, such as RFID sensor transponders.

Energy efficiency through active pull-up emulator instead of resistors

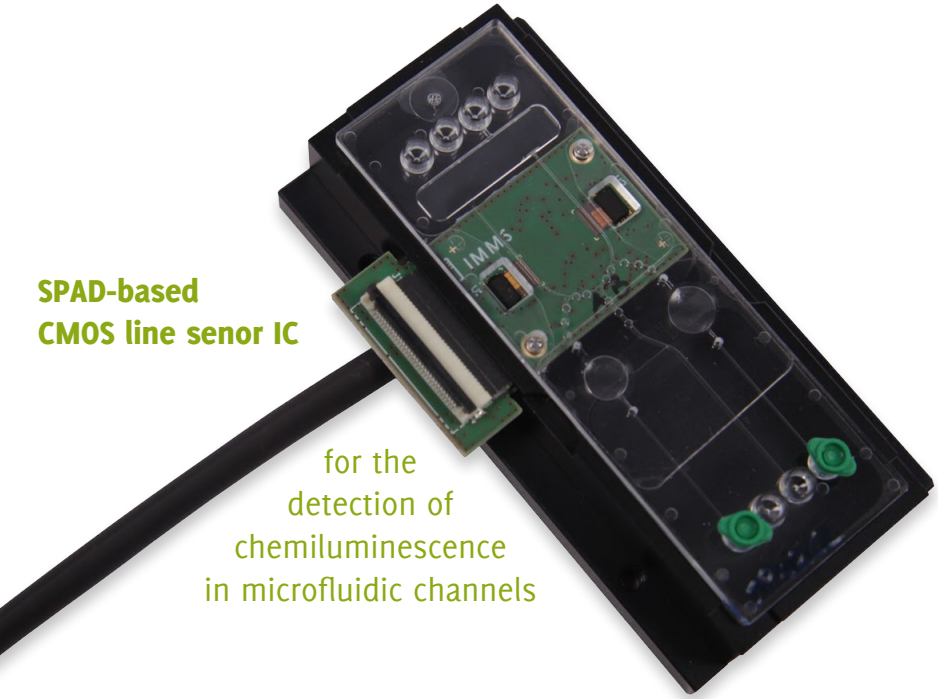
The innovative circuit concept dispenses with pull-up resistors and uses an active pull-up emulator to provide the charging energy for a level change required for signal transmissions in a very energy-efficient manner.

"A permanent current flow via pull-up resistors is not necessary during a pull-down phase with our solution," explains Georg Gläser, Team Lead Digital IC Design and Design Methology at IMMS. "Instead of pull-up resistors, we use latches as state memories, switches and a logic circuit that controls these switches. During the pull-down by a communications subscriber, the latches are reset with defined small amounts of charge – periodically instead of permanently and until the pull-up is successful. The energy required for this is many times less than with pull-up resistors." The new circuit concept can reduce the energy requirement of an active or passive sensor system consisting of commercial sensors and evaluation electronics. This allows the operating time of battery-operated systems to be extended or the applicability of the protocols to be extended to alternative supply concepts such as energy harvesting.

German patent: DE 10 2016 119 927 B4, IP available, patent applicant/owner: IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH), inventors: Georg Gläser, Benjamin Saft.

www.imms.de/patent

SPAD-based CMOS line senor IC for the detection of chemiluminescence in microfluidic channels



The picture shows the application-specific mount for aligning the microfluidic chip directly above the sensor IC. Photograph: IMMS.

Motivation and overview

Light can be produced by chemical reactions. This chemiluminescence or chemoluminescence appears for a few seconds as a flash of light or as a glow over many minutes to hours. Chemiluminescence not only makes fireflies and glow sticks glow, it also enables the reliable detection of enzymes in very low concentrations down to individual molecules in biochemistry and medical diagnostics, for example. Chemiluminescence immunoassays (CLIA) can be used to determine the smallest concentrations of antibodies or antigens, which is why the method is often used for highly sensitive laboratory analysers.

To detect the chemiluminescent light, highly sensitive light sensors are needed. Photomultiplier tubes (PMTs) are typically used for this purpose, which can detect the smallest amounts of light down to individual photons due to their very high sensitivity. PMTs have a very low dark count rate (DCR), i.e. they count very few events that are not caused by incoming photons, but by thermal charge carrier generation. PMTs are state-of-the-art for low-light sensing, especially for laboratory analysers and the

equipment infrastructure in central laboratories. However, compared to integrated CMOS sensors, they are large and expensive. They are difficult to miniaturise and integrate with complex electronics or microfluidics. For this reason, chemiluminescence-based point-of-care tests are rather the exception in cost-sensitive applications, although they can be used to achieve high sensitivity and test quality.

IMMS is therefore researching alternative sensor concepts for low-light sensing based on CMOS SPADs. A single-photon avalanche diode (SPAD) is operated above the breakdown voltage and can therefore also resolve single photons. The advantages of CMOS SPADs are that they are easier to miniaturise and integrate, for example in the form of image sensors, and can be produced very cheaply in mass. With PMTs, on the other hand, only scanning methods for spatial resolution can be achieved, which in turn entails complex mechanical components.

www.imms.de/biosensors

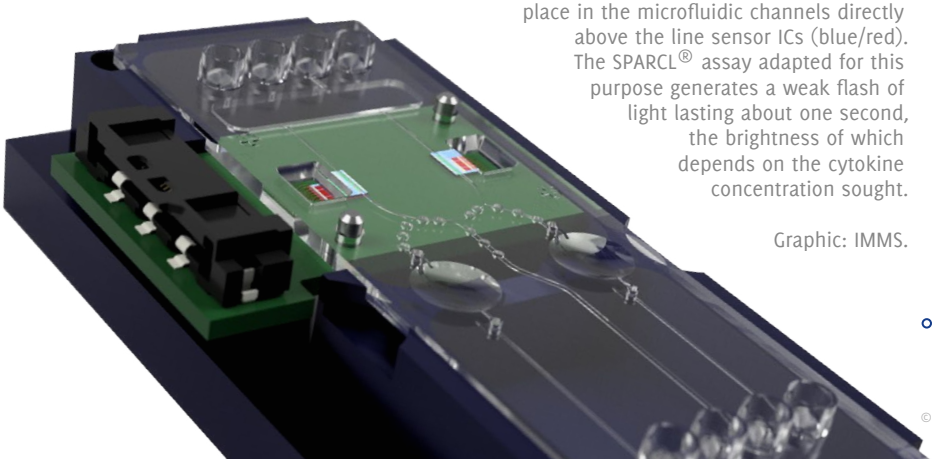
In the KODIAK project, IMMS and its five partners from Thüringen – X-FAB Global Services GmbH, Lucas Instruments GmbH, the Fraunhofer Centre for Microelectronic and Optical Systems for Biomedicine (MEOS) and the CiS Research Institute for Microsensor Technology GmbH – conducted research on a point-of-care test system (see Figure 1) for the rapid diagnosis of cytokine release syndrome (CRS) and developed a SPAD-based CMOS line senor IC for the detection of chemiluminescence in microfluidic channels.

www.imms.de/kodiak

Figure 1:

Concept for the detection system: Carrier (black) with sensor PCB (green) and microfluidic cartridge (transparent). The chemiluminescence reaction takes place in the microfluidic channels directly above the line sensor ICs (blue/red). The SPARCL® assay adapted for this purpose generates a weak flash of light lasting about one second, the brightness of which depends on the cytokine concentration sought.

Graphic: IMMS.



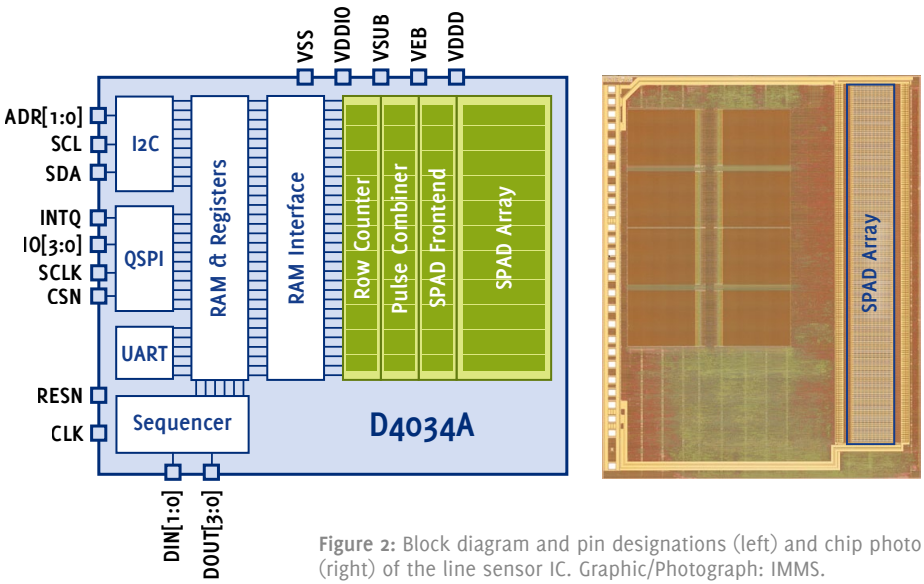


Figure 2: Block diagram and pin designations (left) and chip photo (right) of the line sensor IC. Graphic/Photograph: IMMS.

Structure of the line sensor IC

The challenge in developing the line sensor IC was to carefully design both X-FAB's SPADs and their readout circuits to be developed at IMMS to achieve a high fill factor and a low dark count rate (DCR).

The line sensor IC consists of a SPAD array with a length of 3.4 mm in the direction of the channel and a width of 0.35 mm, see Figure 2. Along the microfluidic channel, the array is divided into 192 sensor rows. Each row consists of 20 SPADs that are packed to the maximum with minimal spacing. Each row is also equipped with individual switches to enable/disable each individual SPAD, a common active quenching circuit to stop the avalanche breakthrough and reset the SPADs, with two programmable analogue timers for extinguishing and charging time, as well as an after-pulsing filter and a 16-bit counter. Furthermore, each row contains a pull-up power source to prevent high DCRs due to leakage currents in the quenching circuit. In addition to the SPAD series, the line register and line multiplexers for their selection, the line sensor IC contains a programmable sequencer for controlling image acquisition (uC Control Engine) and a computing unit (ALU) that can apply memory-saving bfloat16 encoding to the acquired sensor data, see Figure 3. A 64-kB SRAM is used to buffer the counter values of complete measurements. The IC is configured and read out via the I²C and QSPI interfaces.

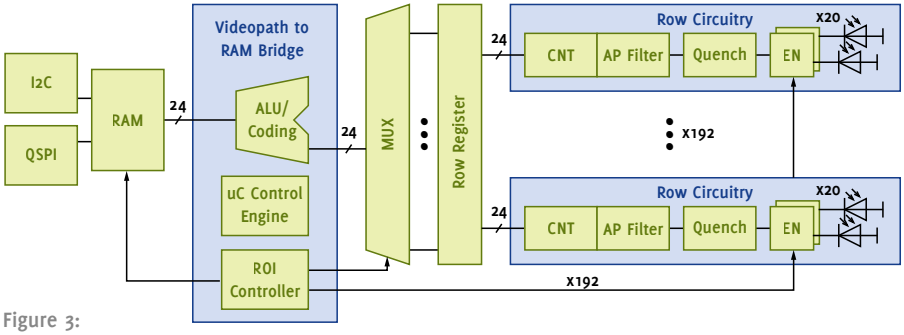


Figure 3:

Signal path of the line sensor IC with optical inputs (SPADs) on the right and digital outputs (I^2C and QSPI) on the left. Graphic: IMMS.

Sensitivity optimisation

A total of 12 variants of the line sensor IC were manufactured, which differ only in the SPADs used. X-FAB has designed six optimised SPAD layouts of two SPAD components for this purpose. The DCRs of each 3,840 SPADs in each SPAD array vary greatly due to manufacturing tolerances, which is why some SPADs have a low DCR and others have a high DCR. The DCR fluctuations between the best and worst SPAD in the array can be up to four orders of magnitude. Since the 20 SPADs in each row share a quenching circuit, the SPAD with the highest DCR will also determine the DCR of the entire range. To maximise the effective sensitivity of the line sensor, algorithms for the targeted deactivation of SPADs with poor performance, so-called screamers with high DCR, were therefore also implemented. These work as follows, for example: First, the DCR of all SPADs is measured individually in the sensor array and a histogram is created. Then, a certain percentage of the worst-performing SPADs, the screamers, are disabled. For example, disabling the 20% worst SPADs can reduce the DCR mean of the sensor array by more than half.

Measurements

Figure 4 shows which SPADs within the array have been classified as screamers and disabled. At higher cut-off thresholds (the upper diagrams in Figure 4), the effective DCR is further reduced, see Figure 5, whereby the spatial resolution of the array is maintained due to the homogeneous distribution of the screamers across the array.

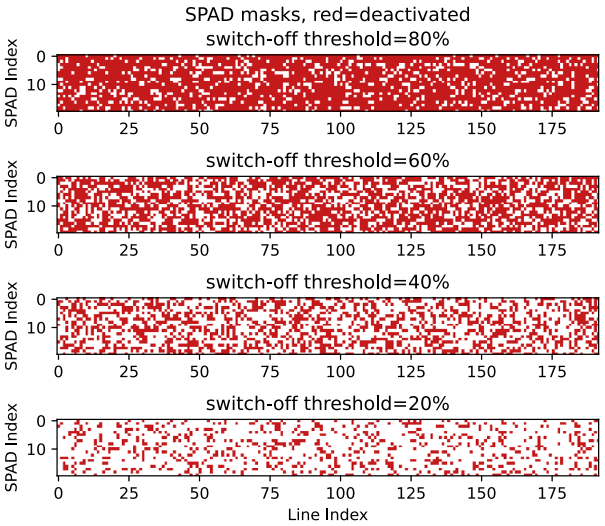


Figure 4:

Distribution of the disabled SPADs (screamers) over the SPAD array as a function of the shutdown threshold. The Line Index stands for the row number and the SPAD Index denotes the SPAD within the row. The higher the shutdown threshold, the more SPADs will be disabled. At a shutdown threshold of 80%, only the 20% DCR-best SPADs are activated. Disabled SPADs are shown in red.

Source: IMMS.

By additional measurements with the line sensor IC in very low light illumination from an LED, it could be shown that it is advantageous for the detection of very low light outputs to use even only the 20% – 30% of SPADs with the best DCR, see Figure 5.

Outlook

The line sensor IC achieves a DCR of about 0.01 counts per second per square micrometre in the best case, which is a very good value. This means that the sensor

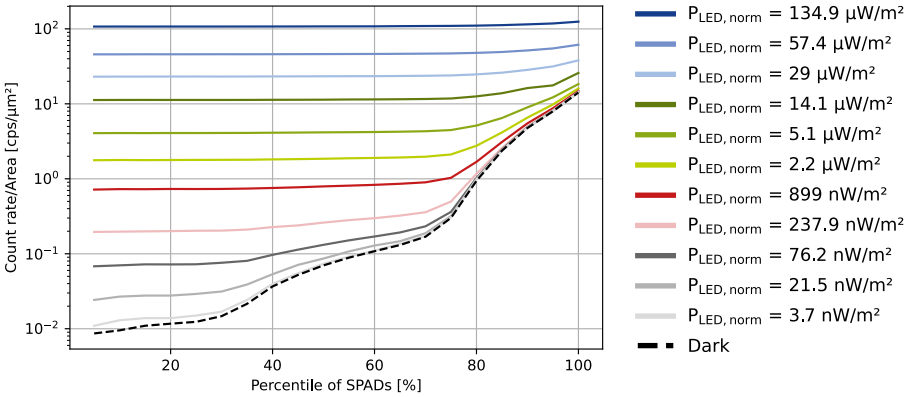


Figure 5: Area-normalised count rate of the best chip variant as a function of the percentile of the activated SPADs (percentile = 100% – cut-off threshold) under different illuminances. At high percentiles (low cut-off threshold), the counting rate is dominated by the DCR. Low illuminance levels can still be detected if only the 20% – 30% of SPADs with the lowest DCR are used. Source: IMMS.

does not reach the DCR of commercial PMT, which is about two orders of magnitude lower. However, it has a sufficiently high sensitivity for many applications and is much cheaper than PMTs.

The project partners from KODIAK have used the presented line sensor IC to perform first chemiluminescence measurements for the detection of the cytokine interleukin-1β within the microfluidic channel and have demonstrated the basic feasibility of the detection concept (Figure 1). Currently, more in-depth investigations are underway on the achievable sensitivity of the overall system of chemiluminescence assay, microfluidics and SPAD-based line sensor ASIC.

On 01 August 2024, the project "ScoreChip – Modular Platform for PoC Diagnostics Using the Example of Sepsis Diagnostics" will also start, in which IMMS will build on previous developments and develop a chemiluminescence scanner for microfluidic cartridges.

Contact person: Benjamin Saft, M.Sc., benjamin.saft@imms.de

REACT-EU – Als Teil der Reaktion der Union auf die COVID-19-Pandemie finanziert.

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The KODIAK project was funded as part of the European Union's response to the COVID-19 pandemic through the European Regional Development Fund (ERDF-OP 2014 – 2022) under the reference 2021 FE 9127.

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Miniaturised CMOS-ISFET sensor for analytics and diagnostics

IMMS has developed a sensor platform based on miniaturised pH sensors (ISFETs), which are manufactured in a cost-effective, mass-compatible standard CMOS process. In terms of pH resolution and drift it is up to 10 times and 1.400 times better than comparable state-of-the-art CMOS-ISFET chips. Photograph: IMMS.

Motivation and overview

Molecular diagnostics for the detection of viruses and bacteria as well as specific types of tumors is performed today with very precise, but also very large and complex measuring systems[1]. Only trained laboratory personnel perform the time-consuming procedures, which are often based on fluorescence, using systems that require expensive optical components such as lenses, mirrors and filters. IMMS has developed a sensor platform based on miniaturised pH sensors, so-called ion-sensitive field-effect transistors (ISFETs), which are manufactured in a cost-effective, mass-compatible standard CMOS process.

In future, this non-optical detection of pH value changes can enable fast, precise and cost-effective molecular diagnostics using miniaturised analysis systems for point-of-care and in-vitro diagnostic applications, for example. This platform also enables many other diagnostic and analytical applications.

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1 *POPP, Jürgen; BAUER, Michael: Modern techniques for pathogen detection. John Wiley & Sons, 2015, https://onlinelibrary.wiley.com/doi/book/10.1002/9783527687978*

Basic principle and background of ISFETs

Since the 1970s, Piet Bergveld had already been working on using the ISFET to detect ions in electrochemical and biological environments.[2] Due to its ability to reversibly bind hydrogen ions (H^+ ions) on its surface, its precise signal conversion from a chemical to an electrical signal, its robust, miniaturised design, storage stability and reusability, the ISFET was long deemed to be the ultimate follow-up technology to the pH glass electrode. In particular, the size and fragility as well as the maintenance-intensive storage of pH glass electrodes called for alternatives, e.g. for food production or in medical technology catheters.

However, it took 40 years before Jonathan Rothberg helped the ISFET in CMOS technology to commercial success and revolutionised non-optical DNA sequencing.[3] This uses the effect that H^+ ions are released with the formation of base pairs during the sequencing process, which can be detected with the pH-sensitive ISFET. But the ISFET sensor arrays used for this purpose, which are manufactured in CMOS technology, are based on complex customer-specific processes that are associated with high development costs. For this reason, this technology has so far been reserved for a small group of users and is mainly used in research. During the coronavirus pandemic in particular, this technology has demonstrated its importance and potential by sequencing numerous SARS-CoV variants as well as many other viruses and bacteria.

Design and function of the IMMS CMOS ISFET

To make miniaturised pH sensors available to more people for more applications, IMMS has developed an ISFET platform and demonstrated it with an ISFET sensor array chip in standard CMOS technology. This platform is based on the CMOS ISFET shown in Figure 1.

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The fundamental device is the underlying metal-oxide-semiconductor field-effect transistor (MOSFET). Simplified, it corresponds to a controllable electrical resistor

2 *BERGVELD, Piet. Development of an ion-sensitive solid-state device for neurophysiological measurements. IEEE Transactions on biomedical engineering, 1970, Nr. 1, S. 70-71.*

3 *ROTHBERG, Jonathan M., et al. An integrated semiconductor device enabling non-optical genome sequencing. Nature, 2011, 475. Jg., Nr. 7356, S. 348-352.*

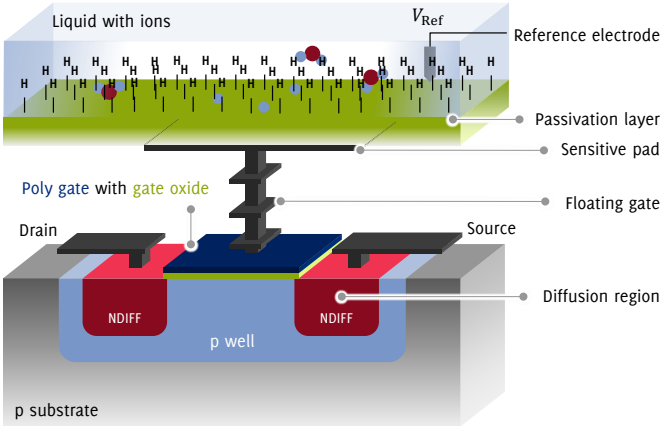

Figure 1:

CMOS ISFET with standard passivation as ion-sensitive layer, extended gate electrode for signal conversion and the MOSFET underneath.

Graphic: IMMS.

and consists of three electrical terminals: Gate, Drain and Source. Depending on the size of the electrical potential at the gate terminal, a correspondingly high current flows between the drain and source terminals. The ISFET in CMOS technology differs from the ISFET in a customised process in the design of the gate terminal. It is equivalent to an extended gate electrode (floating gate) in the stack structure of the CMOS process and is connected to the passivation layer, which is sensitive to hydrogen ions (H^+). The adsorption or release of H^+ changes the gate potential, which changes the current flow between source and drain. Accordingly, an electrical signal change proportional to the H^+ ions bound to the surface can be measured.

ISFETs in a standard CMOS process can be developed and manufactured more cost-effectively than in a customisable special process. However, this also has several disadvantages: Firstly, the standard passivation as an ion-sensitive layer evokes a reduced sensitivity regarding the maximum slope according to Nernst of 59 mV/pH at 25 °C and an increased signal drift. Furthermore, operating point shifts of the ISFETs and a loss in the conversion of the chemical signal into an electrical signal result from the stack structure and production steps of the CMOS process. To counter this, IMMS has found ISFET modeling, dimensioning and circuit design solutions that specifically use the standard process modules of X-FAB's CMOS technology. For example, trapped charges at the gate terminal of the transistor can be removed by an integrated tunnel programming circuit. As a result, the operating points of the ISFETs can be balanced to those of the electronic base component, the MOSFET, and negative reference voltages can be avoided. In addition, design aspects and size ratios between the gate electrode and MOSFET determine the strength of the signal attenuation, which has been optimised for maximum possible signal coupling and transmission.

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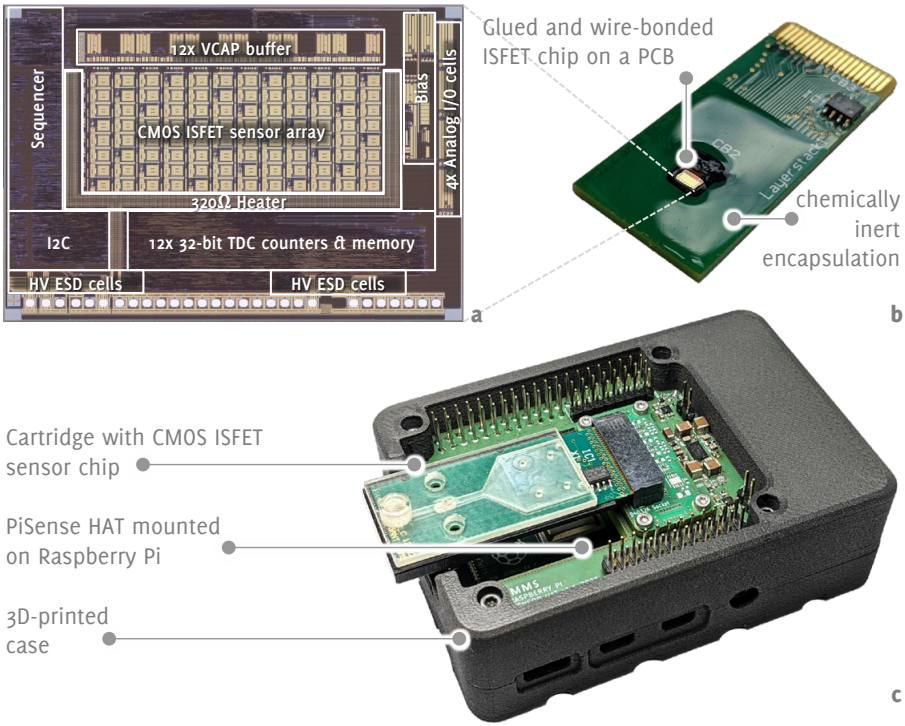
After the development of an ideal ISFET sensor design in an initial test chip, a complex 3.9 mm x 3.1 mm mixed-signal ASIC with a 2.6 mm x 1.2 mm array consisting of 72 ISFET sensors was designed (Figure 2a), manufactured, assembled and tested. In addition to the goal of developing the most sensitive CMOS ISFETs possible using standard technology, IMMS implemented additional circuit solutions to remove trapped charges from the gate of the ISFET and thus enable simplified operating point programming and automated sensor calibration. Furthermore, direct digitisation of measured values was implemented using the integrated pH-to-time converter in the chip. A standardised digital I²C interface guarantees simple programming of the ISFET array and readout of the sensor values. The built-in sequencer allows simple measurement routines to be executed directly on the chip. IMMS developed a packaging concept to enable the handling and functionality of the ISFET chips even in liquid media with widely varying pH values. It contains a suitable encapsulation

Figure 2 (Photographs/graphics: IMMS):
(a) CMOS ISFET chip and functional blocks;
(b) Glued and wire-bonded chip with chemically inert encapsulation on a PCB;
(c) Miniaturised measurement system based on Raspberry Pi in 3D-printed case.



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material to insulate the exposed electrical contacts of the chip and protect it from strong acids and bases (Figure 2b).

The sensor ASIC was glued and wire-bonded to a 54 mm x 22 mm cartridge before encapsulation. For the most versatile and variable characterisation possible, the measurement environment was initially carried out with modular but very bulky measuring instruments. By intelligently integrating a large number of functions into the ISFET chip, the measurement peripherals could be reduced to a minimum: The small, inexpensive Raspberry Pi-based measurement setup (Figure 2c) with PiSense HAT is supplied with power via USB-C, includes low-drop voltage regulators (LDOs) for the analogue and digital supply of the ISFET sensor ASIC, voltage regulators for ISFET programming as well as digital interfaces such as I²C, UART and GPIOs.

Results of characterisation

Commercially available pH calibration buffers 4, 7 and 10 and a silver/silver chloride reference electrode were used to characterise the CMOS ISFETs and to determine the performance values. Before the pH change measurement, the successful ISFET programming was carried out at pH4, as shown in Figure 3. As a result of the programming, the sensor values (Figure 3, left), which were previously clearly distributed, firstly, slip together considerably and, secondly, into the positive reference voltage range (Figure 3, right).

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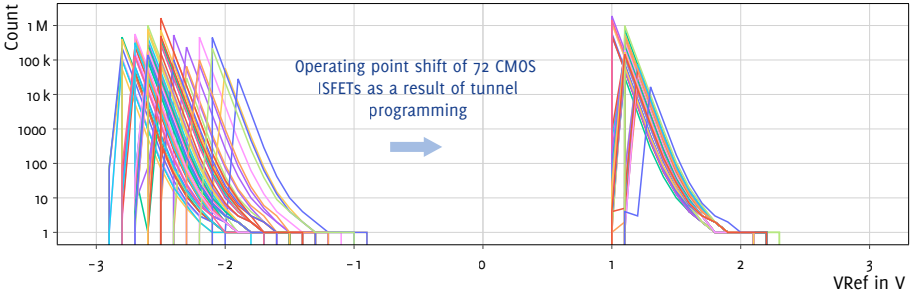
Figure 4 presents pH change measurements with pH buffers 4, 7 and 10. Figure 4a shows the sensor chip measured values (Count) for all 72 CMOS ISFETs. Figure 4b illustrates the converted and averaged voltage curve of all ISFETs, whereby signal

Figure 3:
Calibration and operating point adjustment of the CMOS ISFETs through tunnel programming.
Source: IMMS.



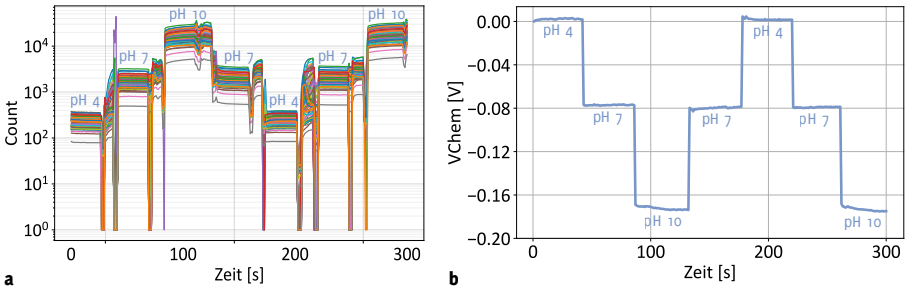


Figure 4:
(a) pH change measurements with pH buffers 4, 7 and 10: Sensor chip measured values (Count) for all 72 CMOS ISFETs; (b) converted and averaged voltage curve of all ISFETs as a result of the pH value change over time. Source: IMMS.

jumps due to pH changes and cleaning processes were filtered out. Characteristic are the steps that correspond to the pH sensitivity of the CMOS ISFETs.

The drift and noise of the ISFET array were also determined. On average, the ISFET sensor ASIC achieves a sensitivity of approx. 33 mV/pH, a pH resolution of 0.01 pH and a drift of approx. 1.8 mV/h. In terms of pH resolution and drift in particular, the CMOS-ISFET sensor array developed by IMMS is up to 10 times and 1.400 times better than comparable state-of-the-art CMOS-ISFET chips.[4]

Possible applications and outlook

One of the most promising applications is molecular diagnostics, as the technology is predestined to identify any biological carrier of nucleic acids. Viruses, bacteria and cancer cells are just a few examples that could be detected. Large ISFETs arrays in particular, which can be very easily implemented in CMOS technology, would make it possible to detect multiple pathogens with genetic material, so-called multiplex tests. Veterinary medicine could benefit from this to distinguish and separate infected livestock from healthy ones quickly and cost-effectively. During epi- or pandemic emergencies, rapid molecular tests using CMOS-ISFETs could bridge the gap between inaccurate, inexpensive rapid antigen tests and lengthy, high-precision PCR tests. Therefore, IMMS is currently working on detecting synthetic nucleic acids using commercially available RT-LAMP-PCR test kits and the heater integrated on the

www.imms.de/ivd

4 LIU, Yan; CONSTANDINOU, Timothy G.; GEORGIOU, Pantelis. Ultrafast large-scale chemical sensing with CMOS ISFETs: A level-crossing time-domain approach. IEEE Transactions on Biomedical Circuits and Systems, 2019, 13. Jg., Nr. 6, S. 1201-1213.

CMOS-ISFET chip. In addition, areas of CMOS-ISFET arrays can be modified with layers that make it possible to detect other ions such as Na^+, K^+ or Ca_2^+ in addition to H^+. The so-called multi-ion imaging could be used in environmental monitoring, agriculture, the food industry and water analysis. In addition, the areas of "organ-on-chip for less animal testing" and the "biosynthesis of nucleic acids, proteins and cells" offer further fields of application for CMOS ISFETs. For use in bioreactors in particular, where a large number of measuring probes have to be used and parameters determined, sometimes only once, IMMS is working on combining other sensor types such as temperature sensors and optical sensors for optical density or scattered light measurement on one chip to save costs. In the future, further electrochemical sensor modalities for e.g. conductance, flow rate, O_2, redox, impedance measurement etc. could be added to the portfolio of CMOS sensor arrays at IMMS using the noble metal process at X-FAB.

www.imms.de/asics

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Freistaat Thüringen
Hier hat Zukunft Tradition.

The results were compiled in the internal research group SenpH (potentiometric sensor system for pH value and ion concentration determination). SenpH is funded by the German Land of Thüringen.

Silicon Science Award

RESEARCH FIELD

SMART DISTRIBUTED MEASUREMENT AND TEST SYSTEMS

In 2023, Jakob Hampel was honoured with the Silicon Science Award for his work on time-correlated single-photon counting.

It is the basis for the SPAD eval kit developed with X-FAB in the QuantumHub Thüringen project. This is based on the method of time-correlated single-photon counting and enables measurements with a temporal resolution of 20 picoseconds. This allows quantum-based applications to be researched and new solutions for in-vitro diagnostics and medical technology to be developed.

Photograph: IMMS.

The Quantum Hub Thüringen research project is funded by the German Land of Thüringen via the Thüringer Aufbaubank under the reference 2021 FGI 0042.

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Hier hat Zukunft Tradition.

Research field: **Smart distributed measurement and test systems**

Integrated sensor ICs represent the heart of sensor and measurement systems. These can be wireless sensors, handheld diagnostic devices or high-performance stationary device solutions for machine monitoring, for example.

For increasingly performant sensors, we are working on the following research questions

Increasingly performant sensors and their rapidly expanding number lead to immense amounts of data, which are ever more pushing previous technologies to their limits when it comes to transmitting, processing and using them. Therefore, it will be necessary to design systems for sensing, measuring and testing in such a way that they can validate, process and evaluate data automatically in the future. We intend to achieve this by directly incorporating intelligence into the devices. Interconnecting these systems creates the possibility of distributing the tasks in the network. However, new challenges arise in the form of dynamic aspects due to network protocols and changing tasks over time.

www.imms.de/distributed

In this research field, we therefore focus on three questions: How can sensor data be automatically processed into usable information as close as possible to the point of origin in a fast, cost-effective and energy-efficient way? What additional information can be obtained with the help of distributed sensor systems? How can such a system be modelled based on different subsystems to evaluate energy requirements, the optimal distribution of functionalities in the network and the influence of topology decisions?

With our solutions we address the following applications

To address our research questions, we work on the one hand on the analysis of distributed IoT systems to implement energy- and resource-optimised embedded systems, for example for the “Internet of things” (IoT) or autonomous sensor networks for environmental monitoring or smart city applications. On the other hand, we conduct research on embedded artificial intelligence (AI) to be able to efficiently implement AI algorithms on highly resource-constrained systems, e.g. for automation technology and Industry 4.0.

In the field of real-time data processing and communications, we optimise embedded systems for signal processing and data transmission in real time so that, for example, connected, spatially distributed edge AI systems can communicate smoothly. In addition, we develop concepts and implementation architectures for modular and mobile test systems. With these modular hardware-software platforms, integrated circuits and embedded systems for various applications can be tested and characterised extensively, yet quickly and flexibly.

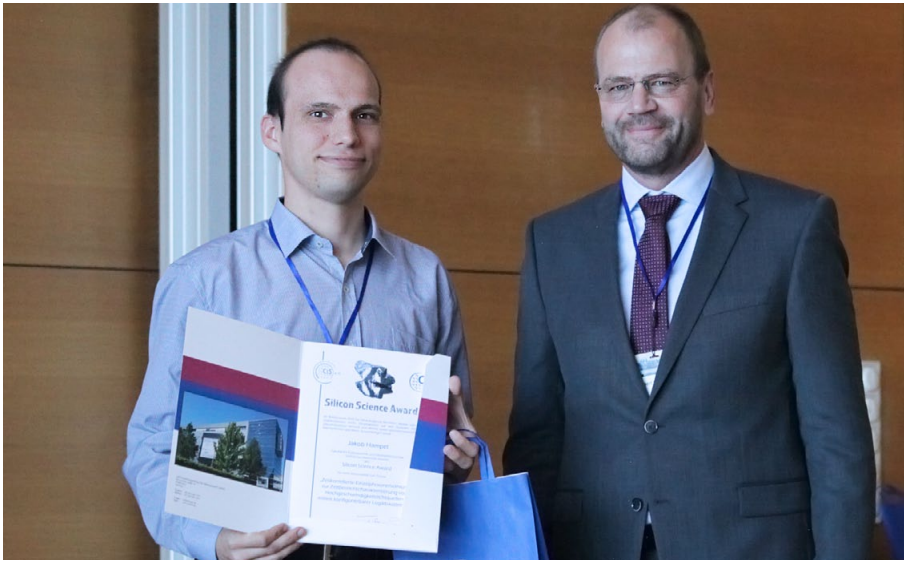
Highlights of 2023 in our research on smart distributed measurement and test systems

Silicon Science Award goes to young researcher from IMMS and Ilmenau TU: **Work honoured on time-correlated single-photon counting for measurements in the picosecond range**

Jakob Hampel, computer engineering specialist and researcher at IMMS, was honoured with the Silicon Science Award for his master's thesis 'Time-correlated single photon counting for time domain characterisation of high-speed light sources using configurable logic devices', supervised by IMMS and Ilmenau TU, at the Ilmenau Sci-

www.imms.de/awards

Jakob Hampel (IMMS) and Geert Brokmann (CiS e.V.) at the award ceremony for the CiS Silicon Science Award on 4 September 2023 at Ilmenau TU. Photograph: IMMS.



SPAD-Evalkit, which was developed with X-FAB in the QuantumHub Thüringen project. It is based on Jakob Hampel's work on time-correlated single-photon counting, for which he was honoured with the Silicon Science Award in 2023. Photograph: IMMS.

entific Colloquium ISC 'Engineering for a Changing World' at Technische Universität Ilmenau on 4 September 2023. The prize, awarded by CiS e.V. and CiS Forschungsinstitut für Mikrosensorik GmbH, recognises his demanding research work carried out at a very high level with very high practical benefits. The results are already being incorporated at IMMS into application developments for point-of-care devices that will enable highly sensitive analyses for medical and biochemical examinations. In addition, the hardware/software evaluation unit developed to determine impulse responses of fast light sources is an important contribution to research into quantum technology in the QuantumHub Thüringen project.

Fast light pulses cannot be sufficiently characterised using conventional methods

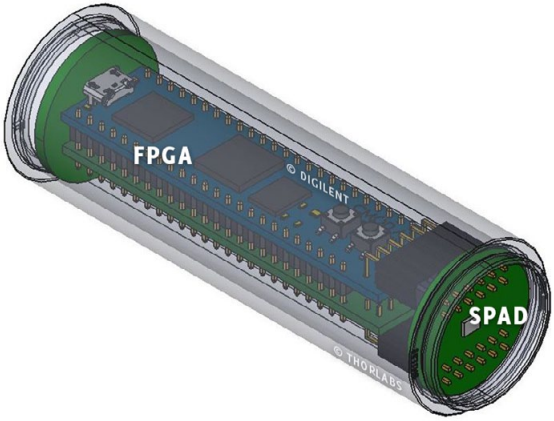
"Fast light pulses are required for many applications, often down to the nanosecond or picosecond range. One example is fluorescence-based bioanalysis procedures in medical technology," explains Jakob Hampel, scientist at IMMS. Light sources that generate these pulses, such as those for fluorescence, therefore need to be characterised. This is the only way to reliably assess the reaction of an optical system. Traditionally, fast photodiodes can be used for this and their signals analysed with an oscilloscope down to the nanosecond range, Hampel continues. "However, every oscilloscope has a background noise that distorts the results." In contrast, a much more precise evaluation would be possible with a different method, time-correlated single photon counting: "In very simplified terms, the light source is excited to then

observe the individual photons and the time delays of the impulse responses. These are accumulated into a histogram through repeated excitation and statistical evaluation of the results of hundreds of thousands to millions of measurements. This then describes the behaviour of the light source over time." The idea of this method is not new, but for a long time it was only possible with relatively bulky hardware with high power requirements. This is exactly what Hampel wanted to change.

Research results in a hand-sized USB device that opens up new applications

In his master's thesis, Jakob Hampel developed the hardware description and the readout software for implementing time-correlated single-photon counting using a configurable logic module. Together with a single-photon avalanche diode (SPAD) as a light sensor and other analogue components implemented at IMMS, he has built a cost-effective system that can accurately measure light pulses with a resolution of 20 picoseconds and fits into a tube measuring just 100 mm x 25 mm.

"Jakob Hampel has taken advantage of the emergence of commercially available semiconductor-based single-photon detectors in recent years and the increasingly powerful configurable logic modules to address current research questions on ever more sensitive sensor systems in an exemplary manner in his work," says Univ.-Prof. Dr.-Ing. habil Hannes Töpfer, Dean of the Faculty of Electrical Engineering and Information Technology and supervisor of Jakob Hampel's master's thesis. This should not only be emphasised from a scientific point of view, Töpfer continues: "The contribution is further proof that our research at Ilmenau TU is very close to practice-relevant topics. This solution represents an important step for a well-known process that can now be miniaturised and used for many new applications."



Structure of the SPAD-EvalKit: The SPAD (single-photon avalanche diode) can be used to detect individual photons. Their signals are measured in many cycles and analysed by a field programmable gate array (FPGA) as an impulse response from the light source.

Graphic: IMMS/Digilent/Thorlabs.

Measuring system for research into quantum technology and new application developments

The relevance of the work can also be seen in the fact that it has already led to further developments such as the research into quantum technology in the QuantumHub Thüringen project. Among other things, IMMS is working on characterising semiconductor-based single-photon detectors for use in quantum communications systems. "I am very proud of the award. I am particularly pleased that it honours a topic in which research and industry are equally interested," says Jakob Hampel. He was immediately able to contribute to a product development with X-FAB based on his master's thesis in the form of the SPAD-EvalKit, which can be used to characterise SPAD chips. He also characterised fast laser light sources in the FluoResYst project with another measuring system that works on a similar principle. This enabled the feasibility of developing a SPAD-based application-specific microelectronics chip to be successfully evaluated, which, together with the partners' microfluidic systems, will be incorporated into a point-of-care device for diagnosing tuberculosis.

www.imms.de/qhub

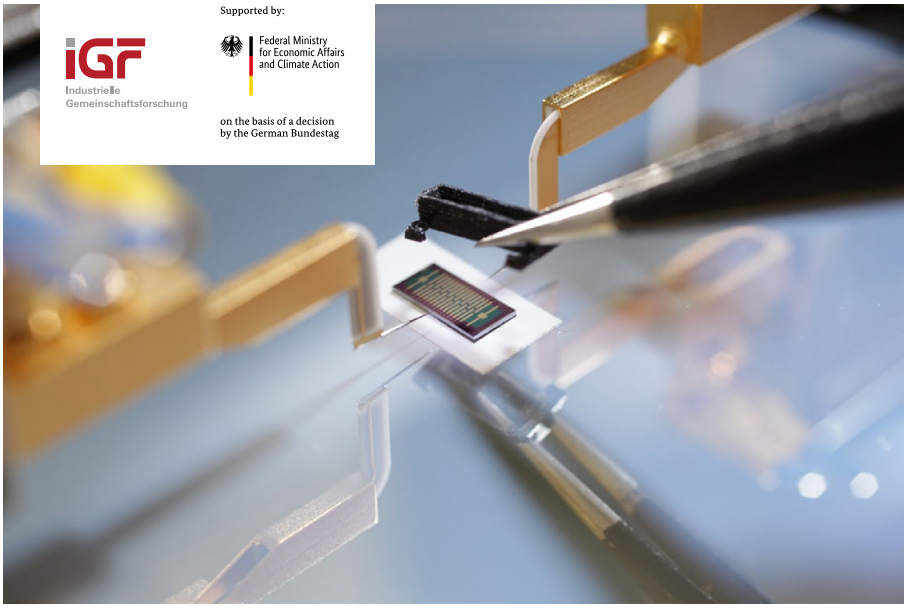
www.imms.de/fluoresyst

Mix of theory and practice as a springboard for junior staff in research and development

"Thanks to the support at IMMS and the opportunities to always learn new things close to applications, I was able to develop from beginner level to a level of knowledge at which I can successfully work on a practical research topic in a master's thesis and with which I was able to continue working seamlessly at IMMS," says Hampel, expressing his thanks for his good supervision. Thanks to the proximity to Ilmenau TU and other institutes, you are constantly confronted with new, exciting tasks and can always develop further, Hampel continues. As his supervisor, Töpfer draws the following conclusion: "Mr Hampel's work should not only be emphasised on a professional level. It also impressively illustrates how the theoretically sound training at Ilmenau TU can be combined with practice-orientated mentoring programmes such as those offered at IMMS. This not only allows research results to be transferred into practice, but also provides the next generation with all the necessary tools for the innovations of tomorrow."

www.imms.de/students

IGF Industrielle Gemeinschaftsforschung
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag



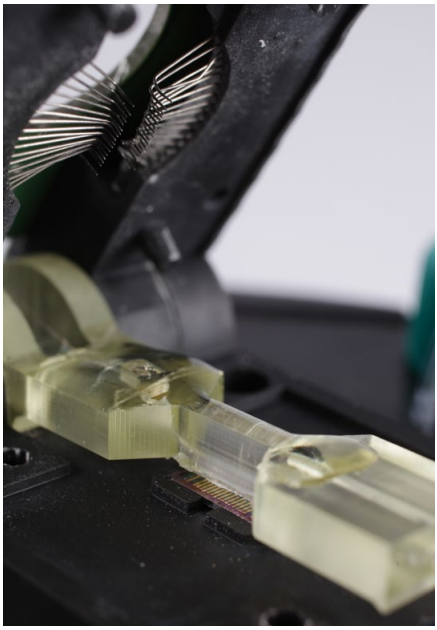
Preliminary tests for the development of a measuring environment on a sensor chip with 15 graphene field-effect transistors. Photograph: IMMS.

ViroGraph* project completion: Multiplex detection system for the diagnosis of viruses based on graphene field-effect transistors

www.imms.de/virograph

In the ViroGraph project, research work was carried out to develop a mobile, multi-channel, highly sensitive and highly selective sensor system. It was shown that a specially optimised graphene-based sensor can be modified by special capture molecules in such a way that specific analyte concentrations in the femtomolar range can be detected. This is achieved by various assays developed for the specific binding of antigens, RNA and antibodies of the SARS-CoV-2 virus in combination with multi-channel electronics for parallel time-discrete detection of the sensor parameters. Finally, the research results obtained were incorporated into the development of a demonstration set-up.

IMMS developed an environment for the metrological investigation of the resulting graphene field-effect transistors (GFET) and implementd a portable setup to demonstrate the functionality of the researched sensor system. This involved solving two challenges in the development of a suitable measurement environment: Firstly, all GFETs on a chip must be reversibly contacted electrically and supplied with sample



Folding holder for analysing the GFET sensor chip with probe needles for electrical contacting and flow cell for media supply. Photograph: IMMS.

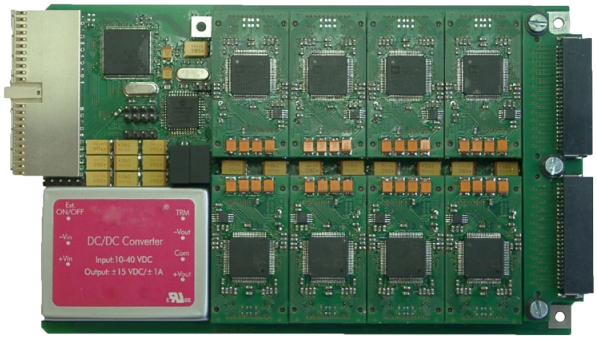
liquid. Secondly, all 15 GFETs should be able to be stimulated and measured simultaneously, but individual measurements per GFET should also be possible and the system should be flexibly expandable.

Electrical contacting and adaptation of a flow cell

The provided sensor chips each contained 15 GFETs, which had to be measured and probed simultaneously. Probe needles were used for their reversible electrical contacting, based on classic cantilever probe cards from semiconductor testing. These offer the advantage of a secure electrical connection, which can be released again with little influence to further process the sensor chip or to examine another chip in the same measuring environment. At the same time, the liquid sample medium had to be channelled to the surface of the GFET to enable sensory detection. The crucial factor here was the design of a reaction chamber that has inlets and outlets for the media flow and does not allow any lateral media leakage in the direction of the electrical contacts. This component also had to create a reversible connection with the sensor chip, which was achieved with the help of a flexible sealing lip. The development process resulted in a folding holder with probe needles and flow cell made from 3D printed components. It enables the sensor chips to be inserted, aligned and contacted.

Measuring electronics

The second component of the measuring environment is the electronics used to record the electrical characteristics of the GFET. It enables the simultaneous stimulation and measurement of at least 15 GFETs. To achieve a flexibly expandable solution, development was started on the basis of a basic module with four measuring channels, each designed as a four-quadrant source. This enabled current measurements

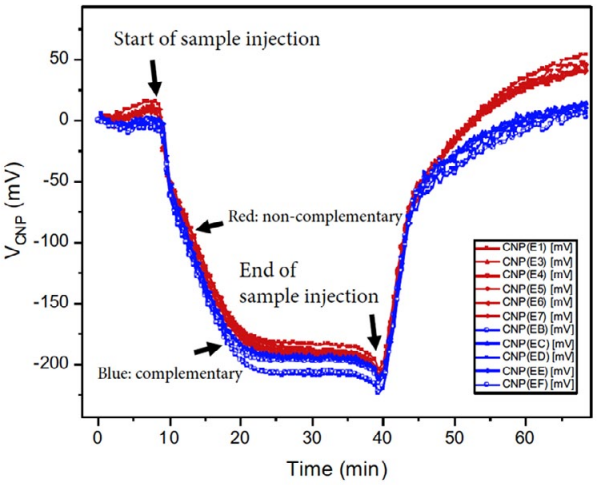


32-channel measurement electronics for time-resolved recording of the CNP voltage of the GFETs.

Photograph: IMMS.

with an accuracy of 1 nA. A total of eight of these modules are being used for the intended measurement electronics in the ViroGraph project. This provides a 32-channel system that allows potential-independent measurement of each individual GFET. In addition to the hardware, software was developed to ensure an automated measurement process. The aim is to monitor the charge neutrality point (CNP) of each GFET over time. The variation of this parameter correlates with the concentration of the analyte within the sample medium. By utilising the developed measurement environment in combination with the research work of the partners FSU Jena, IPHT and fzmb, it was possible to carry out investigations into the sensitivity of the sensor system to SARS-CoV-2 viruses in ideal media. The results showed a very high sensitivity in the single-digit femtomolar range.

www.imms.de/modtest



FSU Jena used the measurement environment to monitor samples in real time. The example shows the time course of the CNP (charge neutrality points, i.e. voltages at minimum current) for 11 transistors on a GFET array during the injection of a target sample. 5 GFETs are labelled with a complementary capture molecule (blue) and 6 GFETs with a non-complementary reference molecule (red). The concentration of the substance in the sample can be deduced from the different curves.

Graphic: FSU Jena/AG Turchanin.

Demonstrator setup for determining the SARS-CoV2 virus concentration using GFET sensor chips.

Photograph: IMMS.

Demonstrator design

To illustrate the applicability of the researched results, a demonstrator was developed that combines all the individual components and processes. In addition to reservoirs for reagents and samples, the components of the measuring environment are also integrated into the small table-top device. Fluidic components such as valves and micropumps were also added and integrated into the control system. 3D-printed mechanical parts were used to create a compact, portable structure that allows customisable analysis protocols to be carried out using a specially developed programme.

www.imms.de/modtest

Sensor developed at IMMS to measure fruit growth to optimise irrigation measures. These and other sensors will become part of the digital twin that IMMS will develop in the MIRO project. Photograph: IMMS.

With support from

Federal Ministry of Food and Agriculture

by decision of the German Bundestag

Project manager

Federal Office for Agriculture and Food

MIRO* project launch: Future-proof regional fruit growing through systematic data collection (digital twin) and data exchange along the value chain

www.imms.de/miro

A rapidly changing climate and a challenging skilled labour and competitive situation are key conflicting objectives in agriculture, especially in fruit growing. The aim of the MIRO project is to strengthen the future viability of the entire fruit value chain from cultivation and processing to marketing in the Central German region and to develop design options for known challenges.

To this end, seven use cases from different partners will be analysed in detail. Preliminary work from the two Central German experimental fields EXPRESS and LANDNETZ will be taken up and linked at regional level with other players in the value chain.

IMMS is working on two use cases in MIRO. The first is aimed at data exchange between stakeholders in the region and the second at the targeted use of digitalisation to analyse feedback on variety characteristics at different locations along the value chain.

Data exchange use case

The exchange or consolidation of data from different systems or different players is central to digitalisation. For example, it is desirable to transfer data on processing difficulties that can be avoided by adapting cultivation methods. However, such a

comprehensive data exchange at regional level currently only works to a limited extent, as there are many individual solutions whose data cannot be automatically made available to other systems.

IMMS will investigate which platforms are fundamentally suitable for fruit growing and which interfaces need to be created for this. In the consortium, IMMS will look at what an equivalent value for data provision could look like. The resulting concepts will be incorporated into a guideline for protagonists and implemented using examples to demonstrate the potential.

Digital twin use case

Here, IMMS is working on a digital representation of fruit varieties at a location, as this combination has a significant influence on the yield and quality of the fruit, but can only be adapted in the long term due to the lifespan of the trees. Information about the fruit, climate, etc. is therefore important for future-proof planning. Such a platform does not exist yet.

IMMS will systematically analyse a few selected fruit varieties, such as certain apple or cherry varieties. The institute will automatically record site conditions using sensors and scoring data and develop an app for this purpose. In addition, characteristics of the variety from breeding and testing as well as characteristics of the fruit and the products produced from it will also be recorded. This will create a comprehensive knowledge base on a variety across different locations. This makes it possible to analyse future scenarios and thus react to changing climate conditions through adapted variety selection and breeding, which should be carried out together with the relevant players.

www.imms.de/monitoring

Preliminary investigations for the development of adaptive energy-autonomous sensor systems for the monitoring of habitat factors in the forest environment in the Waldmonitor project. Photo: IMMS.

Start of the Waldmonitor* project: Robust communications solutions and energy-autonomous sensors for monitoring abiotic factors in forest conversion

www.imms.de/wald

Climate change requires a smart early warning system for young trees

Rising average annual temperatures and changing precipitation patterns make it necessary to reforest sustainably, i.e., to plant other tree species and test them for later use. In addition, large open areas need to be reforested quickly and larger young trees in avenues should soon act as windbreakers. These young plants are very sensitive to stress factors. The Waldmonitor (“Forest Monitor”) project has set itself the goal of developing a sensor system as an early warning system for stress indicators. It is intended to determine vital parameters and growth status as well as biotic and abiotic influencing factors.

Approach: Remote monitoring of young trees

The Waldmonitor project is developing a sensor system that continuously collects information on young trees without the forester having to be on-site. A stationary overall system as a pilot installation evaluates various optical and classic sensor

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principles. The results will flow into a proposal for the optimal selection of sensor systems for a tailored monitoring system that also offers the potential to be used on mobile platforms at a later date.

IMMS contributes adaptive energy-autonomous sensor systems and data transport

The aim of the IMMS WaldSensCom sub-project is to develop adaptive energy-autonomous sensor systems for monitoring site factors in the forest environment and to ensure a continuous flow of data from the study areas in the forest to a central evaluation system.

The challenge here is that there is no comprehensive mobile phone coverage in the forest. To ensure continuous transmission despite this, concepts for interruption tolerance and the use of multi-hop LoRa communications to bridge gaps are being tested. To transmit the required amount of data efficiently, concepts for data reduction and local evaluation of the recorded abiotic site parameters are also being investigated with regard to forestry aspects. The aim is to ensure the transport of all relevant data, even if the connection from the test areas to the server cannot be permanently established due to, e.g., a lack of energy or communications infrastructure.

www.imms.de/monitoring

In addition, wireless sensor networks are being designed and implemented together with project partner Orbit. IMMS provides support with the energy-autonomous and size-optimised implementation of sensor nodes for abiotic parameters and takes care of the evaluation of the recorded data.

Events and information for SMEs

In 2023, IMMS employees offered a total of 11 lectures, 28 online seminars, 12 regulars' tables and 7 specialist workshops as well as 56 information and workshop discussions on digitalisation as part of the "Smart Sensor Systems Model Factory" at the "Mittelstand-Digital Innovation Hub Ilmenau". The aim of these events was to support small and medium-sized enterprises (SMEs) with the introduction of digitalisation and AI solutions. Model Factory employees also took part in 31 regional events organised by industry networks and regional trade fairs. A further 29 activities were also organised with the nationwide "Mittelstand Digital" network. The offers are developed and implemented in close cooperation with the partners Ilmenau TU, where the office and the "Networking Model Factory" are located, the Ernst Abbe University of Applied Sciences in Jena as the "Virtualisation Model Factory" and the Gesellschaft für Fertigungstechnik und Entwicklung e.V. in Schmalkalden as the "Process Data Model Factory".

www.imms.de/md

The "Mittelstand-Digital Innovation Hub Ilmenau" focuses on sustainability, platform economics and AI in addition to the specialist areas indicated by the model factory names. As "Model Factory Smart Sensor Systems", IMMS is primarily dedicated to the topics of retrofitting, predictive maintenance, smart sensor systems, diagnostic solutions and AI-based sensor data analysis. For example, retrofit solutions can be provided for machines that automatically record and visualise the machine status. Another core area of expertise is the practical implementation of smart sensor systems, which can be used to monitor machine tools using artificial intelligence, amongst other things. Demonstrators also show digital diagnostic solutions that use mobile measuring devices to find cost-intensive leaks in compressed air systems, for example. Questions from small and medium-sized enterprises relating to the use of AI are addressed by the AI trainers at all of the centre's partners.

www.imms.de/i40

Parallel to the events, various **news articles** and other **publications** were produced, e.g. on cooperation with companies in projects or on demonstrators, which are distributed to interested parties on the hub's website, via newsletters and social media.

Climate monitoring in transport containers: Digitalisation solution, developed by the "Mittelstand-Digital Innovation Hub Smart Cycles", SGT GmbH, DUX Lederwaren, the Saxon Textile Research Institute (STFI) in Chemnitz and IMMS at the ''Mittelstand-Digital Innovation Hub Ilmenau''.

Photograph: Dirk Zschenderlein, STFI.

New demonstrators and digitalisation projects

In addition to the various events, the "Smart Sensor Systems Model Factory" at IMMS is also working on demonstration and implementation projects.

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Climate monitoring in transport containers

Particularly sensitive goods require special climatic conditions during storage and transport, such as a certain humidity or temperature. This applies in particular to transport in the cargo hold of aeroplanes or on container ships. Damage to the goods can have both financial and ecological consequences that should be avoided. The "Mittelstand-Digital Innovation Hub Smart Cycles" has developed a suitable solution concept with the two companies SGT GmbH and DUX Lederwaren as well as with its partner, the Saxon Textile Research Institute in Chemnitz, and the "Mittelstand-Digital Innovation Hub Ilmenau". Sensors in the transport containers measure temperature, humidity, relative humidity and movement. A wireless interface then transmits the measured values to an app on the smartphone, which enables the user to react to them. The climatic environmental conditions are thus digitally monitored throughout the entire transport process without having to have direct access to the goods.

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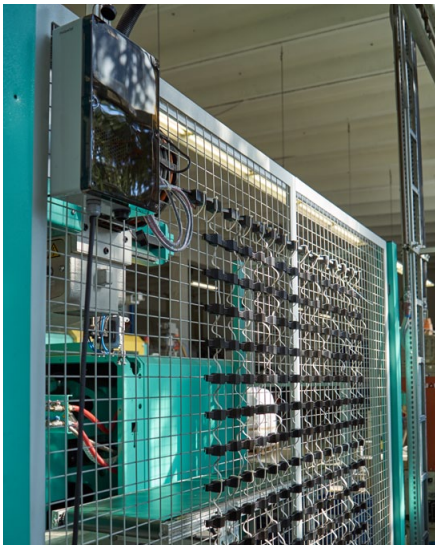

Sensor curtain and mini PC installed at eitech GmbH as a data collector for the continuous recording of environmental conditions in production. Photograph: eitech GmbH.

Sensor technology for the automated optimisation of productivity and quality in the injection moulding process

Together with eitech GmbH, the microclimate in the immediate machine environment in factory halls was recorded and monitored. Environmental conditions such as air temperature and the condition of windows and doors are monitored to automatically optimise productivity and quality in the injection moulding process. Sensors on the injection moulding machine provide additional measured values. The long-term goal is to adapt the machine parameters to changing environmental conditions. Climate sensors, door and window contacts and a sensor curtain were installed in one of the company's production halls to record and wirelessly transmit data. A mini PC acts as a data collector, while the data is recorded and analysed on a remote server system. The data is stored in a time series database, which enables subsequent analyses. A dashboard with Grafana software visualises the recorded data for control and demonstration purposes.

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Networking with digitalisation key players expanded

Another important component of the work in the "Mittelstand-Digital Innovation Hub Ilmenau" is the networking of the players involved in the digital transformation of companies. There was a regular exchange in the nationwide "Mittelstand Digital" Network, including in topic-specific working groups or at regional conferences of the participating hubs. Topics included the needs of the companies, the expansion and the target group-specific design of the support services. IMMS also regularly exchanged information with Thuringian networks and initiatives, such as the Cross-Cluster Initiative Thüringen (CCIT), the Cluster for Electronic Measurement and

Device Technology Thüringen (ELMUG), the Centre for Digital Transformation Thüringen (ZeTT) and the Thuringian Centre for Learning Systems and Robotics (TZLR).

In addition, the Ilmenau Innovation Hub, together with the one in Chemnitz, the ScaDS.AI Dresden/Leipzig and other partners forms the AI Hub Saxony-Thuringia. The AI Hub is dedicated to transferring the results of basic AI research from ScaDS.AI and its partners via the Mittelstand-Digital Innovation Hubs to companies. At the same time, the Mittelstand-Digital Innovation Hubs bundle the requirements of SMEs so that these are taken into account in basic and applied research.

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Retrofittable monitoring of street lamps — smart and cost-effective defect detection

Prototype sensor node installed in the Ilmenau urban area for automatic and wireless lamp monitoring as the first IMMS smart city test setup in the thurAI project. Photograph: IMMS.

Motivation and overview

The maintenance of comprehensive street lighting is associated with considerable expense for local authorities. One problem that often remains unsolved is the prompt and automatic detection of defective streetlights across the entire area of responsibility, including surrounding municipalities. Defective or flickering lamps are detected during night-time inspections by municipal staff or are usually reported late by citizens.

With automatic monitoring, not only can defects be detected more quickly, but route planning for maintenance cases can also be optimised. LED-based smart lamps available on the market monitor and report their status themselves and often also include other functionalities, such as WLAN hotspots or electric charging points. However, it is financially impossible for many municipalities to switch to them on a large scale or even completely; at best, this is happening gradually. At the same time, in an increasingly connected world, municipalities also want to rely more on the Internet of Things (IoT) to collect data and carry out effective analyses.

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In the thurAI research project at IMMS, a solution for monitoring streetlamps was therefore developed, set up, and evaluated with long-term measurements in

Ilmenau and surrounding municipalities, which can be retrofitted as a more cost-effective alternative. This implements defect detection with optical sensors in wireless sensor nodes, which can be easily installed on lampposts without interfering with the lamp's electrical system. The system of battery-operated and remotely configurable wireless sensor nodes and a gateway communicates via the LoRaWAN low-power wide-range radio technology. This energy-efficient communications technology enables a wide variety of sensors to be used and a wide range of solutions to be implemented. Local authorities can thus make every existing street lamp smart, promptly detect its condition and defects, plan maintenance work and inform citizens via a website.

Complete system with modular platform for IoT systems

The solution for monitoring street lamps developed at IMMS in collaboration with the city of Ilmenau uses optical sensors to detect defects in wireless sensor nodes that are installed on lampposts. Due to the non-invasive installation, no integration with the electrical system of the lamp is required and retrofitting is therefore easy. The system consisting of wireless sensor nodes and a gateway communicates via LoRaWAN long-range radio technology. The sensor nodes are battery-powered and can be configured remotely. Defects are detected from the measurement data on the server side and the results are visualised in dashboards.

In addition to the retrofittable sensors on the lamp, IMMS has developed the entire system from the sensor to the

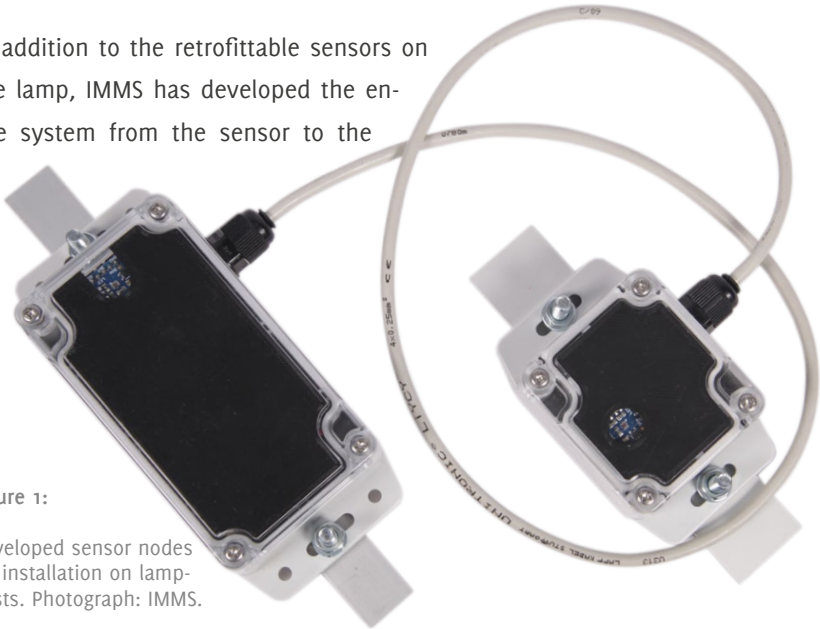

Figure 1:

Developed sensor nodes for installation on lampposts. Photograph: IMMS.

visualisation for municipal offices. This was created on the basis of a modular platform for IoT systems developed at IMMS. It allows sensors, database and analysis tools, as well as visualisation options to be flexibly adapted to quickly implement application-specific solutions.

Configurable sensor nodes with independent power supply for heterogeneous lamp types and light sources

For the solution presented, special sensor nodes were developed that are mounted on lamps to record the data required to monitor the lamp function by measuring the optical light intensity of the lamp and the ambient light (Figure 1). The values are periodically transmitted via LoRaWAN to a dedicated gateway with the ChirpStack as an implementation of the LoRaWAN protocol stack, from where they are quality-checked and stored in an InfluxDB database. The evaluation is currently carried out on the server side using a specially developed algorithm that relates the two values per lamp and can thus also draw attention to lamp faults, such as very bright ambient light that interferes with twilight switches on lamps. The result of the evaluation is then stored in the database and visualised on a map using Grafana.

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Challenges in implementing the project were the large number of different physical lamp types (mast and lamp shape), a large number of heterogeneous light sources with different fault patterns and operation without integration with the lamp electrics to minimise installation and maintenance costs. The first two points require a certain degree of adaptability or configurability of the sensor nodes on the

Figure 2: Sensor nodes on lampposts in the Jesuborn district of Ilmenau. Photograph: IMMS.

lamps, while the last point requires energy-efficient operation by means of a self-sufficient energy supply. The latter is achieved by using batteries that are designed for an expected service life of at least two years with a measuring interval of 30 minutes at night. To put into effect the other points, IMMS has developed two basic variants of the sensor nodes.

Standard sensor node for day/night differentiation of measurements

The standard version has two light sensors and measures both the lamp light and the ambient light, enabling a direct comparison of the two values. This makes the difference between day and night clear. To save energy, the sensor for the lamp light is only used when it is dark; the second sensor is only activated when the ambient light falls below a configurable threshold value. This also enables automatic detection of the length of day throughout the year. The second sensor is positioned so that it faces away from the light source and captures as little light as possible from it.

Simplified sensor node with indirect assignment of measurement periods

If this is not possible due to the lamp geometry, the second variant with just one sensor is used. This only measures the lamp light. On the server side, this lamp is then assigned another sensor for evaluating the ambient light, the start of the measurement periods (day/night) is determined on a daily basis and the sensor node is then configured accordingly.

Figure 3:
Status visualisation in dashboards, here with a status history over 90 days. Source: IMMS.

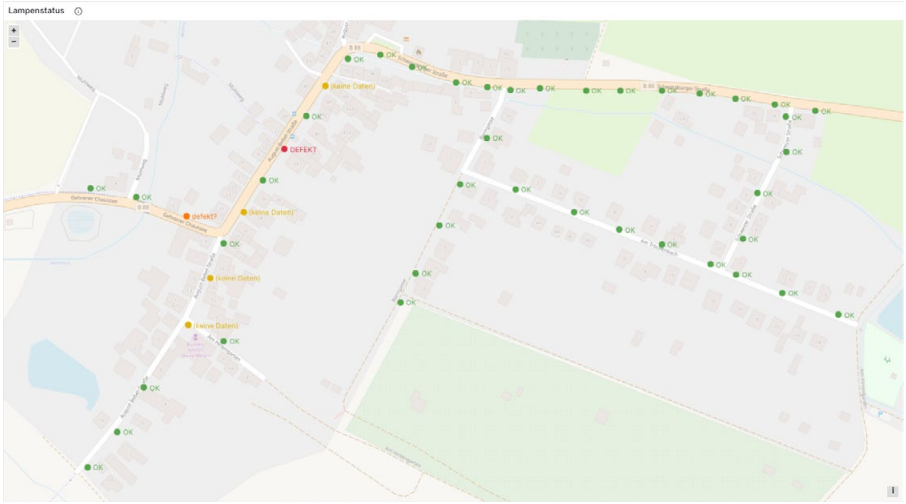

Figure 4: Status visualisation in dashboards. Top: current status top on a map of the district. Source: IMMS on the basis of OpenStreetMap (CC BY-SA 2.0).

Remote configurability for specifics

To be able to respond to different light sources, IMMS has created a way of configuring the nodes remotely via messages in the return channel (LoRaWAN downlink). In addition to adjusting the measuring range of the sensors, this also makes it possible to start predefined special measurements, e.g., to detect flickering later.

Proof of function and outlook

The system developed has been undergoing extensive testing in the Ilmenau district of Jesuborn since August 2023 (Figure 2). This district has a total of around 50 street lamps of various types. The sensors were installed under the lamps relatively high up on the masts using a hydraulic lift.

During the tests to date, the system has successfully detected first defects in lamps (Figures 3 and 4): defects caused by construction work and a traffic accident in which a pole was damaged were detected.

The data also shows a change in the intensity of the lamps when a bulb has been replaced, and thus, in addition to the currently possible status detection, another potential of such a system: in the long term, a database for analysing maintenance cycles can be built up, which can then also be used for AI models.

In addition to these functions, various suspected cases of flickering have also been identified, but these can only be clarified with a special measurement that takes place at shorter intervals. The system is already capable of carrying out such a measurement. However, the evaluation on the server side or, as soon as sufficient data is available, by AI is still open and is to be tackled as the next step.

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An inexpensive system for near-real-time monitoring of particulate matter pollution

In the thurAI project, IMMS has developed a compact, energy autonomous system for continuous particulate matter monitoring, which can be integrated into existing infrastructure with low-power wide-range wireless technology LoRaWAN and which was installed for measurements in the Ilmenau districts and holiday resorts of Frauenwald, Manebach and Stützerbach. Photo: Marco Götze, IMMS.

Motivation and overview

Particulate matter, the main pollutant in air pollution, is partly responsible for around 300,000 premature deaths per year and for critically excessive nutrient inputs into currently two thirds of ecosystem areas in the EU. For this reason, there are legal limits for particulate matter pollution that must be monitored and adhered to, and these will be significantly tightened by the EU's Air Quality Directive currently under revision. Compared to cities, stricter requirements already apply to state-approved health resorts and recreation resorts in particular. For certification as a spa-town or health resort, measurements are taken at intervals of several years by the German meteorological service (Deutscher Wetterdienst, DWD), in which dust collectors are deployed at neuralgic points, collected again after periods of one to several weeks, and analysed in the laboratory. The results are accumulated measurements of particulate matter pollution over the entire period under consideration. It is not possible to draw conclusions about causal events or fluctuations within the period.

If there was an inexpensive and flexible system that could be deployed at potentially representative locations for continuous particulate matter monitoring with a higher temporal resolution, it would be possible to draw conclusions about polluters, identify other dependencies, and, if necessary, take countermeasures at an early stage.

This is where existing citizen science approaches (e.g. AirRohr from LuftDaten.Info) have entered the stage and use low-cost hardware and software to enable continuous measurement. The resulting systems measure particulate matter, but the sensors used are very large. Moreover, at the beginning of the observations in our context, better sensors were already available than those used in the AirRohr design at that time.

In the thurAI research project, IMMS has developed a compact, energy-autonomous system for continuous particulate matter monitoring that can be integrated into existing infrastructure with low-power, wide-range LoRaWAN radio technology. For this purpose, a dedicated hardware including housing with integrated solar cell holder was developed. The system can be installed at various locations for continuous monitoring. In addition to recording the different particle sizes and micro-climate parameters, an autonomous humidity correction of the particulate matter measurement values is carried out. These are visualised with dashboards, whereby different representations from time series to “traffic lights” for limits as well as adaptations to specific requirements of an application are possible. In addition to spa climate monitoring, the solution is also suitable for monitoring particulate matter in general, e.g., in urban areas.

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System structure

The solution developed at IMMS in collaboration with the city of Ilmenau for monitoring particulate matter pollution is based on an optical measuring principle. The sensors are part of wireless sensor nodes that also measure the micro-climate parameters of air temperature and humidity and transmit them wirelessly to a gateway within range. From there, the data is transmitted to a central server, stored, and visualised in dashboards.

Figure 1:

Sensor node: assembled on the left, inside on the right.

Photograph: IMMS.

To avoid maintenance costs, the wireless sensor nodes were designed to be energy-autonomous: They charge a buffer battery via a small solar panel, which enables them to operate even over periods of several weeks with little sunshine.

Sensors and electronics are housed in a "weather hut", which is common for microclimate sensor technology (Figure 1). A specially designed, 3D-printed inner construction holds the components in place. The sensor node is suitable for mounting on masts and the solar panel for the energy supply is installed on top of it.

The optical dust sensor (by Sensirion) used detects dust particles in the air with the help of a laser, similar to a light barrier. For this purpose, outside air is blown through the inside of the sensor housing at regular intervals via a fan. The darkening of the laser beam allows particles to be detected and counted in four size classes. These range from coarse dust of the PM10 class with an aerodynamic diameter of less than 10 micrometres to PM4 and fine dust with PM2.5 and PM1, i.e. 2.5 and 1 micrometre particle size respectively.

Correction calculations for humidity influences

The optical measuring principle is influenced by the humidity in the air. If this is high, it is absorbed by the particles and they appear larger to the sensor than they actually are. To compensate for this, there are various approaches to correction calculation from relevant publications, one of which was implemented in the IMMS

Figure 2: Sensor on a light pole at the spa park in Stützerbach. Photograph: Marco Götze, IMMS.

system.[1] The local micro-climate measurement of temperature and humidity was also integrated into the system for this purpose.

If the micro-climatic conditions are close to the dew point, the result of the correction calculations approaches the zero value exponentially. In such situations, which occur more frequently in the valleys of low mountain ranges, for example, the measured values are correspondingly less reliable in quantitative terms. However, this is a known problem for optical particulate matter measurement.[2] This can currently only be solved in the large measuring stations commonly used. The particulate matter collected there is determined by weight and therefore dried beforehand.

Proof of function

From June 2023, the developed system was successively rolled out in the Ilmenau districts of Stützerbach (spa-town), Manebach, and Frauenwald (both resorts), each with several sensor nodes (Figure 2), and has been in an ongoing trial ever since. The current values and time series curves are visualised for the city and the spa administrations using dashboards in Grafana (Figure 3).

1 *Soneja, S.; Chen, C.; Tielsch, J.M.; Katz, J.; Zeger, S.L.; Checkley, W.; Curriero, F.C.; Breysse, P.N.: Humidity and Gravimetric Equivalency Adjustments for Nephelometer-Based Particulate Matter Measurements of Emissions from Solid Biomass Fuel Use in Cookstoves. Int. J. Environ. Res. Public Health 2014, 11, 6400-6416. https://doi.org/10.3390/ijerph110606400*

2 *LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg: Messungen mit dem Feinstaubsensor SDS011. Ein Vergleich mit einem eignungsgeprüften Feinstaubanalysator. Karlsruhe 2017. https://pd.lubw.de/90536*

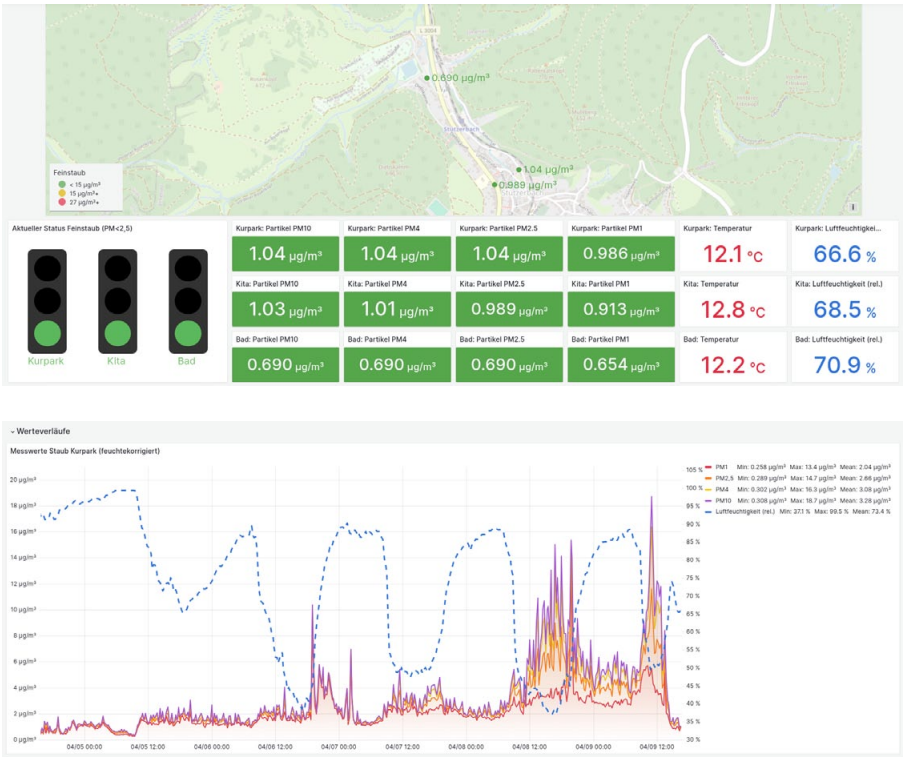

Figure 3: Status visualisation in dashboards: **top**: current status on a map of the town of Stützerbach and "traffic lights" indicating adherence to limits; **bottom**: measurement time series curves showing (right) the phase of increased exposure to Saharan dust in April 2024. Source: IMMS.

In the course of testing, no quantitative comparison with DWD measurements has been possible so far due to a lack of reference: there are no public measuring points in the locations under consideration and the measurement data available from public sources such as the Thuringian environmental portal are of lower temporal resolution. However, qualitative correlations with expected or large-scale reported increases could be recorded, e.g., a clear peak after midnight on New Year's Eve, the weeks with Saharan dust in spring 2024, and other phases with increased particulate matter pollution throughout Germany. In Manebach, a sensor was installed at a location of interest below the height of neighboring chimneys due to the local conditions — as a result, heating periods could be detected in certain weather conditions.

The measured values for particulate matter monitoring in the districts of Ilmenau will also be displayed on citizen information pages in future.

In addition, the continuous measurement of particulate matter with a comparatively high temporal resolution will be used over the longer term to examine the extent to which the measured values correlate with DWD measurements and what conclusions can be drawn about the causes of fluctuations over the course of the year and selective spikes.

As particulate matter is especially relevant for spa-towns and health resorts, but also for cities in general due to legal requirements, the solution is also suitable for a wider range of applications. In the EU Air Quality Directive currently being revised, the annual limit value for the main pollutant particulate matter (PM2.5) has been reduced by more than half. It can therefore be assumed that the number of measuring stations will increase and the demand for more cost-effective solutions such as this could rise in the future.

The data collected can also form the basis for systematic correlation observations and analyses (also using AI), root cause analysis, and also the review of the effectiveness of measures taken.

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Intelligent, networked camera systems for greater safety in the mobile use of loading cranes

In the EdgeCam project, a solution was developed to create safety zones around mobile cranes with networked cameras. Photograph: ArtisticOperations/Pixabay.

Motivation: Accident prevention in mobile danger zones with anonymous persons

www.imms.de/edgecam

Safety zones ensure that no persons are present in the danger zone of machines when these are in operation. This applies to many applications, from production cells to warehouses with autonomous forklifts as well as loading cranes on trucks. In any case, the aim is to guarantee safe operation by warning the operator of the machine if there is a potential hazard or by moving the system into a safe state.

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While there are already very good and restrictive solutions for production cells, where the robot can only be started if the cell is free of obstacles and/or people, this is more difficult for applications with mobile machines. Here too, there are various solutions that can be used inside warehouses or on enclosed company premises. Technically, this is typically done using light barriers or special tags that people who are working in the area carry with them enabling the system to recognise them.

If the machine operates outside of a company site, such solutions are limited. Random people passing by the operation site will not carry any specific hardware and might be oblivious regarding light barriers if they even notice them. In this case, the system should be able to monitor the safety zone autonomously, detect, and recognise obstacles outside of the field of view from the operator. When it detects such hazards, the system warns the operator with the goal to avoid any accidents.

Virtual security zone solution at a glance

To build such a system, IMMS has been working on the realisation of a virtual safety zone that can be spanned around any vehicle in the EdgeCAM project. The system should enable safe truck operations with a loading crane, for example, at any location. To achieve this, together with our partner emsys GmbH, we have developed special multi-camera nodes that autonomously connect themselves wirelessly and use the images from all attached cameras to create a seamless virtual safety zone around the truck. The system monitors the safety zone around the crane autonomously and continuously and can thus warn the crane operator of any potential hazards at an early stage, even if they are outside his field of vision. The captured image data remains within the system and is not transmitted to a third party to meet data privacy requirements. To develop this system, emsys and IMMS first designed a modular hardware platform that is built using different cameras and communications modules.

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www.imms.de/iot

www.imms.de/monitoring

The goal is a system that intelligently selects the communications option that is most suitable for the respective location and the current task from the various communications options available. The system can also be extended with additional cameras on the crane itself or at the storage location to further increase safety.

The developed system is not only flexibly adaptable to the use case of trucks with cranes, other applications such as counting people waiting at bus stops can also be implemented with the hardware.

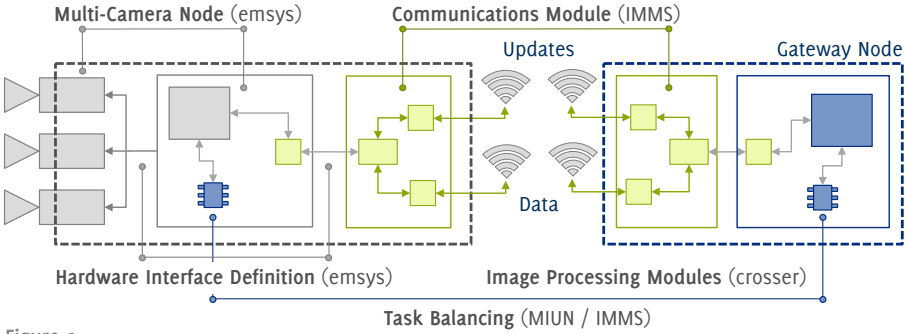

Figure 1:
Schematic system structure. Diagram: IMMS.

Overall system architecture

The EdgeCam system represents an overall system architecture for mobile monitoring tasks in the field and consists of multi-camera nodes, which can be equipped with several camera modules, a gateway node, a human-machine interface (HMI) as feedback to the crane operator and flexible communications support between the nodes involved and, if necessary, the Internet. The system also enables the distribution of processing tasks between the nodes involved to achieve load distribution. OPC UA is used to exchange the required information. Figure 1 shows the schematic system structure.

The gateway is a special node and differs from the other nodes by performing additional tasks. These include the configuration and quality monitoring of the local wireless communications network with the existing multi-camera nodes and communications with the HMI. The gateway is also responsible for managing the results of the EdgeCAM system. The result data from the multi-camera nodes must be collected, processed and post-processed. The final result must be periodically forwarded to the HMI. If hazardous situations occur (e.g. “people in the work area”), this must be signaled within the required time. The gateway can be implemented as a dedicated gateway without a camera or as a node with an integrated camera.

Hardware for EdgeCam multi-camera nodes

The “Variscite DART MX8M PLUS” platform serves as the basic hardware for all node types. The module offers interfaces for up to two cameras and enables the flexible connection of wireless modules via PCIe, for example. This makes it ideal for setting

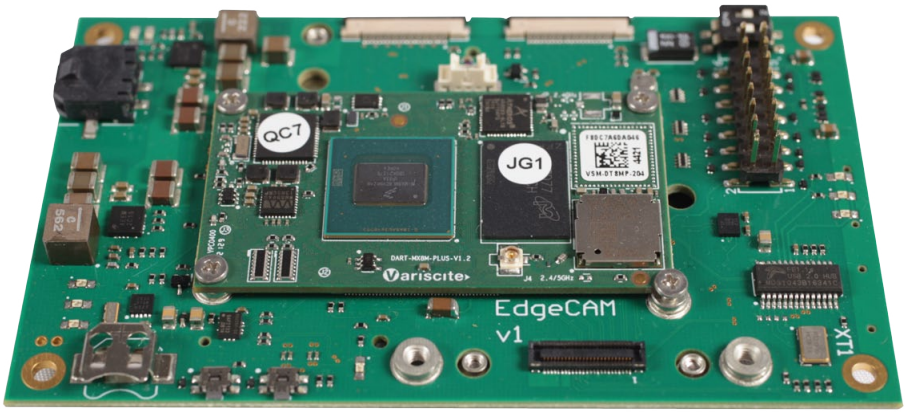

Figure 2: Multi-camera node hardware. Photograph: IMMS.

up multi-camera nodes with several wireless modules that can be used in parallel. The aim was to create a compact design that integrates all the wireless interfaces provided as well as various other interfaces to ensure that the hardware can be used as flexibly as possible. The layout of the board was put into practice in close consultation with the project partner emsys. Figure 2 shows the finished board.

Adaptive WLAN-based EdgeCam network

The EdgeCam system operates autonomously, i.e. it first establishes a stable and reliable WLAN network between the system components at the installation site. The gateway coordinates this and ensures that all nodes of the EdgeCAM system are seamlessly integrated into the network and can communicate with each other. To this end, it acts as an access point for a WLAN infrastructure network into which the other nodes and the HMI are directly integrated. To set up such a network at any location, the system should flexibly select the used channel. This is achieved via a scan procedure performed by the gateway on all available WLAN channels after the system is started and then selects a free WLAN channel based on the results.

As **WLAN channels overlap** due to their bandwidth, i.e. a WLAN signal on channel n can still interfere with channel n+1, the system searches for a non-overlapping channel that is undisturbed by other WLAN signals. This is done with the help of a sliding window, which ensures that the necessary channel spacing is maintained in the respective frequency band. The first free undisturbed WLAN channel is then selected for setting up the EdgeCAM WLAN network.

As it cannot be guaranteed that a channel that was initially recognised and selected as free will remain so throughout the entire period of use, **monitoring and channel change functions** have been added that enable the system to change channels later. To evaluate the quality of the current channel or the connection parameters, the gateway periodically prompts the other nodes to perform a scan for existing external WLAN activity. The nodes then inform the gateway about other WLAN networks found on the current EdgeCAM WLAN channel. If problems are detected, the gateway initiates a switch to an available free channel. Ideally, this switch can take place using the WLAN feature Channel Switch Announcement (CSA), which was first specified in the IEEE 802.11h standard. However, this feature requires support from the WLAN hardware used as well as full support from the associated Linux drivers on the nodes used.

Dynamic load balancing

To minimise the **latency** in the processing of the video streams, various platforms were examined in the project with regard to their performance and a load balancing concept was implemented that allows multi-camera nodes to outsource part or all of the processing of the recorded image data. This is implementd via a framework for the distributed processing of image processing algorithms, based on openCV. The framework consists of a client unit on a multi-camera node and a processing server running on another node in the EdgeCAM network.

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The **monitoring** of a virtual security zone was implemented as a multi-stage image processing task in openCV as an example. After each stage, processing can be stopped on the client side and the remaining steps can be processed on the server. The processing of the script on the current node can be stopped at various points via a command interface if, for example, the computing power of the node is insufficient. In this case, the image data or already calculated intermediate results and the remaining part of the processing script are forwarded to the processing server. The point at which the processing of the script is split can be changed dynamically during operation.

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This enables simple load distribution between the nodes of the system. This essentially follows the concepts for intelligence partitioning developed by the Swedish partner Mid Sweden University and thus demonstrates a practical realisation of these concepts.

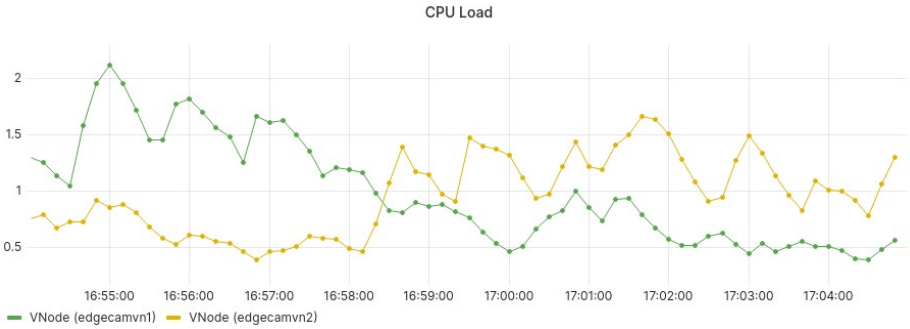

Figure 3: Load change after switching the image processing to the server. Source: IMMS.

OPC UA (Open Platform Communications Unified Architecture) was used in the project to control and transfer the results of the distributed image processing. This allows the connection between the image processing client and server to be established and terminated dynamically via OPC UA (e.g. if new nodes are registered in the network) and the processing of image data to be moved dynamically between the client and server. This created the basis for dynamically distributing the image processing tasks among the nodes based on the current load situation of the overall system.

OPC-UA-based information exchange

OPC UA was used to exchange the necessary information for communications and the data to be processed as well as the monitoring results. OPC UA is a very universal, service-oriented communications protocol and offers a good starting point for networking in Industry 4.0 installations. With the Companion Specification for Machine Vision (OPC 40100-1), a specification for components for image recognition already exists, which covers various aspects of the EdgeCAM application area and thus provides an already standardised interface.

Each node in the EdgeCam network implements an **OPC UA server**, which provides all relevant status information of the node in its information model. The function of the node can be controlled via methods in the information model. Events and alarms are used to forward events. OPC UA PubSub communications can also be used to transfer image data streams from the multi-camera nodes to other nodes in the network for further processing.

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The OPC UA server of the gateway connects to all **multi-camera nodes** via server-to-server communications and thus has access to the overall status of the system, including all alarms and events. In its function as a server, it in turn provides the interface to the respective EdgeCAM installation.

A **local discovery server** (LDS) also runs on the gateway and serves as a registration point for the camera nodes. The last part of the OPC UA communications components is the **gateway client**. This acts both as a client in relation to the camera nodes and as a server in its role as an interface to a possible administration in the cloud.

The gateway client establishes a connection to all camera nodes in the system, collects their parameter information and provides an interface with which the camera nodes can be controlled. It also establishes a connection to a time series database that can be used to record all information from the EdgeCAM network.

The **implementation** was based on the OPC UA open-source stack open62541. This defines various data types as a basis, which serve as an API for accessing the camera node with their objects, attributes and methods. Local components can connect to this interface, e.g. to provide or receive parameter updates to the other nodes in the EdgeCAM network, as well as the gateway client, which handles communications and control with all camera nodes. The procedure for initialising communications via OPC UA in an EdgeCAM network is as follows: First, the discovery server starts on the gateway. The gateway client, which also runs on the gateway, connects to it. An

Figure 4: Demo setup in the IMMS foyer with multi-camera node and additionally marked safety zone. Photograph: IMMS.

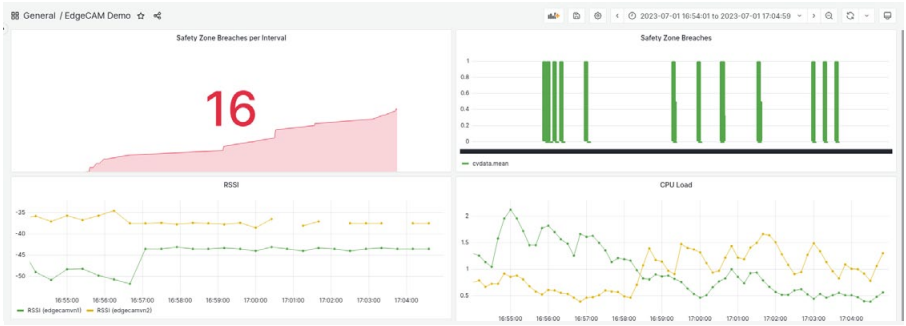

Figure 5: Screenshot of the Grafana-based visualisation of the demo for the Long Night of Science in Ilmenau with the number of violations of the security zone (top), reception strength of the multi-camera nodes (bottom left), and change in computing load (bottom right). Souce: IMMS.

OPC UA server is now started on the camera nodes in the system, which registers with the gateway's local discovery server. This registration automatically notifies the gateway client, which now establishes a connection to the respective server of the camera node. The camera nodes are managed dynamically. This means that the connection to the nodes is monitored via various mechanisms. If it is lost, the camera node is automatically removed from the network.

Demo setup

A demonstrator was set up to show how the EdgeCAM system works. This consists of a multi-camera node, a gateway and a laptop as a human-machine interface (HMI) with visualisation of the camera image, the results of the detection and an interface for controlling the system for tests.

A simple **image processing algorithm** was selected as the image processing task, which can detect and display changes in a selected image area of a live video stream. This comes very close to the scenario of a virtual security zone. For this purpose, the camera image is captured, and the difference to the frame of the previous recording is calculated in several steps, such as blurring. Using edge detection and appropriate filtering of the results, movements can be detected in the desired image section. Figure 4 shows an installed multi-camera node and the safety zone in the image area. This was also marked on the ground for test purposes. However, this marking is not necessary for the function.

The **visualisation** of the recorded data of the EdgeCAM demo setup is implemented with the help of Grafana (see figures 3 and 5). This provides an extremely powerful method of gaining comprehensive insights into the operation of the system. Grafana also offers the possibility to set up alarms and notifications to be alerted to critical events or deviations from defined thresholds. This can be done via different channels, for which the system forwards the corresponding alarm to an external service. However, this only affects the detection of hazards, not the actual video image.

Conclusions and future work

The demo showed that the system developed in the project is able to create a virtual safety zone without additional hardware, even with simple classical image processing algorithms. However, the system is designed in such a way that it adapted to different situations flexibly and could also be used for other applications such as passenger counting at bus stops or similar. The advantage here is that the image information from the cameras does not leave the system, thus ensuring privacy. In this project, IMMS has used its expertise in dealing with communications networks and protocols to develop a system that can adapt to given radio situations. In addition, concepts for the distribution of processing tasks and dynamic load balancing for small embedded systems were developed and successfully tested.

www.imms.de/monitoring

www.imms.de/iot

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Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

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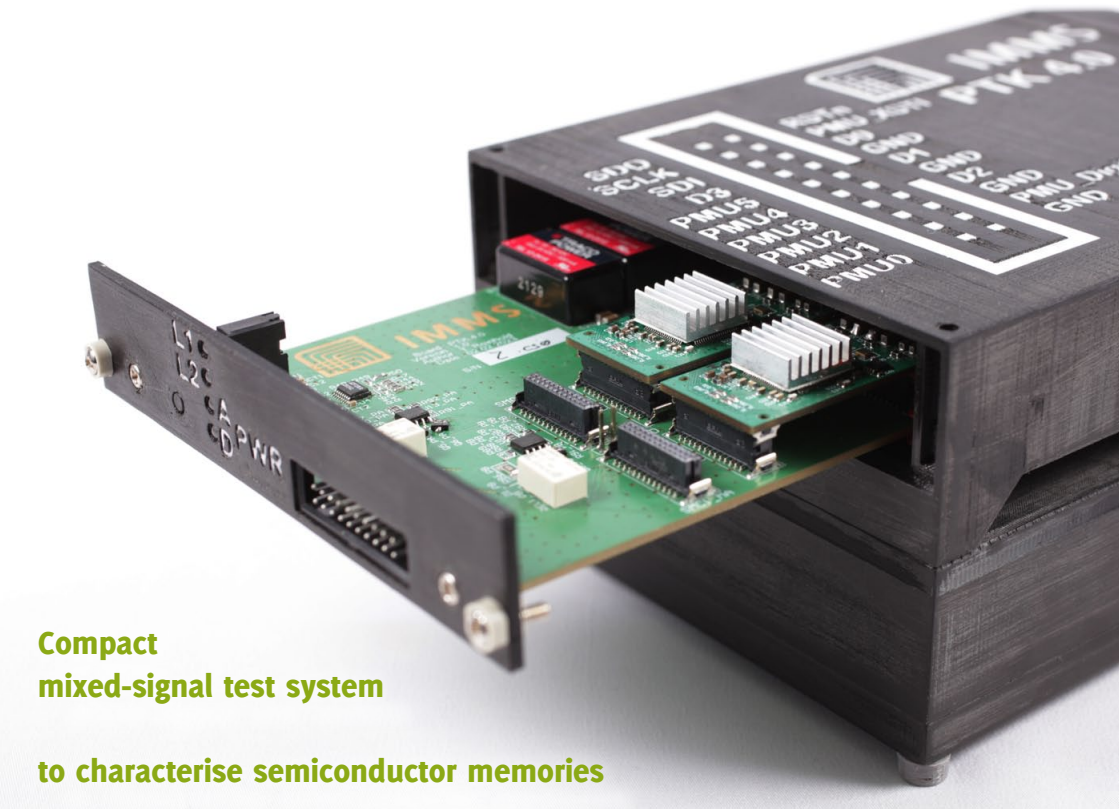
www.imms.de/edgecam



Compact mixed-signal test system to characterise semiconductor memories

Figure 1: The new PTK 4.0 test system with analogue/mixed-signal capability enables circuits to be tested, measured and even characterised without additional equipment. It is also compatible with the modular AMS ASIC Scope system developed at IMMS. Photograph: IMMS.

Motivation and overview

IMMS has developed a new standalone device for operating, testing and characterising test structures with semiconductor memories as well as mixed-signal circuitry and circuits with digital control, commissioned by X-FAB Global Services GmbH. With the size of a Tetra Pack juice box, the "Programmer Toolkit" version 4, the PTK 4.0, is ideal for mobile use or as a space-saving addition to established measuring stations. No additional test equipment is required for most applications, as all the necessary digital and analogue functions are provided by the PTK 4.0. Measurement tasks are carried out automatically in conjunction with a laptop for control and data processing.

www.imms.de/modtest

The core component is a measuring module with eight analogue and eight digital measuring channels. In addition to the implementation of the X-FAB's internal serial protocol "XSTI", standardised serial interfaces such as SPI or I²C can also be controlled. The digital voltage levels can be set between 0.65 V and 3.6 V. In addition,

the analogue measuring channels can provide voltages (–6 V to +16 V) and currents (–50 mA to +50 mA) and record them with a high degree of accuracy (±1 nA / 2 mV). A sequencer makes it possible to programme and repeat measurement sequences so that stress and long-term tests can also be carried out.

PTK 4.0 hardware

For operation, the PTK 4.0 has a USB interface and an input for a power supply unit. Test objects can be connected via eight digital and eight analogue channels, which can be configured as input and output. Some of the digital channels are intended for data transmission to the test object via a specific communications protocol.

Two parts were developed for the system: the module board, which gives the device its actual function, and the module driver, which adapts the USB interface into a QSPI bus (quad serial peripheral interface) for data transmission. Analogue and digital functions are implemented using FPGA and analogue circuit components. As a module with the format of a Eurocard, this part of the test system is also compatible with the AMS ASIC Scope of IMMS.[1]

Module board

The basic function of the PTK 4.0 is located on the module board. This provides analogue source and measurement channels for supply and digital channels for controlling test chips. Eight digital IOs in the voltage range between 0.65 V and 3.6 V are available for this purpose. These are controlled by an FPGA and enable implementation for a wide range of digital protocols.

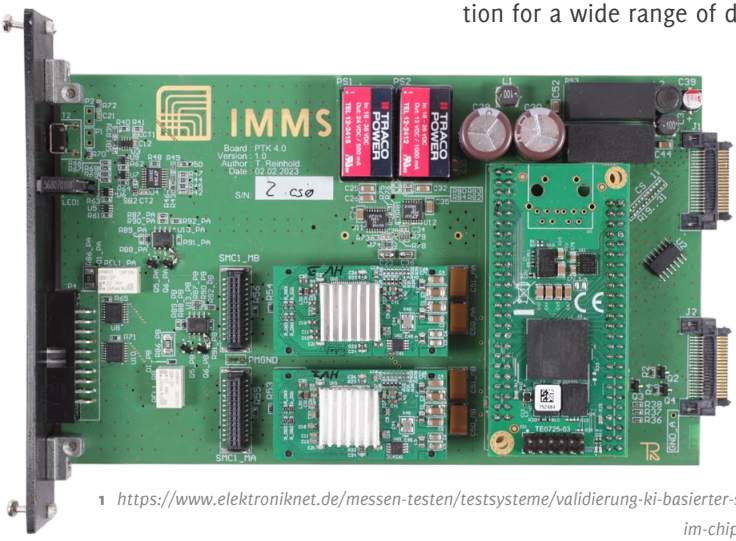


Figure 2:
PTK 4.0 – module board.

Photograph: IMMS.

1 *https://www.elektroniknet.de/messen-testen/testsysteme/validierung-ki-basierter-simulationsmethoden-im-chip-entwurf.213109.html*

The voltages of the digital signals are specified as four signals each by two of the eight analogue channels. This means that the eight digital channels are divided into two groups, each containing four digital channels. The digital voltage level of each group can be varied independently of the other.

The eight analogue channels are four-quadrant sources with simultaneous measurement functionality from the field of ATE (automatic test equipment). These are capable of sourcing or sinking voltages or currents between –6 to 16 V and ±50 mA per channel. The accuracy for the output of analogue voltages corresponds to approx. ±2 mV. For currents, accuracies of up to ±1 nA are achieved, depending on the configured range.

The simultaneous measurement functionality enables the measurement of operating parameters of the circuit under test (DUT, device under test) with mV voltage and nA current resolution. This makes it possible, for example, to examine the current consumption of a test object.

To ensure high absolute accuracy of the analogue components, calibration and fine adjustment are carried out beforehand using calibrated measuring devices. This ensures that the desired measuring accuracy of the test device is achieved.

Module driver

The module driver represents the connection between the module and a user interface. The module driver contains a protocol converter from USB 2.0 to QSPI for this purpose. A power supply unit, which is connected to the module driver, serves as the power supply for the device.

Another advantage of the module driver is its compatibility with the modular system – the AMS ASIC Scope. Components of this modular system can therefore be operated with the module driver as stand-alone devices. On the other hand, the module board of the PTK 4.0 can also be used in the AMS ASIC Scope.

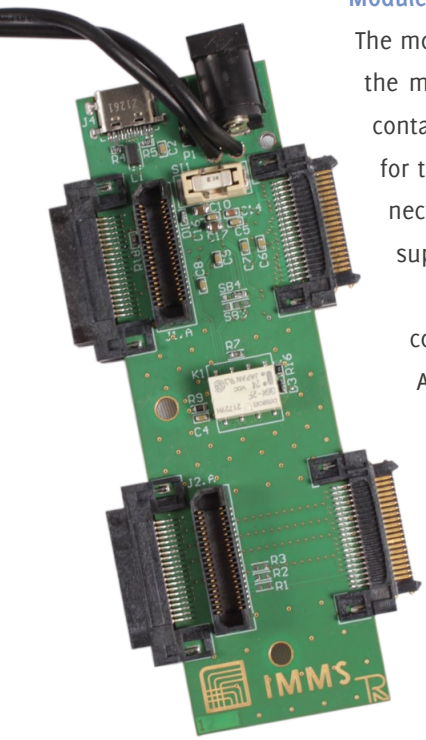


Figure 3: Module driver for the PTK 4.0 module board (also compatible with AMS ASIC Scope modules). Photograph: IMMS.

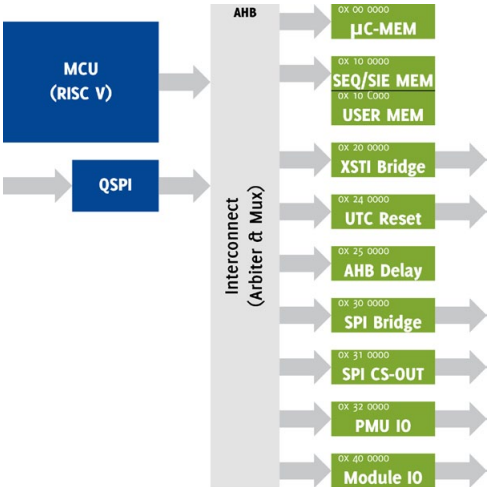


Figure 4: Schematic representation of the bus system implemented in the FPGA. Graphic: IMMS.

FPGA

An FPGA is installed as the control element of the PTK 4.0. This contains a microcontroller-like structure with an internal address bus system – the AHB (advanced high-performance bus).

This bus system contains two controlling components (bus master). These are shown in blue in Figure 4. When the module is switched on, a processor core with RISC-V instruction set enables the initialisation of the module components as well as programme sequence control for carrying out automated test sequences. Data access and control takes place in the form of a QSPI. This provides access to the programming of measurement sequences and the direct control of hardware components on the module board.

The slave components of the AHB (shown in green in Figure 4) include data memory, GPIO modules and digital bus interfaces such as SPI for controlling the analogue channels.

One slave component is a communications controller that implements a special communications protocol – the X-FAB Serial Test Interface (XSTI). This was implemented in the FPGA according to customer specifications and shows that the modularity of the architecture also enables the addition of proprietary, application-specific interfaces.

Microcontroller

The microcontroller integrated in the FPGA in the form of a RISC-V core implements an initialisation sequence, an interface for system control and a sequencer. During initialisation, function checks of the analogue components are performed and the calibration data is loaded. The status of this initialisation is indicated by the LEDs on the front panel. This means that it is immediately visible after switching on the device whether the hardware is ready for use or whether an error or defect has been detected.

The microcontroller is then available for the execution of more complex operations and provides a sequencer for automated test sequences. In addition, there are sequencer commands for more complex operations, which reduce the utilisation of the sequencer and at the same time improve its user-friendliness. An example of this is the control of the ADC, which is configured to the corresponding analogue channel, starts a measurement and then reads back the result.

When a sequencer programme is running, the LEDs on the front panel show the user what state it is in. This makes it easy to see whether it is still being executed or if the process has been successfully completed or interrupted with an error message.

PC control

The PTK 4.0 is controlled by software that runs on a connected PC. An object-oriented C++ API exists for this purpose, which enables complex operations to be controlled at a high level of abstraction. At the same time, however, work at a lower level of abstraction is accessible, so that the desired level of abstraction can be used for the application.

Summary and outlook

The PTK 4.0 is a new test system with analogue/mixed-signal capability. It is compatible with the modular AMS ASIC Scope system developed at IMMS. In the form factor of a mobile device, the PTK 4.0 combines analogue and digital functions. It is designed for testing circuits with a digital serial interface. Supply voltages can be generated and digital communications protocols can be operated. At the same time, it is possible to measure analogue parameters such as current and/or voltages.

www.imms.de/modtest

All measurement functions can be accessed via the USB interface. In addition, it is possible to run tests automatically using the sequencer and thus speed it up considerably.

This tabletop device makes it possible to test, measure and even characterise circuits without additional equipment. It has great potential, as the same range of functions is otherwise only available in very expensive and large measuring devices,

which in turn are so universal that a great effort has to be invested in test development. The PTK 4.0, on the other hand, is designed directly for operating digital and mixed-signal circuits. The test setup is simple, as all signals are connected to one device and the functions required for programming with the C++ interface are provided directly. This makes the PTK 4.0 suitable for a complete test setup as well as for ad hoc tasks.

Similar to the PTK 4.0, setups specially adapted to customer requirements can be developed at IMMS for other tasks, for example for automation, miniaturisation or flexibilisation of measurement tasks.

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RESEARCH FIELD

MAGNETIC 6D DIRECT DRIVES WITH NANOMETRE PRECISION

Magnetic 6D direct drives with nanometre precision

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.

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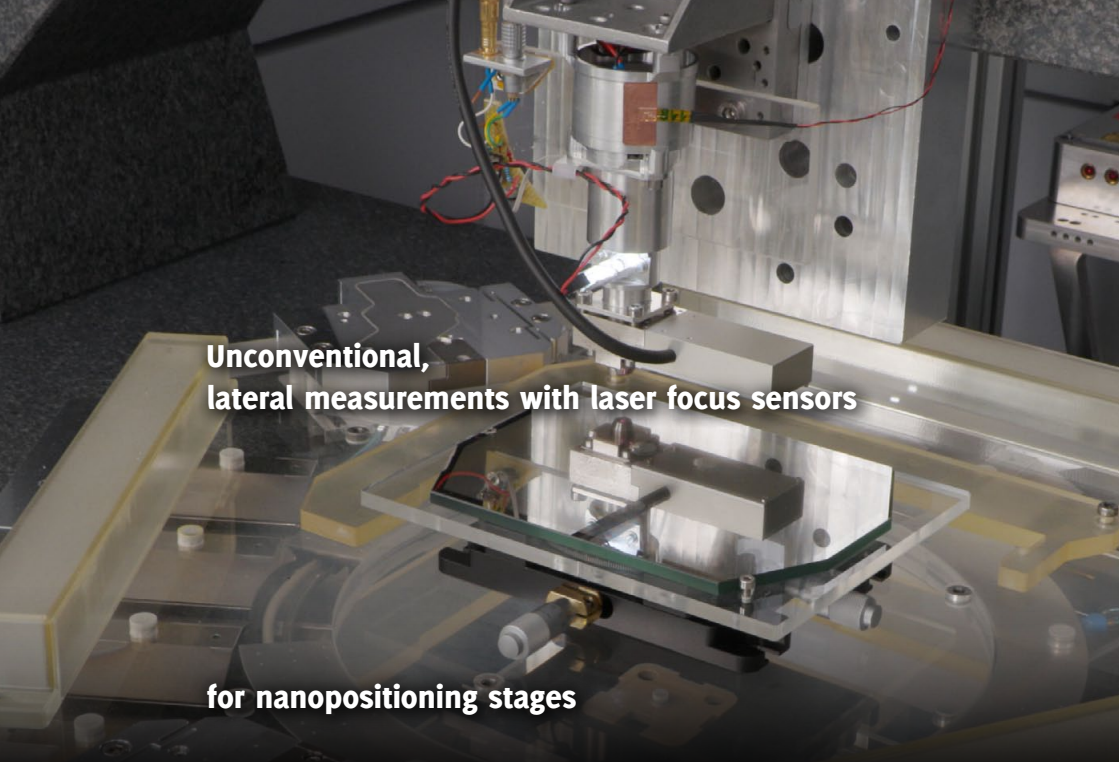


Unconventional, lateral measurements with laser focus sensors for nanopositioning stages

Using its NPS6D200 positioning system as an example, IMMS has demonstrated that a laser focus sensor for lateral distance measurement can be used as an alternative to optical microscopes or linear encoders for characterising nanopositioning systems. Photograph: IMMS.

Motivation and overview

www.imms.de/nanofab

Highly accurate nanopositioning stages are an important component in the production of modern nanotechnological devices. The measurement and calibration of nanopositioning stages using unidimensional or bidimensional artifacts is possible with various instruments. Traditionally, optical microscopes and linear encoders represent a common choice for that. However, an alternative tool for lateral measurements is applicable, the laser focus sensor (LFS). Originally designed to detect vertical distances between the sample and its objective lens, LFS can also characterise lateral stage motion using specific artifacts. The principle of LFS operation is to emit a circular laser spot and monitor changes in vertical positioning by changes in the shape of the reflected spot. By use of a quadrant detector, an LFS achieves nanometre resolution in vertical measurements. In an alternative operation mode, an LFS can also obtain an intensity signal from the returned spot that can be correlated to lateral movement. This is achieved by detecting different reflective materials on a cross grid consisting of a glass substrate with chromium lines.

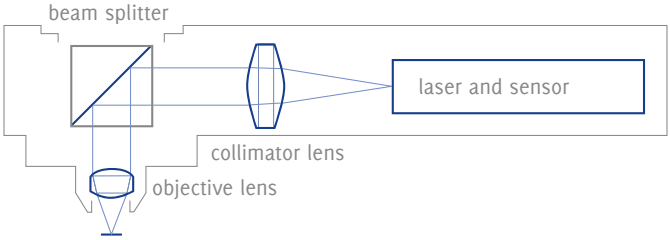


Figure 1:

LFS structure. Diagram: IMMS.

Functional principle of an LFS system

The LFS is a precise metrological tool capable to measure vertical distances within a narrow range around its focal point, with a typical measuring range of 3 µm. Illustrated in Figure 1, its design is composed by a single collimated laser beam, deflected by a beam splitter towards the sample. This beam, shaped by the objective lens, interacts with the sample before returning along the same path to a quadrant detector sensor.

Vertical measurements with quadrant detector

Throughout this optical path, the beam's characteristics suffer some transformations. When precisely focused, it manifests as a circular spot; however, deviations from focus result in an ellipsoidal shape, as presented in Figure 2. Furthermore, the orientation of this ellipsoid varies depending on the proximity to or distance from the sample. Signal analysis involves knowing the differences between the quadrants.

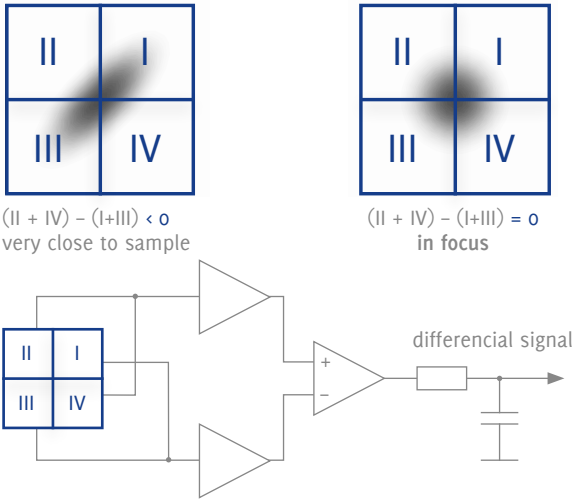


Figure 2:

Top: Spot shape depending on the object's distance from the focus. **Bottom:** Block diagram of electronics for the evaluation of the LFS differential signal. Diagram: IMMS.

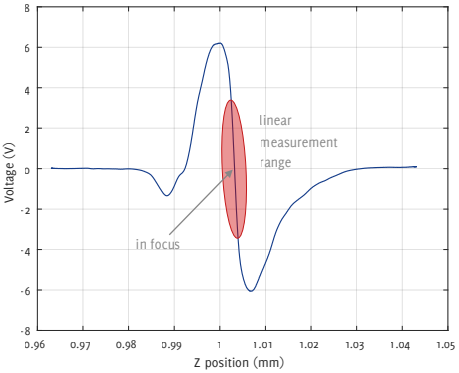


Figure 3:

Difference signal obtained by vertical movement with respect to sample proximity – central zero crossing indicate the focus position.

Diagram: IMMS.

Two signals are provided by the LFS with respect to the laser beam detected by reflection in a sample. The difference signal is obtained from the difference between the diagonal quadrants and is proportional to the vertical position (Figure 3) within the measurement range of the sensor. To characterise the relationship between the vertical position and the voltage obtained in the difference signal, it is necessary to have a vertical movement in the region close to the focus and to align the sample with the axis that will realise the movement. When the distance to the sample is close to the focus, the intensity remains approximately constant.

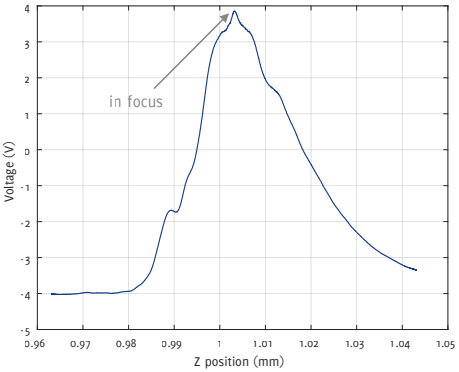


Figure 4:

Sum signal obtained by vertical movement with respect to sample proximity – maximum obtained when the focus is reached.

Diagram: IMMS.

Simultaneously to the above-mentioned difference signal, the LFS also provides a sum signal of all quadrant signals, which is realised by exchanging the difference block by a sum block in Figure 2. This sum signal provides an impression of the beam intensity, as illustrated in Figure 4. Within the measurement range, the intensity peak means an optimal focus. Beyond this range, signal reduction occurs, as an indicative of the spot exceeding the detector's area. Consequently, intensity remains until reaching a minimum threshold.

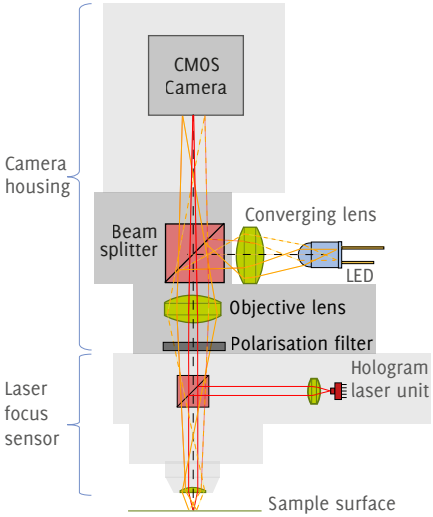


Figure 5: Non-contact probing system of LFS with camera microscope. Graphic: IMMS.

Experiment details

For enhanced visualisation, in the following setup a CMOS camera is combined with the LFS (figure 5), promoting the identification of structures within the region of interest. Positioned on top of the LFS, this camera supplements visual guidance, particularly with the aid of additional lighting to enhance image brightness.

A cross grid is selected as a sample to evaluate the performance of the complete system with integration of a nanopositioning machine and the LFS. This artifact is composed of different layers with an approximately constant lateral pitch. The type of cross grid used is basically a glass substrate with chromium deposited on top, as shown in Figure 6. Using chemical etching in a microfabrication process, a mask defines areas where the chromium layer is removed, resulting in this physical configuration of lines or squares.

The LFS application here involves the measurement of lateral distances between structures within an available cross grid with a pitch of 40 µm. In this configuration, the motion of the cross grid is realised by a 6D nanopositioning system. This nanopositioning system with six degrees of freedom and 200 mm of planar motion (NPS6D200), shown in Figure 7, incorporates planar direct drives that move a platform in three degrees of freedom over a planar travel range of ⌀ 200 mm. The motion is precisely referenced by differential laser interferometers. To ensure the stability of vertical movements within a range of 25 mm, the platform is supported by three planar aerostatic bearings complemented by three lift modules. Consequently, additional three degrees of freedom in motion can be achieved. This combination of technology and precision engineering results in a 6D motion system capable of pushing the limits of precision measurement and calibration in nanopositioning stages.

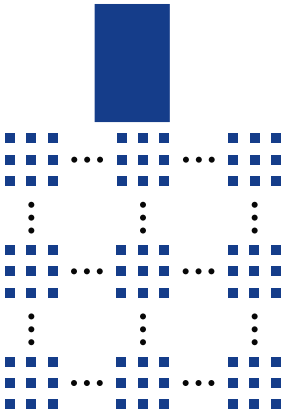


Figure 6: Example of a cross grid where blue parts are the base layer made of glass and white are a chromium layer. Diagram: IMMS.

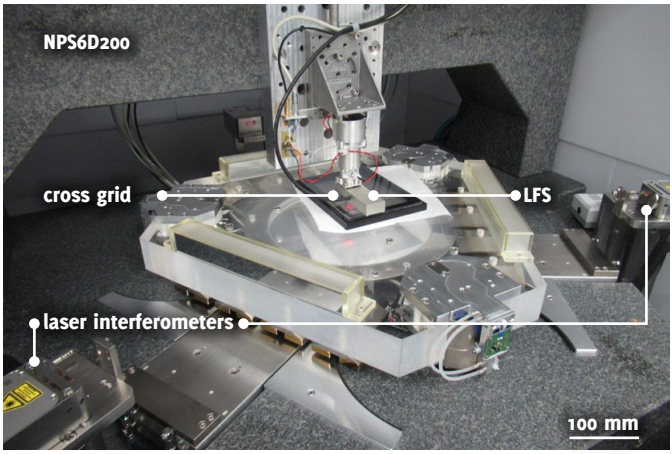


Figure 7:

Laser focus sensor (LFS) assembly with NPS6D200 for cross grid measurements.

Photograph: IMMS.

LFS as an edge detector

Because the cross grid used is made of different materials – glass and chromium – and the distance between the layers is less than 1.5 µm, the LFS detects a square wave for the sum signal in linear motion, as shown in Figure 8. The difference signal shows some non-linear transitions (peaks in Figure 8) at the edges, which are not useful for the required detection. Consequently, the difference signal cannot be used for lateral measurement based on detected edges. However, the edge positions can be determined from the zero crossings of the sum or intensity signals of the LFS using the laser interferometer data, which means that the LFS can be used as an edge detector.

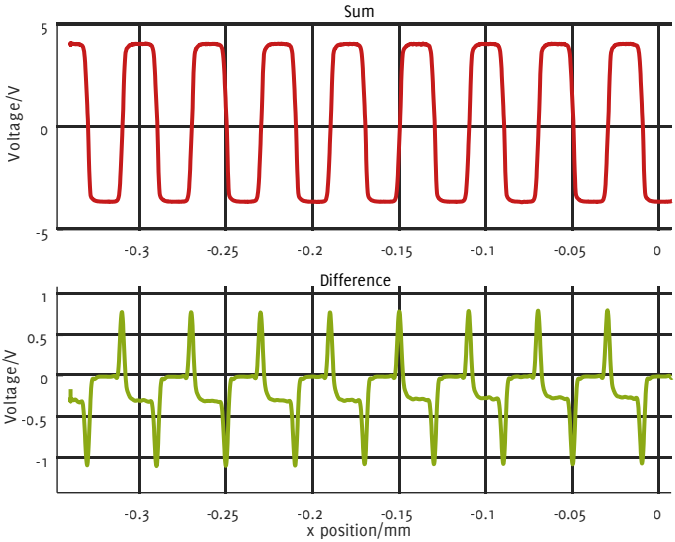


Figure 8:

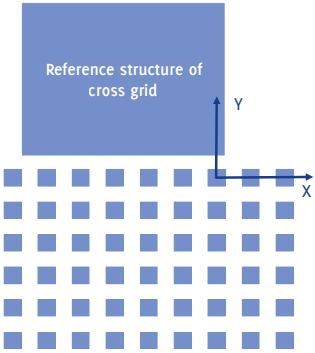
Sum (intensity) and difference (vertical distance from focus) signals with motion in one of the cross grid's major axis.

Diagram: IMMS.

Figure 9:

Coordinate system used to measure cross grid distances.

Diagram: IMMS.



Procedure

Given the coordinate system adopted in Figure 9, the distances between each square shape were calculated from centre to centre. The centre was obtained as the midpoint between the edges of the square.

Each measurement cycle was performed from 0 position to –4 mm and repeated 10 times in X and Y directions. To evaluate the reproducibility, the procedure was repeated on 5 different days. No refractive index correction was applied to these measurements. From the instrumental bias – figures 10 and 11, the standard deviation of the measurement system was evaluated.

Instrumental bias – IB

IB = average of (nominal value – reference value)

– The nominal value is the theoretical value obtained from the accumulated amount of cross grid pitch.
– The reference value is the square centre obtained by laser interferometer positions.

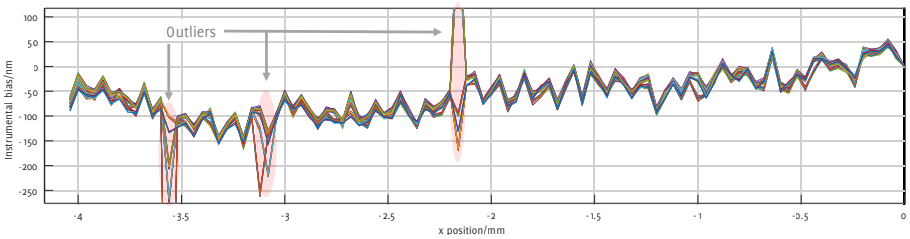


Figure 10: Small changes in cross grid measurements with LFS for X axis on 5 different days – total of 40 measurements. Outliers – contamination – were excluded from the analysis. Diagram: IMMS.

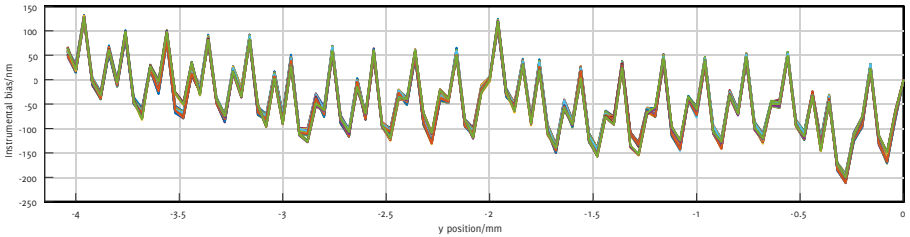


Figure 11: Small changes in cross grid measurements with LFS for Y axis on 5 different days – total of 40 measurements. No major contamination was found. Diagram: IMMS.

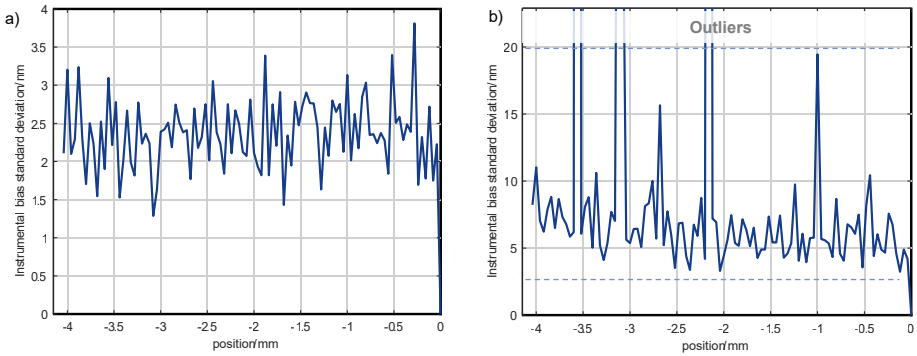


Figure 12: Good repeatability and reproducibility of measurements (outliers not used for analysis) – worst case scenario presented:
a) short term – 10 measurements (1 day); **b) long term** – 40 measurements (5 days). Diagram: IMMS.

Results

For this combination of the LFS and the NPS6D200, less than 4 nm standard deviation of the cross grid centre distance is achieved over a range of 4 mm for X and Y directions in the short term – Figure 12a. In the long term, less than 20 nm standard deviation is determined, Figure 12b, with standard indoor environmental conditions and no further corrections. At the same time, height measurements with the LFS are still possible, although the different reflective properties of the cross grid may reduce the accuracy. The LFS is very sensitive to contamination, which links the outliers in the standard deviation in the long term – Figure 12b – to the instrumental bias detected for the same configuration – Figure 10. These outliers were not included in the analysis. Based on these results, the use of an LFS to measure lateral distances is considered a suitable alternative to optical microscopes and linear encoders in the characterisation of nanopositioning stages.

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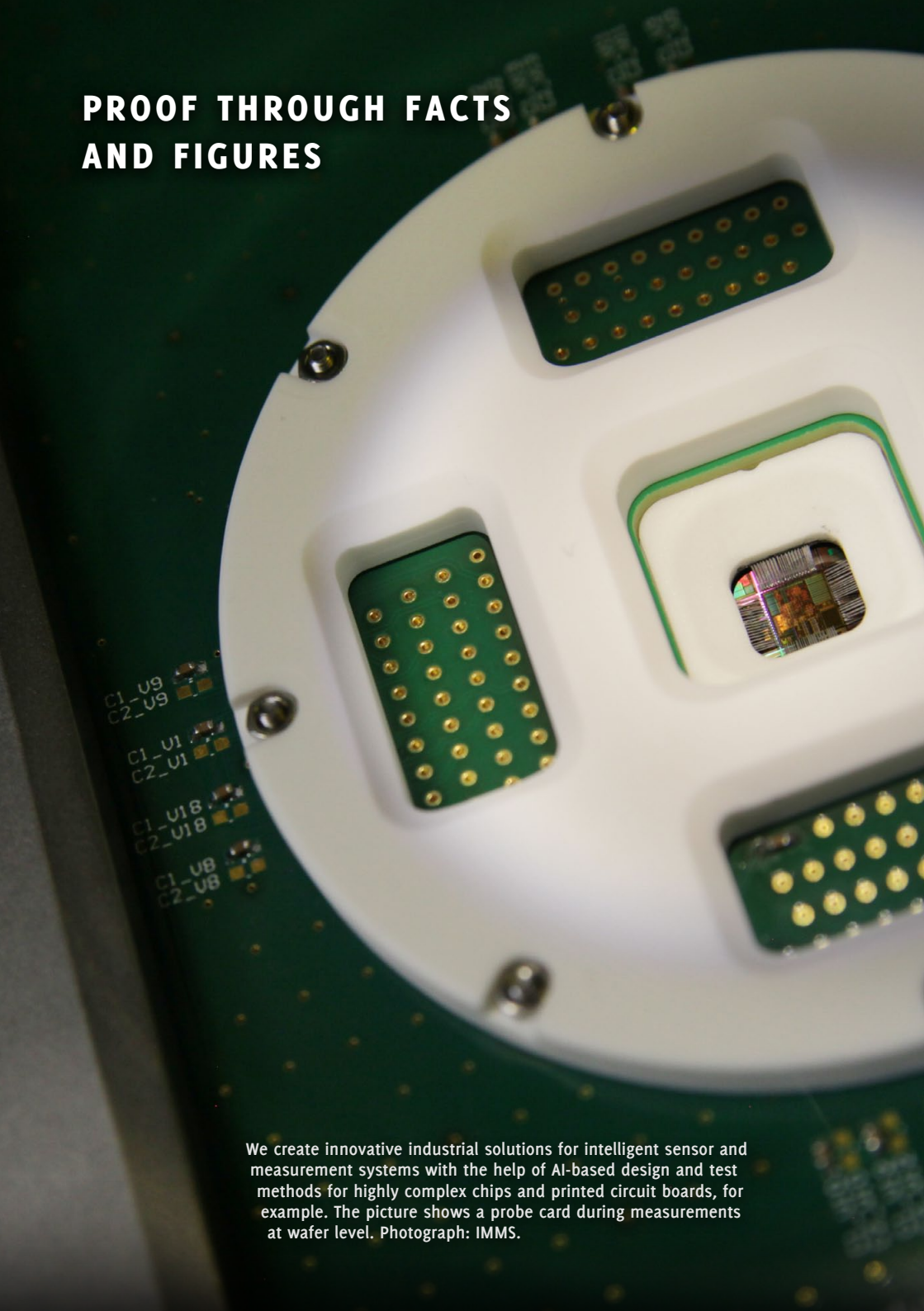
PROOF THROUGH FACTS AND FIGURES

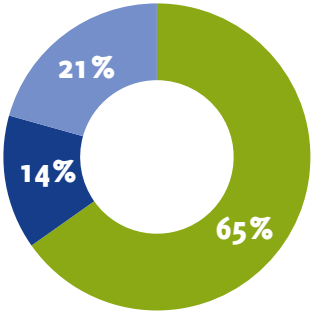


We create innovative industrial solutions for intelligent sensor and measurement systems with the help of AI-based design and test methods for highly complex chips and printed circuit boards, for example. The picture shows a probe card during measurements at wafer level. Photograph: IMMS.

Facts and figures in 2023

At the end of the 2023 financial year, 92 **employees** of various nationalities and disciplines worked at IMMS.[1] Of these, 60 scientists and 19 students were employed in research and development. This corresponds to around 86 % of all employees. In addition, five of the 13 employees assigned to administration were directly involved in research support.

Staff structure



Scientists | administration | students

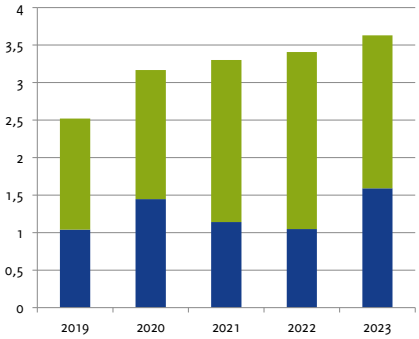
As part of training in practice-oriented research, a total of 40 students were supervised at IMMS in the 2023 financial year, including seven bachelor's theses and three master's theses. Nine employees were enrolled as doctoral students at a university.

Despite the increasingly challenging competition for outstanding minds, further researchers were recruited to work at IMMS in 2023. However, despite a wide range of activities to recruit new talent, the planned demand for scientists could not be fully met.

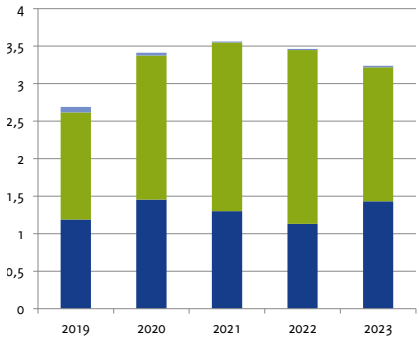
As in previous years, the financial year was characterised by the performance of public research projects and the transfer of research results to industry (industrial contract research and services). The growth of previous years continued seamlessly, with **third-party funding earnings** (project earnings) increasing by a total of around 6 % in 2023 compared to the previous year. The very high industrial earnings had a particularly positive effect here (+52 %). Due to the limited personnel capacity, fewer working hours were therefore available for publicly funded projects (funded projects). This led to a decline in earnings from funded projects (–14 %). Two publicly funded research projects were started in the financial year. In contrast, industrial contract research and services continued to be characterised by a large number of small orders from small and medium-sized enterprises in the German Land of Thüringen (approx. 34 %).

1 *As the employment figures given are actual numbers for 31 December 2023 without calculation of full-time equivalent, only limited comparison with those in earlier annual reports is possible.*

Project **earnings**
Industrial projects / funded projects
in million €



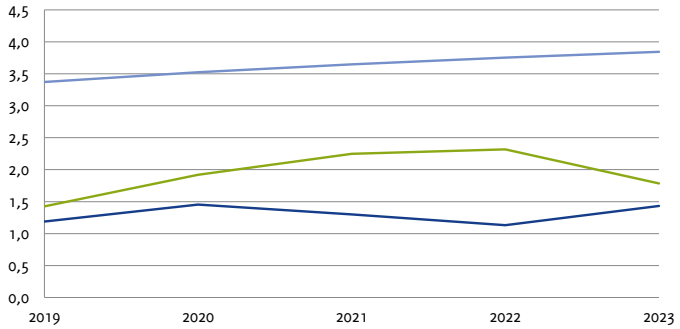
Project **revenues**
Industrial projects / funded projects / others
in million €



Third-party funding revenues (project revenues) were around 7% below the previous year's figure. As in the previous year, the distribution of total project revenues between revenues from funded projects and revenues from industrial contract research and services essentially corresponds to the distribution of earnings.

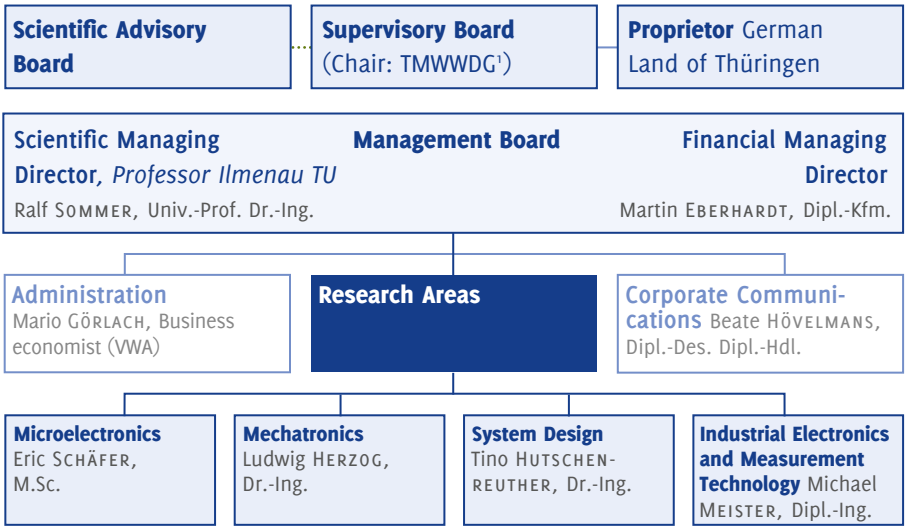
The internal research groups funded by the German Land of Thüringen continued to pursue key research topics for the strategic development of the institute in the 2023 financial year. The financial basis for the research activities of IMMS in 2023 was again provided by institutional funding from the Land of Thüringen. This remained at the previous year's level in the 2023 financial year. However, the general cost increases were compensated by increased industrial income.

Pillars of financial support in million €



www.imms.de/funding

Organisation*



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* as of 31 December 2023

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* as of 31 December 2023

Lectures, lecture series

Prof. Dr. Ralf Sommer,
at Technische Universität Ilmenau, Department Electronic Circuits and Systems:

- Basics of analogue circuit technology, lecture and tutorial,
- Computer-aided circuit simulation and its algorithms (EDA), lecture and tutorial
- Modelling and simulation of analogue systems, supervised teamwork

Prof. Dr. Hannes Töpfer,
at Technische Universität Ilmenau, Department of Advanced Electromagnetics:

- Theoretical electrical engineering I and II, lecture
- Quantum information processing circuits, lecture
- Electromagnetic field, lecture
- Technical electrodynamics, lecture
- Superconductivity in information technology, lecture
- Project seminar TET

Events

www.imms.de/events

Conferences / events with contributions by IMMS

21/02/2023 – AI Regulars' Table on energy management, *talk, organisation, moderator,* Ilmenau
26/02/2023 – TuZ 2023 35th ITG/GI/GMM workshop on Test methods and reliability of circuits and systems, *talk,* Erfurt
12/03/2023 – 16th Photonics Workshop, *talk,* Kopaonik, Serbia
22/03/2023 – AI Spring 2023 AI in production – sensors, data, applications, *2 talks, organisation,* online
22/03/2023 – IID 2023 Industry Innovation Dialogue: New paths in microelectronics – diversification for more resilience, *talk,* Erfurt
26/04/2023 – Digitisation in SMEs 2023 Theme Days, Part 1: Cloud and IT security for SMEs, *talk, organisation,* Erfurt

27/04/2023 – Experimental Fields Conference 2023 Conference of the Federal Ministry of Food and Agriculture (BMEL) on 14 experimental fields for the transformation of digitalisation in the agricultural sector, *talk,* Berlin

08/05/2023 – edaWorkshop23, *talk,* Hannover

09/05/2023 – CPS-IoT Week Workshops '23, *talk,* San Antonio, TX, USA

31/05/2023 – ENC 2023 European Navigation Conference, *talk,* Noordwijk, Zuid-Holland

07/06/2023 – IID ISAS 2023 "Industry innovation dialogue: Intelligent signal analysis and assistance systems", *talk, booth with demonstrators*, Ichtershausen

12/06/2023 – Digitisation in SMEs 2023 Theme Days, Part 2: "Digital business models – methodical development and practical examples", *talk, organisation,* Saalfeld

14/06/2023 – 5th Thuringian Transformation Workshop Automotive, topic AI, *talk, booth with demonstrator,* Ilmenau

03/07/2023 – SMACD 2023 International Conference on Synthesis, Modeling, Analysis and Simulation Methods, and Applications to Circuit Design, *3 talks, Funchal/Madeira, Portugal*

09/07/2023 – IFAC 2023 The 22nd World Congress of the International Federation of Automatic Control, *talk,* Yokohama, Japan

18/07/2023 – SAS 2023 IEEE Sensors Applications Symposium, *talk,* Ottawa, Canada

23/08/2023 – Thuringian Hazelnut Day 2023 Thuringian Federal Office for Agriculture and Rural Areas, Teaching and Research Centre for Horticulture, *talk,* Erfurt

24/08/2023 – Smart manufacturing industry forum – image processing and AI-based data analysis, *talk, organisation*, Wutha-Farnroda

04/09/2023 – ISC 2023 60th Ilmenau Scientific Colloquium Engineering for a Changing World, *talk,* Ilmenau

04/09/2023 – FGSN 2023 20th expert discussion on sensor networks, *talk,* Potsdam

07/09/2023 – IEEE IDAACS 2023 12 th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems, *talk,* Dortmund / hybrid

14/09/2023 – Digitisation in SMEs 2023 Theme Days, Part 3: Combining skilled labour recruitment & digitisation: Finding, retaining & efficiently planning employees, *talk, organisation,* Ilmenau

26/09/2023 – CiS Workshop 2023 Workshop Simulation & Design at the CiS Research Institute for Microsensors, *2 talks*, Erfurt

17/10/2023 – elmug4future 2023 technology conference "Sensor systems of the future – from measured value to information", *talk, booth with demonstrator,* Friedrichroda

www.imms.de/events

23/10/2023 – Network meeting of the Lean Production Network Thüringen, *talk, demonstrators,* Ilmenau
23/10/2023 – MST 2023 Microsystems Technology Congress 2023, *talk,* Dresden
06/11/2023 – MetroAgriFor 2023 International IEEE Workshop on Metrology for Agriculture and Forestry, *1 talk, 1 specialist* poster, Pisa, Italy
14/11/2023 – Smart Manufacturing Industry Forum – Automation in production, *talk, organisation,* Seebach
20/11/2023 – Digital summit of the German government, *talk, booth with demonstrator*, Jena
28/11/2023 – euspen SIG 2023 euspen Special Interest Group Meeting: Micro/Nano Manufacturing, *specialist* poster, Ilmenau
05/12/2023 – Digitalisation in SMEs 2023 Theme Days, Part 4: Sensor technology / smart sensor systems, *3 talks, organisation, moderator, demonstrator,* Ilmenau

Workshops / IMMS as host, organiser or co-initiator

21/02/2023 – AI Regulars' Table on energy management, *talk, organisation, moderator,* Ilmenau
22/03/2023 – AI Spring 2023 AI in production – sensors, data, applications, *2 talks, organisation,* online
26/04/2023 – Digitisation in SMEs 2023 Theme Days, Part 1: Cloud and IT security for SMEs, *talk, organisation,* Erfurt
27/04/2023 – Girls'Day 2023, event at IMMS with *coding workshop, soldering, experiments and demonstrators,* IMMS Ilmenau
12/06/2023 – Digitisation in SMEs 2023 Theme Days, Part 2: "Digital business models – methodical development and practical examples", *talk, organisation,* Saalfeld
23/06/2023 – Long Night of Science Erfurt, event at IMMS with *demonstrators, guided tours and hands-on activities*, IMMS Erfurt
01/07/2023 – Ilmenau Science Night, event at IMMS with *demonstrators, guided tours and hands-on activities*, IMMS Ilmenau
24/08/2023 – Smart manufacturing industry forum – image processing and AI-based data analysis, *talk, organisation*, Wutha-Farnroda
14/09/2023 – Digitisation in SMEs 2023 Theme Days, Part 3: Combining skilled labour recruitment & digitisation: Finding, retaining & efficiently planning employees, *talk, organisation,* Ilmenau

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05/12/2023 – Digitalisation in SMEs 2023 Theme Days, Part 4: Sensor technology / smart sensor systems, *3 talks, organisation, moderator, demonstrator,* Ilmenau

Trade fairs and exhibitions

31/03/2023 – AI Spring 2023 closing event "Experience AI live", *booth with demonstrator,* Erfurt
24/04/2023 – ETD 2023 Erfurt Technology Dialogue, *booth with demonstrator,* Erfurt
07/06/2023 – IID ISAS 2023 "Industry innovation dialogue: Intelligent signal analysis and assistance systems", *talk, booth with demonstrators*, Ichtershausen
08/06/2023 – Career Fair Schmalkalden Contact exchange for academic career guidance, *booth with demonstrator,* Schmalkalden
14/06/2023 – 5th Thuringian Transformation Workshop Automotive, topic AI, *talk, booth with demonstrator,* Ilmenau
29/06/2023 – InnoCON Thüringen 2023 High technology as a future factor, leading innovation policy event of the German Land of Thüringen, *2 booths with demonstrators,* Erfurt
27/09/2023 – Thuringian Mechanical Engineering Day, *booth with demonstrator,* Erfurt
17/10/2023 – elmug4future 2023 technology conference "Sensor systems of the future – from measured value to information", *talk, booth with demonstrator,* Friedrichroda
25/10/2023 – inova 2023 career forum at Ilmenau TU, *booth with demonstrator,* Ilmenau
16/11/2023 – Practice meets Campus career fair of the Ernst Abbe University of Applied Sciences Jena, *booth with demonstrator,* Jena
20/11/2023 – Digital summit of the German government, *talk, booth with demonstrator*, Jena
22/11/2023 – Thuringian AI Forum, *booth with demonstrator,* Erfurt
05/12/2023 – Digitalisation in SMEs 2023 Theme Days, Part 4: Sensor technology / smart sensor systems, *3 talks, organisation, moderator, demonstrator,* Ilmenau

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Publications

Reviewed publications

A Modular Platform to Build Task Specific IoT Network Solutions for Agriculture and Forestry, Silvia KRUG[1,2]. Marco GOETZE[1]. Sören SCHNEIDER[1]. Tino HUTSCHENREUTHER[1]. *2023 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), Pisa, Italy, November 06-08, 2023, pp. 820-825,* **DOI: https://doi.org/10.1109/MetroAgriFor58484.2023.10424104.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ehrenbergstraße 27, 98693 Ilmenau, Germany. [2]Mid Sweden University Sundsvall, Sweden.

Plot-specific drought stress simulation in vineyards using a microclimatic monitoring system in combination with a radiation and water balance model, Rikard GRAß[1]. Hannah BOEDEKER[1]. Marco HOFMANN[2]. Martin SCHIECK[3]. Silvia KRUG[4]. Tino HUTSCHENREUTHER[4]. Hannes MOLLENHAUER[1]. *2023 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), Pisa, Italy, November 06-08, 2023, pp. 343-347,* **DOI: https://doi.org/10.1109/MetroAgriFor58484.2023.10424113.**

[1]Department Monitoring and Exploration Technologies, Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany. [2]Department of General and Organic Viticulture, Hochschule Geisenheim University, Geisenheim, Germany. [3]Information Systems Institute, Leipzig University Leipzig, Germany. [4]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Weighted Pruning with Filter Search to Deploy DNN Models on Microcontrollers, Rick PANDEY[1]. Sebastian UZIEL[1]. Tino HUTSCHENREUTHER[1]. Silvia KRUG[1,2]. *2023 IEEE 12th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), Dortmund, Germany, September 07-09, 2023, pp. 1077-1082,* **DOI: https://doi.org/10.1109/IDAACS58523.2023.10348867.**

[1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Mid Sweden University, Sundsvall, Sweden.

Robust Adaptive Tracking Control for Highly Dynamic Nanoprecision Motion Systems, Alex S. HUAMAN[1]. Johann REGER[2]. *in Engineering for a Changing World: Proceedings; 60th ISC, Ilmenau Scientific Colloquium, Technische Universität Ilmenau, September 04-08, 2023, Ilmenau.* **DOI: doi.org/10.22032/dbt.58700.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Control Engineering Group, Technische Universität Ilmenau, 98693 Ilmenau, Germany.

Towards Multi-hop BLE-Based Communication Using a Custom Routing Approach, Florian Jung[1]. Silvia Krug[1]. *Proceedings of the 20th GI/ITG KuVS Fachgespräch Sensornetze (FGSN 2023), Potsdam, Germany, September 04, 2023,* **DOI: https://doi.org/10.26127/BTUOpen-6637.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

A Circuit Designer's Perspective to MOSFET Behaviour: Common Questions and Practical Insights, Ralf Sommer[1,3]. Carsten Thomas Gatermann[2]. Felix Vierling[1]. *Advances in Science, Technology and Engineering Systems Journal, vol. 8, no. 4, pp. 41-59 (2023),* **DOI: dx.doi.org/10.25046/aj080406** [1]Technische Universität Ilmenau, Electrical Engineering and Information Technology, Electronic Circuits and Systems Group, Ilmenau, 98693, Germany. [2]Technische Universität Ilmenau, Electrical Engineering and Information Technology, Power Systems Group, Ilmenau, 98693, Germany. [3]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ehrenbergstraße 27, 98693 Ilmenau, Germany.

Optimizing the IoT Performance: A Case Study on Pruning a Distributed CNN, Eiraj Saqib[1]. Isaac Sánchez Leal[1]. Irida Shallari[1]. Axel Jantsch[2]. Silvia Krug[3,1]. Mattias O'Nils[1]. *2023 IEEE Sensors Applications Symposium (SAS), Ottawa, ON, Canada, July 18-20, 2023, pp. 1-6,* **DOI: doi.org/10.1109/SAS58821.2023.10254054.** [1]Mid Sweden University, Sundsvall, Sweden. [2]TU Wien, Vienna, Austria. [3]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Robust Adaptive Tracking Control of a 3D Vertical Motion System for Nanometer Precision Applications, Alex S. Huaman[1]. Johann Reger[2]. *22nd IFAC World Congress, Yokohama, Japan, July 9-14, 2023, IFAC-PapersOnLine, Volume 56, Issue 2, 2023, Pages 5332-5339, ISSN 2405-8963,* **DOI: doi.org/10.1016/j.ifacol.2023.10.177.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Control Engineering Group, Technische Universität Ilmenau, 98693 Ilmenau, P.O. Box 10-05-65, D-98684, Ilmenau, Germany.

SHUT OFF! – Hybrid BICMOS Logic for Power-Efficient High Speed Circuits, Christoph W. Wagner[1]. Niklas Bräunlich[1]. Kevin E. Drenkhahn[2]. Georg Gläser[3]. *2023 19th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), Funchal, Portugal, July 03-05, 2023, pp. 1-4,* **DOI: doi.org/10.1109/SMACD58065.2023.10192217.** [1]Technische Universität Ilmenau, Institute for Information Technology, Ilmenau, Germany. [2]Fraunhofer IIS, Fraunhofer Institute for Integrated Circuits IIS, Ilmenau, Germany. [3]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Hot Fuzz: Assisting verification by fuzz testing microelectronic hardware, Henning Siemen[1]. Jonas Lienke[1]. Georg Gläser[1]. *2023 19th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), Funchal, Portugal, July 03-05, 2023, pp. 1-4,* **DOI: doi.org/10.1109/SMACD58065.2023.10192176.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Under Cover: On-FPGA Coverage Monitoring by Netlist Instrumentation, Manuel Jirsak[1]. Henning Siemen[1]. Jonas Lienke[1]. Martin Grabmann[1]. Eric Schäfer[1]. Georg Gläser[1]. *2023 19th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), Funchal, Portugal, July 03-05, 2023, pp. 1-4,* **DOI: doi.org/10.1109/SMACD58065.2023.10192205.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

LO and Calibration Signal Distribution in a Multi-Antenna Satellite Navigation Receiver, Uwe Stehr[1]. Syed N. Hasnain[1]. Björn Bieske[2]. Marius Brachvogel[3]. Michael Meurer[3,4]. Matthias A. Hein[1]. *In Proceedings of the European Navigation Conference 2023, Noordwijk, Zuid-Holland, May 31 – June 2, 2023, Eng. Proc. 2023, 54, 23.* **DOI: https://doi.org/10.3390/ENC2023-15447.** [1]Thuringian Center of Innovation in Mobility, RF & Microwave Research Group, Technische Universität Ilmenau, Ilmenau, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ehrenbergstraße 27, 98693 Ilmenau, Germany. [3]Chair of Navigation, RWTH Aachen University, Aachen, Germany. [4]Institute of Communications and Navigation, German Aerospace Center (DLR), Oberpfaffenhofen, Germany.

Tip-based nanofabrication below 40 nm combined with a nanopositioning machine with a movement range of Ø100 mm, Jaqueline Stauffenberg[1]. Michael Reibe[1]. Anja Krötschl[2]. Christoph Reuter[2]. Ingo Ortlepp[1,2]. Denis Dontsov[3]. Steffen Hesse[4]. Ivo W. Rangelow[1,5]. Steffen Strehle[2]. Eberhard Manske[1]. *Micro and Nano Engineering, Volume 19, 2023, 100201, ISSN 2590-0072,* **DOI: doi.org/10.1016/j.mne.2023.100201.** [1]Institute of Process Measurement and Sensor Technology, Production and Precision Measurement Technology Group, Technische Universität Ilmenau, Gustav-Kirchhoff-Straße 1, Ilmenau 98693, Thuringia, Germany. [2]Institute of Micro- and Nanotechnologies, Microsystems Technology Group, Technische Universität Ilmenau, Max-Planck-Ring 12, Ilmenau 98693, Thuringia, Germany. [3]SIOS Meßtechnik GmbH, Am Vogelherd 46, Ilmenau 98693, Thuringia, Germany. [4]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [5]nano analytik GmbH, Ehrenbergstraße 3, Ilmenau 98693, Thuringia, Germany.

Waist Tightening of CNNs: A Case study on Tiny YOLOv3 for Distributed IoT Implementations, Isaac Sánchez Leal[1]. Eiraj Saqib[1]. Irida Shallari[1]. Axel Jantsch[2]. Silvia Krug[1,3]. Mattias O'Nils[1]. *In Proceedings of Cyber-Physical Systems and Internet of Things Week 2023 (CPS-IoT Week ,23). Association for Computing Machinery, New York, NY, USA, May 9-12, 2023, pp. 241–246,* **DOI: https://doi.org/10.1145/3576914.3587518.** [1]Mid Sweden University Sundsvall, Sweden. [2]TU Wien Vienna, Austria. [3]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Towards Deploying DNN Models on Edge for Predictive Maintenance Applications, Rick Pandey[1]. Sebastian Uziel[1]. Tino Hutschenreuther[1]. Silvia Krug[1,2]. *Electronics 2023, 12(3), 639;* **DOI: doi.org/10.3390/electronics12030639.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Department of Computer and Electrical Engineering, Mid Sweden University, Holmgatan 10, 851 70 Sundsvall, Sweden.

Talks and specialist posters

Unconventional, lateral measurements with laser focus sensors for nanopositioning stages, Davi Anders Brasil[1]. Michael Katzschmann[1]. Steffen Hesse[1]. Ludwig Herzog[1]. T. Fröhlich[2]. T. Kissinger[2]. *euspen Special Interest Group Meeting, „Micro/Nano Manufacturing", 28. – 29. November 2023, Ilmenau, Germany.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ehrenbergstraße 27, 98693 Ilmenau, Germany. [2]Institute of Process Measurement and Sensor Technology, Technische Universität Ilmenau, Germany.

Mit smarten Sensorsystemen und KI zu nachhaltigerer Produktion, Wolfram Kattanek[1]. *Digital-Gipfel 2023, 20. November 2023, Jena.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ehrenbergstraße 27, 98693 Ilmenau, Germany.

KODIAK: Components and modules for improved optical diagnostics, Michael Scholles[1]. Nicole Isserstedt-John[2]. Dirk Kuhlmeier[3]. Martin Jahn[4]. Martin Reuter[5]. Benjamin Saft[6]. Eric Schäfer[6]. Mirjam Skadell[7]. Alexander Zimmer[7]. Ana Leonor H. Lopes[3]. *MikroSystemTechnik Kongress 2023, 23.-25. Oktober 2023, Dresden.* [1]Fraunhofer-Institut Für Photonische Mikrosysteme IPMS & Fraunhofer IPMS, Germany. [2]Microfluidic ChipShop, Germany. [3]Fraunhofer Institute for Cell Therapy and Immunology, Germany. [4]CIS Forschungsinstitut für Mikrosensorik, Germany. [5]LUCAS Instruments GmbH, Germany. [6]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ehrenbergstraße 27, 98693 Ilmenau, Germany. [7]X-FAB Global Services GmbH, Germany.

Edge KI Systeme für die vorausschauende Instandhaltung, Sebastian Uziel[1]. *elmug4future, Technologiekonferenz, 17.-18. Oktober 2023, Friedrichroda, Thüringen.*

[1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, Ehrenbergstraße 27, 98693 Ilmenau, Germany.

Artificially Intelligent EDA, Georg Gläser[1]. *CiS-Workshop „Simulation und Design", 26. September 2023, Erfurt, Germany.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

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Abbreviations

ADC *Analogue-digital converter*
AI *Artificial intelligence*
AHB *Advanced high-performance bus*
ALU *Arithmetic-logical unit*
AMS *Analogue-mixed-signal*
API *Application programming interface*
ASIC *Application-specific integrated circuit*
ATE *Automatic test equipment*

CLIA *Chemiluminescence immunoassay*
CMOS *Complementary metal–oxide semiconductor*
CNP *Charge neutrality point*
CRS *cytokine release syndrome*
CSA *Channel switch announcement*

DCR *Darc cout rate*
DUT *Device under test*

EDA *Electronic design automation*

FPGA *Field programmable gate array*

GFET *Graphene field-effect transistors*
GPIO *General purpose input/output*

HMI *Human-machine interface*

I^2C *Inter-integrated circuit*
IB *Instrumental bias*
IC *Integrated circuit*
IoT *Internet of Things*
ISFET *Ion-sensitive field-effect transistor*

LDO *Low-drop voltage regulator*
LDS *Local discovery server*
LFS *Laser focus sensor*
LFA *Lateral flow assay*
LoRaWAN *Low-power wide-range radio technology*

MOSFET *metal-oxide-semiconductor field-effect transistor*

OPC UA *Open plattform communications unified architecture*

PCB *Printed circuit board*
PCIe *Peripheral component interconnect express*
PCR *Polymerase chain reaction*
PMT *Photomultiplier tube*

QSPI *Quad SPI*

RISC-V *Instruction set architecture based on reduced instruction set computer principles*
RT-LAMP *Reverse transcription loop-mediated isothermal amplification*
RFID *Radio-frequency identification*

SME *small and medium-sized enterprise*
SPAD *Single-photon avalanche diode*
SPI *Serial peripheral interface*

UART *Universal asynchronous receiver transmitter*
ULP *Ultra low power*

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