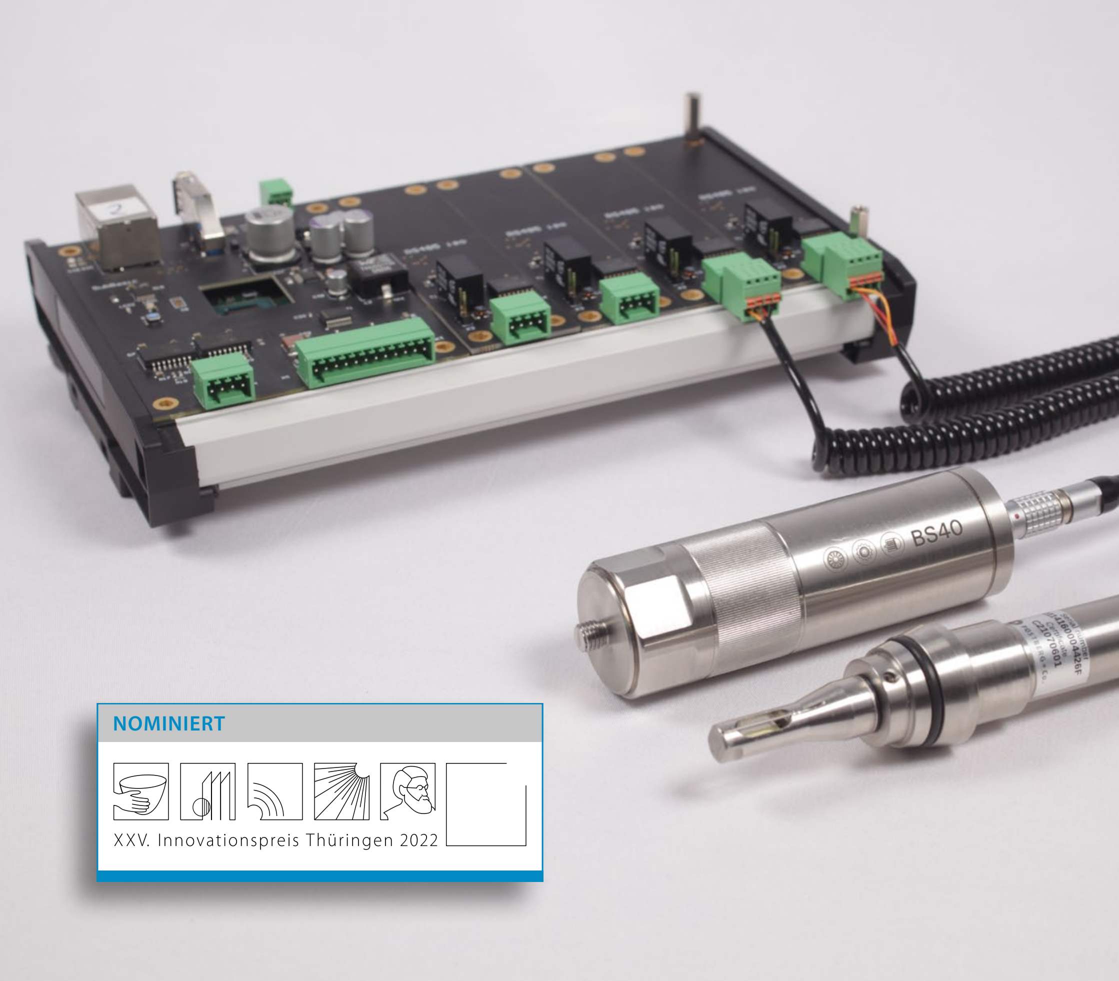


IMMS

ANNUAL REPORT

2022

Contents

Cover photo: The scalable ultrasound and volume flow sensor platform for optimising energy efficiency in industry “sUSe” was nominated in the category “Industry and Material” for the 25th Innovation Award Thüringen.

www.imms.de/annualreports

Ralf Sommer and Martin Eberhardt. Photograph: IMMS.

Dear readers,

In 2022, our activities as innovative researchers were recognised: the “sUSe” sensor platform for optimising energy efficiency in industry received a nomination for the **Thüringen 2022 Innovation Award**. The system is being prepared for market launch with the development partner SONOTEC. This is, among many others, a relevant example of how results from research become innovation for companies and help to support the competitiveness of our partners. We also received an **iENA bronze medal** for a patent on a microelectromechanical acceleration sensor, and together with the Physikalisch-Technische Bundesanstalt a further one for a **patent** on a new sealing arrangement for more precise displacement measurement in high-tech applications.

The last two solutions were developed in our **mechatronics department**. Since the end of 2022, **Ludwig Herzog** has been heading this division. Together with his team, he will continue to advance the **research field** of **magnetic 6D direct drives with nanometre precision** towards sub-nanometre accuracy. Results on a new generation of lifting and actuating units for vertical nanopositioning with up to 25 mm travel range for industrial applications can be found in this report.

In the **integrated sensor systems research field**, important milestones were reached in 2022 for AI-based design and test automation, which will make the design and testing of complex microelectronics chips safer and faster. In three technical articles on more efficient simulations, automated verification and a hardware testbench for chip design, the results are presented in this report.

In the research field of **intelligent measurement and test systems**, we have developed solutions for application developments in industry and health, among others. Three technical articles deal with a mobile multi-sensor testing device for the maintenance of rolling bearings, sensor technology for the online monitoring of membrane reactors for dialysis processes and in-vitro protein synthesis of large sample volumes, as well as a measuring system for single-photon counting and picosecond measurements for research on quantum technology.

The strategic orientation in our research fields, lead applications and target markets as well as services has been visible since 2022 through the **relaunch** of our **website**. This was conceived and realised by the **corporate communications** team, which was restructured at the beginning of 2022. Since then, **Beate Hövelmans** has been heading the team. In addition to the website, the focus here was on the launch of videos for the promotion of young scientists. In the videos, testimonials illustrate how we prepare students for their careers in research and development, from the basics to starting a job, and thus strengthen the region.

All this and more would not have been possible without funding and support and, above all, without our dedicated staff.

Many **thanks** to all those who support us and help us to launch innovations. You will find examples of this in the report.

We wish you much pleasure reading it.

Ralf Sommer
Scientific Managing Director

Martin Eberhardt
Financial Managing Director

www.imms.de/annualreports

New head of Mechatronics

Dr.-Ing. Ludwig Herzog, Head of Mechatronics. Photograph: IMMS.

Dr.-Ing. Ludwig Herzog became head of the mechatronics department at IMMS on 1 December. He had previously led the development at PREMETEC Automation GmbH. The internationally active company for automation and precision measurement technology from Suhl, Germany, had collaborated with IMMS in the past on nano-positioning and nano-measuring machines. Ludwig Herzog had already completed his studies in automotive engineering in Ilmenau, including a doctorate, and now returned to further advance the research and development for magnetic 6D direct drives with nanometre precision and application-specific mechatronic systems for research partners and industrial customers together with the interdisciplinary team.

Head of Corporate Communications

Dipl.-Des. Dipl.-Hdl. Beate Hövelmans, Head of Corporate Communications. Photograph: Rolf Peukert, IMMS.

Beate Hövelmans has been heading the restructured corporate communications team at IMMS since the beginning of 2022. Prior to that, she was responsible for the institute's press and public relations and initiated and expanded topics such as social media, video and cross-media communication. She studied economics and visual communication at the Friedrich Schiller University in Jena and the Bauhaus University in Weimar. Before her time at IMMS, she worked on technology topics in internal communications at Bosch, created image films, corporate designs and websites in a company she founded, and was responsible for public relations and investor relations at the semiconductor manufacturer X-FAB. In her new function, she will further expand the communicative support of the IMMS strategy.

www.imms.de/contact

Relaunch of the website

https://www.youtube.com/watch?v=jo5YHIC66M4

In May 2022, the new IMMS website went online with a new structure, new design and new content: **www.imms.de**. The visual concept relies on images for navigation and recognition as well as illustration. The responsive design allows rendering from desktop monitors to smartphones. New content on research fields with core topics, lead applications and target markets make the central elements of the strategy clear and show how IMMS connects science and industry. The content is underpinned by further information on new and restructured projects, publications, references and press releases. The career pages, including more searchable study-related offers, as well as the services, have been updated. In addition, there are new pages, e.g. on equipment, organisation, figures, regulations and a media library.

www.imms.de

The content is modular and interlinked. It can thus be explored hierarchically not only from the homepage, but also via a direct entry via a detail page on a specific topic, for example via an external link from e.g. **LinkedIn** to a specific project or via QR code or a short URL on a printed flyer, which in the case of **www.imms.de/trf** leads to the detail page on a chip for mobile diagnostic systems for the early detection of diseases using time-resolved fluorescence measurements. Depending on the needs and interests of the target group, the topics can be accessed via a short, easy-to-understand teaser text, a subject-oriented overview or further pages, links and downloads of specialist publications or explanatory videos. The concept forms the basis for cross-media communication for heterogeneous target groups and occasions. It supports the communication of more general topics to subject-specific results and details at project level. The varying degrees of detail and different technical levels aim to pick up as many stakeholders as possible.

www.imms.de/trf

www.imms.de/videos

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 2022, 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*: Sensor technology for SmartCity 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 SmartCity, healthcare and medical technology as well as production and quality assurance. IMMS and Ilmenau TU will implement a "LivingLab" in Ilmenau for the SmartCity topic together with the city. The core of this is data that is needed for a wide variety of AI-based services in the SmartCity 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.

Growth Core HIPS* – High-performance sensor systems for harsh environments

In the HIPS growth core, IMMS and Ilmenau TU, as well as 5 other research institutions and 12 industrial companies from Thüringen, are working to build a technology platform around the SiCer technology researched by Ilmenau TU and Fraunhofer IKTS. It combines silicon technology (Si) with ceramic multilayer technology (Cer) and enables novel, robust, highly integrated SiCer high-performance sensors for liquid and gas sensor technology. IMMS is working on novel functional structures of sensory and actuator micromechanical elements and developing miniaturised evaluation circuits for the SiCer sensors.

IMMS as "Smart Sensor Systems Model Factory" in the „SME Digital Centre 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.

InSignA* high-performance centre

The goal of the "InSignA" high-performance centre in Ilmenau is to enable accelerated technology transfer. With this, regional value-added networks in the future-oriented transfer areas of signal analysis and assistance systems in production, energy supply, and robotics are to be developed and established.

www.imms.de/nanofab

www.imms.de/hips

www.imms.de/md

This is intended to strengthen and further develop the local and regional economy and make it more resilient. For this purpose, the core competencies of the Fraunhofer institutes in and around Ilmenau, the research profile of Ilmenau TU and the competencies of other research institutions are bundled. As an affiliated institute and transfer partner of Ilmenau TU, IMMS was initially involved in the InSignA pilot project on behalf of the latter and is now a partner in the high-performance centre 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

Prof. Dr.-Ing. habil. Dr. h.c. Dagmar Schipanski. Photograph: private source.

OBITUARY

We bid farewell to
Prof. Dr.-Ing. habil. Dr. h.c. Dagmar Schipanski

(*3 September 1943, † 7 September 2022)

She has always been a supporter of IMMS and has accompanied the institute with a lot of initiative from its foundation until today. She was driven by the desire to make a difference. She was always on fire to do something new. She strictly pursued her goals and was successful in bringing people together, promoting creativity, ideas and their implementation.

We will keep her warm and open nature in good memory. We extend our heartfelt condolences to her family.

On behalf of all employees of IMMS

Univ.-Prof. Dr.-Ing. Ralf Sommer, Scientific Managing Director
Dipl.-Kfm. Martin Eberhardt, Financial Managing Director
Dipl.-Ing. Robert Fetter, Chairman of the Supervisory Board

VOICES
FROM INDUSTRY AND ACADEMIA

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

The SPAD-EvalKit developed in the Quantum-Hub Thüringen project 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. Read more in the technical article. 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.

Freistaat Thüringen
Hier hat Zukunft Tradition.

Dipl. Ing. (DH) Andy Carius, CTO, Indu-Sol GmbH. Photograph: Indu-Sol GmbH.

Andy Carius, Indu-Sol

“For industrial communications and automation networks, we at Indu-Sol offer planning, network components, optimisation, service and support to control individual machines and systems or to connect complex process flows in production and manufacturing. We thus contribute to industrial communications that enable smooth and cost-efficient processes. With our innovative range of solutions for industrial networks, we support our customers in mastering the digitalisation of their process level.

This was also the focus of the BeSen research project. It consists of hardware that records sensor data independently of applications and without any pre-configuration and settings and stores it for further processing, and software that is able to recognise patterns, determine a normal state and report deviations from it. IMMS has specifically contributed to classifying the recorded data and identifying anomalies from it.

www.imms.de/embedded

Here, it was important to do particularly intensive research on the classification of the data and functions derived from it, which is why we turned to IMMS for this task. The joint work was characterised by many ideas and a great deal of commitment by IMMS. We will gladly turn to IMMS again in future projects, especially in the area of data evaluation and classification, as we very much appreciate this type of cooperation.“

www.imms.de/ref

Indu Industrial Solutions Sol
WIR LEBEN NETZWERK

www.indu-sol.com

Prof. Ronny Stolz, Head of the Quantum Systems Department at Leibniz-IPHT, Professor for Quantum Engineering at Ilmenau TU. Photograph: ©Leibniz-IPHT.

Dr. Theo Scholtes, Head of the Quantum Magnetometry Research Group, Leibniz-IPHT. Photograph: ©Leibniz-IPHT.

Prof. Ronny Stolz and Dr. Theo Scholtes,
Leibniz-Institut für Photonische Technologien e.V. (Leibniz-IPHT)

“The quantum magnetometry team at Leibniz-IPHT researches and develops ultra-sensitive magnetic field sensors using quantum effects in atomic vapours measured by laser spectroscopy. To transfer these methods from the laboratory to relevant application scenarios such as geophysics or biomedicine, we realise compact, energy-saving and self-sufficient sensor systems. For the selection of a new type of sensor for high-resolution measurement of the earth’s magnetic field, we did not have the expertise to implement application-specific digital sensor electronics based on an integrated FPGA data acquisition board.

www.imms.de/test

In contact with IMMS, their extensive expertise in the field of hardware-related programming became clear and so IMMS appeared to be the ideal partner for us. IMMS implemented the functionalities we needed, such as a lock-in amplifier, a phase-locked feedback loop and an active laser frequency stabilisation as an FPGA design. The communication of specifications and work progress went smoothly, as did the regular mutual coordination of the work. The documentation of the implementation was also done professionally and we are very pleased with the results: The demonstrator is already showing its superiority in the laboratory compared to commercially-available sensor systems and will soon be evaluated in application. We would very much like to continue the cooperation with IMMS in future joint projects.“

www.imms.de/ref

www.leibniz-ipht.de

ENCOURAGEMENT OF YOUNG ACADEMICS

All information on our study-related offers:

www.imms.de/students

https://www.youtube.com/playlist?list=PLalndDF5VubGgU0X4tEzRFTEeCE8muRjW

In a video, students give an overview of their work at IMMS

We are so proud of our students! They not only work on challenging topics for our research and development. Some of them have taken the time to present themselves with their work in a video because they think they can share something of their practical experience at IMMS with others, which will be helpful during their studies and especially afterwards. A first overview was given in a summary that went online at the end of 2022. More about the individual people and topics is to follow in further videos. We would like to thank Vincent, Marie, Nikita, Laetitia, Markus, Lena and Ilmurat and their supervisors at IMMS!

The videos refer to the career pages under **www.imms.de/jobs** and to study-related topics which have been restructured with the relaunch of the website:

www.imms.de/students

- AI implementation
- Design of control / regulation algorithms
- Design of mechatronic systems
- Hardware design of integrated circuits
- Hardware design of printed circuit boards
- Hardware programming
- Simulation
- Software development
- Test / characterisation of electronic systems
- Test / characterisation of electronic systems

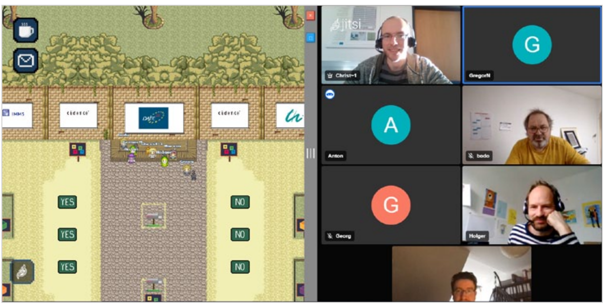
ErstiWoche (Freshers' Week) at Ilmenau TU in October 2022: During the city rally, points could be earned at IMMS for solving puzzles on the topic of artificial intelligence. Photograph: IMMS.

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.

www.imms.de/students

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



The BarCamp organising team gathered at IMMS Erfurt in March 2022 to discuss new ideas for electronic design automation online with the EDA community.

Image source: https://community.cadence.com/cadence_blogs_8/b/can/posts/barcamp-at-date-2022

Rick Pandey, M.Sc., scientist at IMMS

„In the captivating realm of Embedded AI, IMMS extends an inspiring and versatile working atmosphere that fuels my creativity and passion. Collaborating with diverse partners from both scientific and industrial domains consistently exposes me to fresh challenges, stimulating my ingenuity to overcome them. Armed with cutting-edge technology and a team boasting a diverse range of competences, I find myself continually evolving professionally, while thoroughly enjoying the stimulating tasks at hand.

Within the sphere of Embedded AI, my primary focus revolves around the optimisation of big models and their seamless integration into smart sensing and online learning systems. In this dynamic realm, I embrace the challenge of refining and fine-tuning these complex models to ensure optimal performance within resource-constrained embedded environments.

www.imms.de/embeddedai

By harnessing the power of embedded AI, we pave the way for intelligent, self-learning devices that elevate the user experience and enhance overall system performance. Within the fascinating world of smart sensing, my role is to prepare the AI models to seamlessly interact with data streams from a myriad of sources. This involves fine-tuning the models to recognise patterns, detect anomalies, and make

www.imms.de/immsvoices

Rick Pandey, M.Sc., scientist in the System Design department at IMMS.

Photograph: IMMS.

Rick Pandey with an AI-based embedded system for machine diagnosis. Edge AI systems like these are being researched in terms of their energy efficiency and overall system energy modelling in the HoLoDEC* project.

Photograph: IMMS.

intelligent decisions in real-time. By integrating cutting-edge algorithms and leveraging the latest advancements in AI research, we empower our embedded systems to glean valuable insights from their surroundings, making them truly intelligent and responsive.

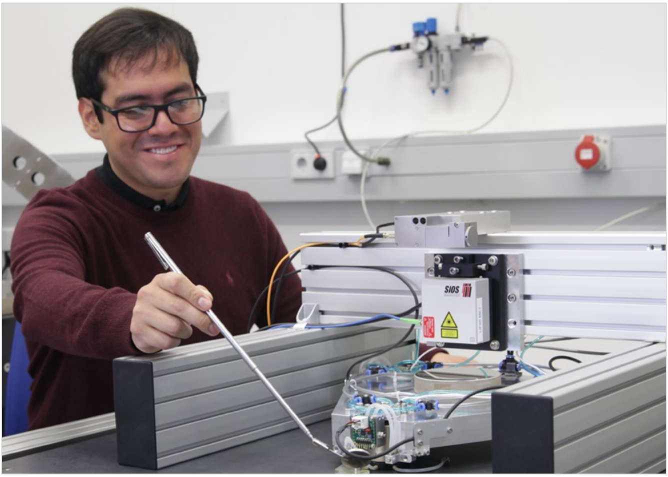
www.imms.de/embeddedai

As part of the vibrant IMMS team, I am continually inspired by the synergy of brilliant minds and diverse expertise. Collaborating with fellow experts we collectively push the boundaries of what's achievable, propelling our projects to new heights. My academic knowledge serves as a foundation, but I'm continuously exploring new concepts and groundbreaking methods to engineer even more refined solutions. The ever-evolving landscape of Embedded AI ensures that each day brings fresh, exciting challenges, making the journey remarkably rewarding and never monotonous.“

Alex S. Huaman, M.Sc., doctoral candidate at IMMS

“Upon joining IMMS, I became part of a multidisciplinary working team with cutting-edge technological equipment. Since I was an undergraduate student, I have been motivated to be part of developing high-impact technologies. This led me to pursue graduate studies in electronics engineering and postgraduate studies in control engineering. However, it was not until I joined IMMS that I had my first hands-on experience with the design and development of high-level technologies and the opportunity to work as part of a multidisciplinary team where different engineering fields converge to meet the firm's objectives.

www.imms.de/immsvoices



Alex S. Huaman, PhD student at IMMS, on a setup for research into nanometre-precise drives in the doctoral programme NanoFab.

Photograph: IMMS.

As a control systems engineer, I am very interested in designing and implementing control algorithms for mechatronic systems. In this context, IMMS offers me the opportunity to analyse and work with complex dynamic systems, as well as to design, implement, and evaluate the performance of control loops for multi-axis motion systems with nanometre precision capabilities. In the mechatronics department, I have also learned about areas unrelated to my research field, such as aided design, measurement systems, mechanical and mechatronics principles, and all working in synergy. This leads to a dynamic working environment where I have to apply, expand, and deepen my competencies to face new challenges.

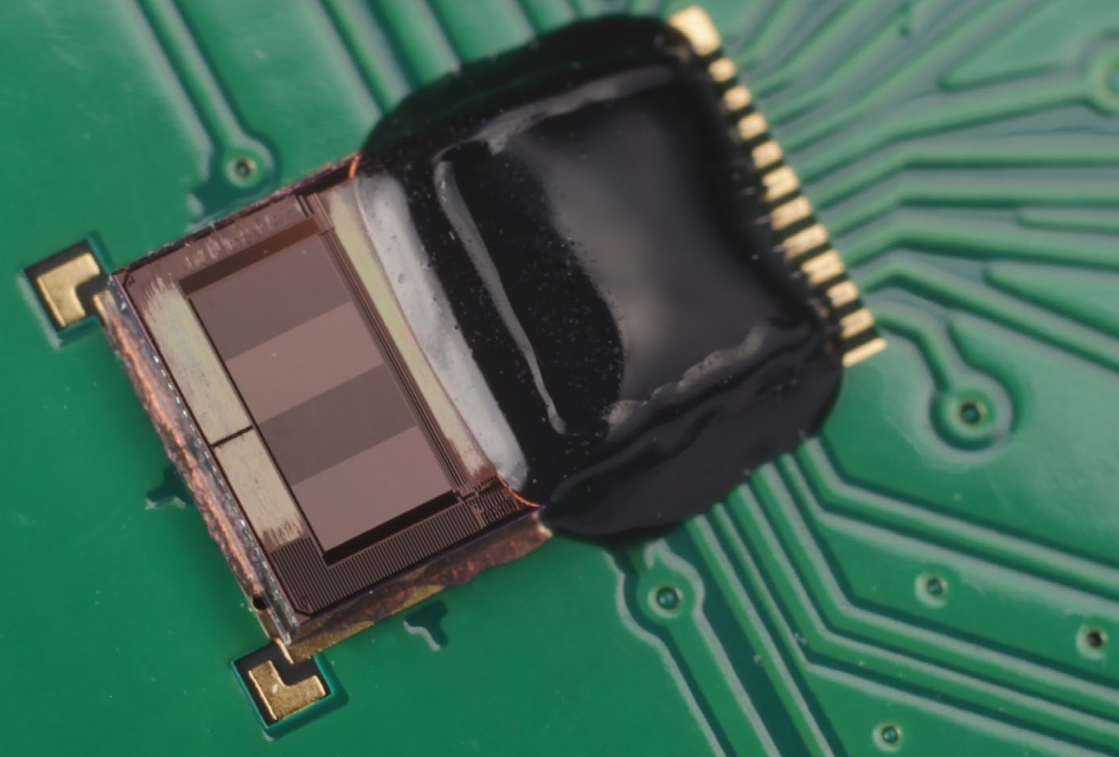
What was my first contact with IMMS? After finishing my master's studies, I could intern as a research assistant for three months, where I found a friendly working atmosphere. Within a few months, the Ilmenau TU started the doctoral programme RTG NanoFab (2nd Generation) in cooperation with IMMS, offering me the opportunity to complement my scientific career with experimental validation using the modern laboratories and infrastructure of IMMS. My main activity consists of finishing my doctoral thesis, where the subject is the design of advanced control strategies for highly dynamic multi-axis nanopositioning systems. The aim is to contribute to improving the precision of these machines and to investigate new possibilities in the field of nanoscale manufacturing. Last but not least, here I am part of a team that works like a family group, where everyone shares a sense of belonging, helps each other when needed, and learns from each other."

www.imms.de/nanofab

www.imms.de/immsvoices

RESEARCH FIELD

INTEGRATED SENSOR SYSTEMS



In 2022, IMMS presented details and functional principles of the institute's chip platform in the video "CMOS image sensor platform for time-resolved fluorescence measurement with europium". The quantitative readout of test strips demonstrates its broad applicability in in-vitro diagnostics.

For chip developments like this, IMMS is researching how to make design and testing more reliable and cost-effective with AI. AI can support developers in the design process to avoid errors and apply informal knowledge in an automated way. New methods are presented in the technical articles.

EFRE
EUROPE FOR THURINGIA
EUROPEAN REGIONAL DEVELOPMENT FUND
EUROPEAN UNION

The project on which these results are based was supported by the German Land of Thüringen and co-financed by European Union funds within the framework of the European Regional Development Fund (ERDF) under the reference 2017 FE 9044.

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 analog 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

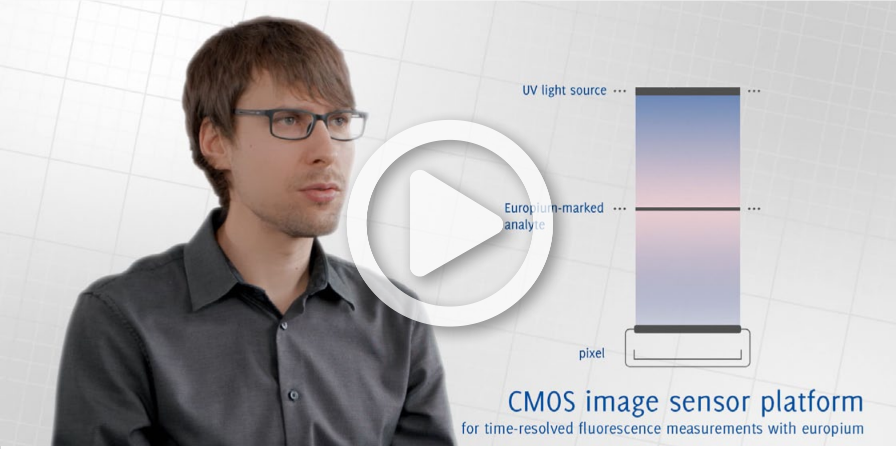
www.imms.de/aidesigntest

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



https://www.youtube.com/watch?v=pEXdMNZZkPA

Highlight 2022 in our research on integrated sensor systems

Video: CMOS image sensor platform for time-resolved fluorescence measurements with europium

IMMS presents the details and the operating principle of a chip platform developed at the institute in the video "CMOS image sensor platform for time-resolved fluorescence measurements with europium". The aim is to use it to open up further applications in in-vitro diagnostics in future research and development projects beyond the exemplarily demonstrated quantitative reading of test strips.

www.imms.de/ivd

Example application quantitative readout of test strips

In in-vitro diagnostics, the labeling of target analytes with fluorescent dyes is becoming increasingly common, as they can be easily distinguished from background and interfering signals. IMMS has developed a lock-in imager chip for time-resolved fluorescence imaging with europium and integrated it into an example application for digital readout of test strips.

Those tests, also called lateral flow assays (LFA), play an important role in in-vitro diagnostics. They are cost-effective, easy to handle and therefore perfectly suited for decentralised and time-critical diagnostics. They are widely used as pregnancy or COVID-19 rapid tests, among others, to make qualitative conclusions (positive or negative). However, quantitative information on concentrations and ratios are

www.imms.de/asic

needed for many diagnostic questions. Common LFA reader combinations with classical dye particles such as gold are not sensitive enough for this purpose. New LFA reader combinations with europium markers offer much higher readout sensitivities, which are supported by our imager. Thanks to its lock-in principle, elaborate optical filters can be omitted.

Operating principle of the CMOS image sensor platform for time-resolved fluorescence measurement with europium

Classic fluorescence measurement

The core of the platform is a five-transistor lock-in pixel, which IMMS has optimised for fluorescent substances that have a particularly long afterglow, such as the widely used europium-based dyes.

Classical fluorescence detection works with optical filters. Here, a UV light source illuminates an analyte that is marked with a fluorescent dye. In this case, this is europium which is excited by the UV radiation and produces a red fluorescent light. An optical filter then separates this light from the UV light and allows only the fluorescent light to reach the detector.

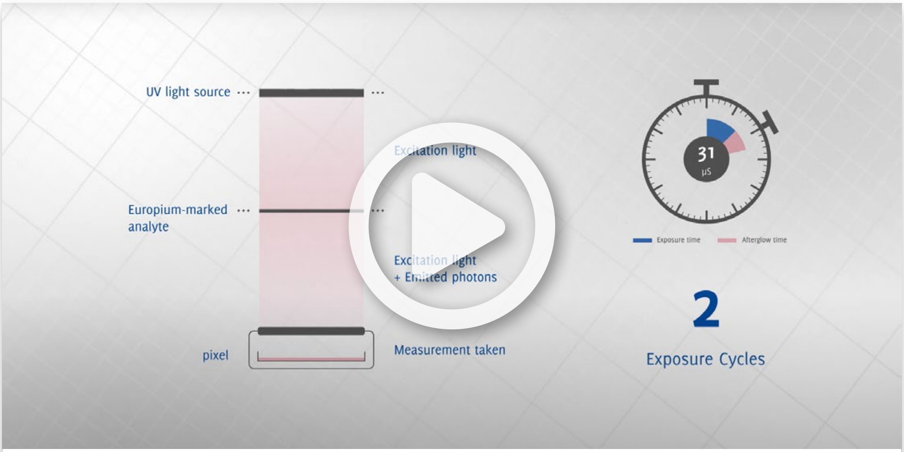
Time-resolved fluorescence detection

"Time-resolved fluorescence detection with lock-in pixels, as we have implemented it, does not require optical filters" explains Eric Schäfer, Head of Microelectronics at IMMS." Distinction between excitation and fluorescence light based on their colours is no longer possible – and we don't need it, because we use the different decay times of the light source and the fluorescent dye after switching off the light source." While the excitation light decays within a few nanoseconds, the europium continues to glow for several 100 microseconds.

www.imms.de/trf

Lock-in-pixel principle

During excitation the pixel is deactivated, i.e. the charge carriers are dissipated. Afterwards, the pixel is activated and the charge carriers generated by the fluorescent light are collected in the pixel. Since the fluorescent light can be very little, it is useful to repeat this process and operate the pixel in the so-called lock-in mode. For this, the light source is pulsed and synchronously the pixel is always activated when the light fades away. This means that the fluorescence signal is being collected over several cycles and thus amplified. At the same time, the noise is reduced.



https://www.youtube.com/watch?v=pEXdMNZZkPA

“We can adjust the number of cycles to the different light conditions: If we have a lot of fluorescent light, because we have a lot of analytes, for example, we can run fewer cycles. If we have relatively little, we can run more cycles” says Eric Schäfer. “This results in a very high dynamic range.” After the analyte has been excited several times and enough charge carriers have been collected, the sensor element is being read out and reset for the next measurement.

Imager platform for a wide range of applications in in-vitro diagnostics

“Since we have developed the sensor element as a pixel, we can use it to build entire image sensors, for example for optical imaging systems or for contact imaging” Eric Schäfer summarises.

The imager platform thus provides the basis for opening up a wide range of applications in in-vitro diagnostics. IMMS aims to use the platform to develop further application-specific time-resolved image sensors and the associated hardware and software modules.

www.imms.de/trf

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AI-based model error estimation makes simulations more efficient

AI supports microchip design

At IMMS, artificial neural networks are used to estimate model errors of behavioural models, which is essential for the simulation of integrated circuits. For system-level simulations, the approach provides reliable information about the validity of the model. Photograph: IMMS.

Motivation and overview

When designing microelectronic circuits, simulations are an essential tool for the developer, for instance, to examine the circuit design's functionality during the initial stages. However, modern circuits' complexity demands significant computational power to perform physically accurate simulations at the level of individual transistors. As a result, simplified models are frequently used, which only describe the principle behaviour of the circuit and are much easier to calculate. The drawback of these simplifications is that model errors can arise in specific situations and may result in misleading simulation outcomes.

IMMS has developed an AI-driven method within the context of the KI-EDA project. It estimates the model error of a behavioural model during simulation which may be used to employ more precise and computationally expensive simulation techniques when essential. Thus, the computational advantage in simulating behavioural models can be exploited while keeping the model error to a minimum.

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In contrast to soldering together individual components to assemble a circuit, the development of integrated circuits has a major drawback: once manufactured, there is virtually no way to modify the circuit and correct errors. While individual components on a printed circuit board can at least still be replaced with some effort, integrated circuits are manufactured monolithically on wafers in very expensive processes.

Without the possibility of a "try and error" approach, the design of integrated circuits has similarities to the construction of a bridge. Here, civil engineers must employ simulations to demonstrate safety and stability before building the structure. Similarly, it is crucial to assess the functionality of integrated circuits by employing hardware simulations before their manufacturing process.

Hardware simulations have been an essential aspect of Electronic Design Automation (EDA) since the 1970s and 1980s and have been continually evolving since then. In particular, various methods are used for simulating circuits. The classic method of using physically derived models for each transistor can almost be considered the gold standard of the industry. The results usually align well with the measured values of the actual circuit.

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However, this approach has a drawback: It is very computationally expensive to solve the model equations numerically at the transistor level. Modern processors have several billion transistors, making it virtually impossible to run such simulations for the entire chip. But even the smaller application-specific integrated circuits (ASICs) built into cars, refrigerators, or sensors are complex enough that transistor-level simulations take several hours or even days. At the same time, many simulations are needed in the design process to test the circuit's operation under many conditions and with different inputs.

Simplification through abstraction

To solve this problem, a different approach to circuit simulation is used: The behaviour is considered only in the abstract. Simplifications can be made in the above example of simulating the structural stability of a bridge. The influence of the wind on the bridge is important, but in order to check its basic load-bearing capacity, complex flow models can be omitted for the time being. This simplifies the calculations and speeds up the design process.

In EDA, simulations of abstract circuit behaviour are essential. The computing time saved is frequently reinvested in the design process to simulate more tests, following the important motto “test early, test often”. However, the level of abstraction comes at a price: simple models of the bridge can provide solid data. But ignoring the wind completely can lead to something like the spectacular collapse of the Tacoma-Narrows Bridge in Washington State in 1940.

Knowing the model error as important information

Therefore, when simulating integrated circuits, it is essential to use behavioural models. However, one must always keep an eye on model errors and know that the model may fail under certain conditions. But how do you keep track of model errors without constantly resorting to computationally expensive transistor-level simulations?

In the KI-EDA project, IMMS has developed a method to estimate this model error during simulation. A neural network was trained to estimate the model error of a behavioral model of a circuit depending on the inputs and outputs of the model. Knowing the model error, simple behavioural models can be used whenever conditions allow and the model error is small. More sophisticated transistor-level simulations are only used when really necessary. Alternatively, the information can be used to estimate the robustness of the simulation result. This can be used, for example, in very long simulations to abort the simulation when the model error exceeds a limit. This saves unnecessary computation time for erroneous data.

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In practice, integrated circuits are divided into blocks, each of which performs a specific function. These modules, called intellectual property (IP) blocks, can be simulated individually or together as a complete chip. The basic idea of error estimation is to provide a pre-trained neural network in a separate block to an IP block for simulation. This does not affect the circuit in any way, but can read inputs and outputs of the IP block and use them as its own inputs for the error estimation. The advantage of this approach is that the error can be estimated online during the simulation, rather than having to be calculated afterwards. All common hardware simulators are able to compute these neural networks, as long as they are available in an appropriate programming language.

The method involves three steps: A) data generation, B) training, and C) setup and actual simulation. These steps are explained below using a comparator as a simple example circuit. This comparator has two main inputs and compares the voltages applied to them. Depending on which voltage is greater, the comparator switches its single output to high or low. In addition, this comparator has connections for a reset signal and the supply voltage, for a total of 5 inputs and outputs.

Data generation

A multilayer perceptron (MLP) was chosen as the learning element. This is a special type of artificial neural network that converts an input vector into an output vector and can have any number of neurons in intermediate layers. During training, the weights of the neuronal inputs and outputs of the intermediate layers are changed in a way that specific input values of the perceptron are associated with output values. Thus, this is a type of regression.

To train the MLP, both simulation data of the behavioural model of a circuit and data of a transistor-level simulation are required. If the input data for the two simulations are matched, the difference between the simulation results can be used as a measure of the model error. As in regression, the trained MLP is able to interpolate intermediate values with sufficient accuracy. Extrapolation, i.e. estimation outside the learned range of values, must be treated with caution. Therefore, it is recommended to integrate as many and different system states of the circuit as possible into the training data. For instance, in the comparator example, it is recommended not only to apply different voltages to the main inputs, but also to vary the supply voltage and trigger the comparator reset. This allows the MLP to learn the behaviour of the circuit even in unusual situations, which is particularly useful for estimating model errors. The data set should represent the possible input space sufficiently, but does not have to cover it completely.

Training

The MLP is trained using the simulation data. This is conveniently done in a general-purpose programming language such as Python. On the one hand, hardware description languages and simulators are able to compute neural networks. However, they lack functions for iterative training. On the other hand, general-purpose programming languages provide easy-to-use tools and extensions, such as scikit-learn, that are optimised for training MLPs. However, the MLP programmed and trained in Python has to be translated into a hardware description language so that it can be integrated into a circuit. For this purpose, a tool such as Mako can be used, which can generate programme code from templates and appropriate parameters. The trained MLP is now available as a fixed block and can be integrated into a circuit and simulated. The MLP is re-trained for each circuit and cannot be combined with unfamiliar IP blocks.

Setup and simulation

The neural network is integrated into the circuit in such a way that it can read the inputs and outputs of the IP block, but does not affect the behaviour of the circuit. Thus, the MLP trained on our example comparator uses the signals of the two main inputs of the comparator, its supply voltage and reset signal, and its output as its own inputs. From these, it estimates the model error, which is not fed back into the circuit (Fig. 1). With this setup, regular tests can now be performed according to the planned development process of the integrated circuit.

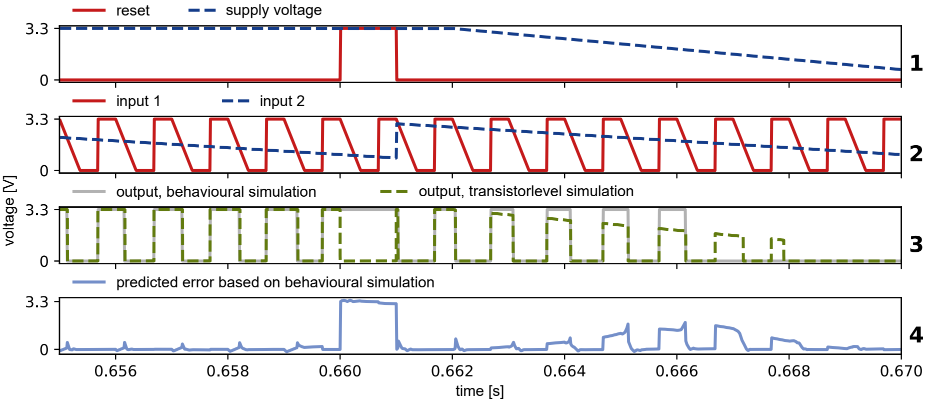

Figure 1: Example of a comparator: The device processes 4 inputs (Graph 1+2). The output was calculated once with a behavioural simulation and once with a transistor-level simulation (Graph 3). The behavioural simulation was used to estimate the behavioural model error (Graph 4). Model errors occur in this example because the behavioural model only considers the supply voltage in binary (on/off) and has a different behaviour during reset. Source: IMMS.

Model error as a measurement

The estimated model error can be used in several ways. First, it can be used as a proxy for a confidence interval of the output values of the simulated IP block. Second, it can be used as a termination criterion for the simulation. If the model error reaches pre-defined critical values, the simulation can be stopped and restarted with changed parameters. This is particularly useful for longer simulations where it would otherwise take several hours or days to obtain a result and analyse the behavioural model failure of the circuit.

To increase the effectiveness of hardware simulation, the model error can be used as a metric to dynamically apply different models to the simulation. In this case, the simulation is started with the behavioural model that is to be computed quickly. If the error of this model reaches a critical limit, the simulation is stopped and automatically restarted with the intermediate values at that point. The new simulation can be adjusted according to the model error. For example, the step size of the simulator's solvers can be changed to achieve higher accuracy, or the block can be simulated at the transistor level.

Cost-benefit analysis of AI-based error estimation

The neural networks used are very small compared to other AI methods. The error estimator of the comparator used in the example has a total of 45 neurons in two layers, no comparison to the 80-100 billion neurons of ChatGPT. Therefore, the computational cost of computing the error estimator in addition to the behavioural model is manageable. In the non-optimised comparator example, the additional computational cost of the error estimator compared to the behavioural model is 75%. However, this is offset by an additional 350% computational cost for the transistor-level simulation. Therefore, the error estimator is not free, but the behavioural model including the error estimator can still be computed significantly faster than the transistor-level simulation.

Why only estimate the error but not the whole behaviour of the circuit?

Since this method is suitable for estimating the error and thus the behaviour of the circuit, the question naturally arises as to why the neural network cannot immediately replace the entire behavioural model of the circuit in the simulation. This is due to a fundamental problem of neural networks: Traceability. In simulations, they behave like a black box, so causal relationships between input and output are difficult for humans to understand. In the bridge example used earlier, a neural network could be used to simulate the statics of the bridge. However, if the bridge collapses in the simulation, it becomes difficult to determine the exact cause and subsequently derive improvements to the design.

In addition, the comprehensibility of the behavioural models also builds trust. Unlike trained neural networks, classical equations are easier to document, understand, and communicate. Therefore, especially in certification procedures, it is advantageous to base the simulation data on conventional behavioural models and estimate only the model error by a neural model.

The described method is able to deal with dynamic systems by considering not only current inputs and outputs, but also a time window when training the model error. However, there are special circuits that are not compatible with this method: If the behaviour of the circuit depends not only on the time history of its inputs, but also on variable intrinsic states, the MLP cannot estimate the model error correctly.

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In addition, our method currently requires a separate MLP for each output of the IP block. However, this is due to the fact that the scikit-learn tool used only supports MLPs with one output. This can be solved by choosing other networks or training tools.

Since the newly developed method has proven its general suitability, it will now be tested at IMMS in the field of ASIC design in an industrial environment in order to gain further experience with it and to develop it further.

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More detail:

H. Siemen, M. Grabmann and G. Gläser, „Learn from error! ML-based model error estimation for design verification without false-positives," 2022 18th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), Villasimius, Italy, 2022, pp. 1-4, doi: 10.1109/SMACD55068.2022.9816317.

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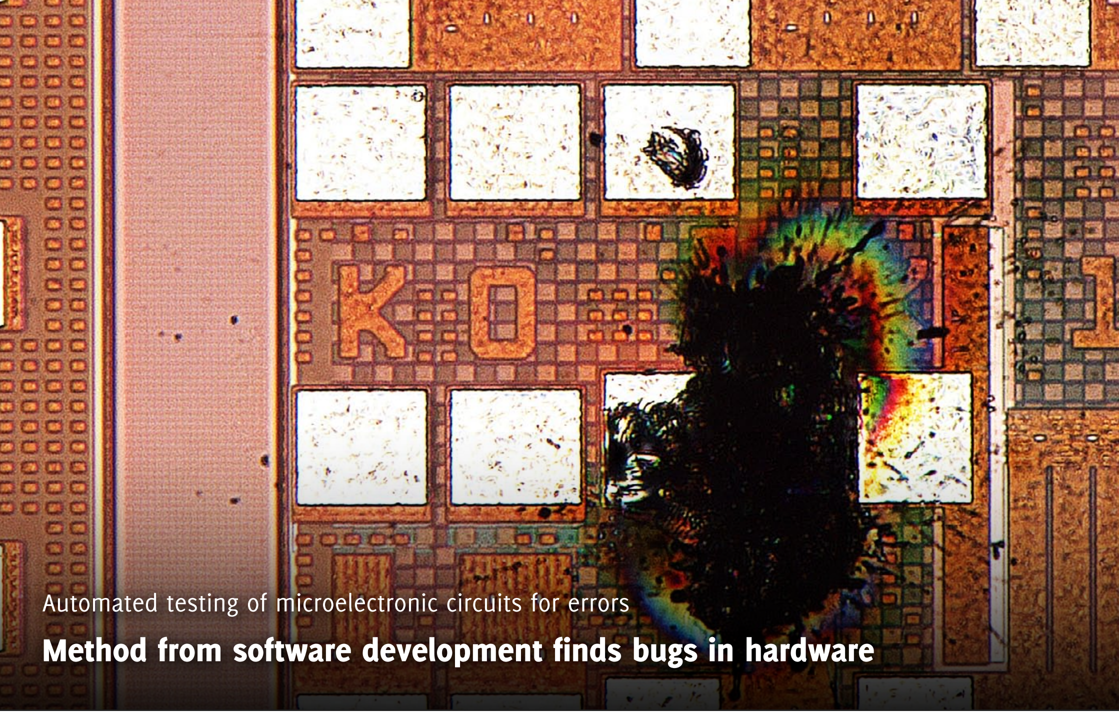

Automated testing of microelectronic circuits for errors

Method from software development finds bugs in hardware

If errors are made in the design of microelectronic chips and not detected in time, the consequences can be catastrophic, for example in network technology, automotive electronics, avionics or pacemakers. The image shows an example of destroyed wafer-level components. Source: IMMS.

Motivation and overview

Verification of integrated circuits is an essential part of the design process and presents unique challenges. The ever-increasing complexity of integrated circuits is being achieved by increasing automation on the design side, and verification must keep pace. Despite partially automated methods such as constrained random testing, an experienced verification engineer is needed to develop targeted test scenarios and verify system states.

In the area of software, so-called “fuzz testing” has become established, which floods the software to be tested with randomly generated inputs and can thus uncover errors in the functioning of the programmes. Inspired by this verification method, IMMS has developed a method in the KI-EDA project that can automatically test microelectronic circuits for bugs and vulnerabilities. For this purpose, the circuit is confronted with randomly generated inputs that are varied step by step by genetic algorithms in order to provoke faulty and unsafe system behaviour. The random nature of the generated inputs makes this type of search particularly suitable for finding faults that

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are not found by typical human-generated test scenarios. The method can be used to augment established verification techniques and assist verification engineers with autonomous fault finding.

Background and challenges

Increasing complexity of integrated circuits

Since the first integrated circuit about 65 years ago, microchips have been a driving force behind technological development. While Jack Kilby's first chip in 1958 consisted of a single flip-flop, modern processors contain billions of components. The complexity of these digital circuits has replaced "rocket science" as the epitome of sophisticated engineering that is hard to keep track of.

In the beginning, circuits were designed by hand, but today engineers rely on specialised electronic design automation (EDA) software. Even the "little brother" of the complex high-performance processor, the application-specific integrated circuit (ASIC), contains logic blocks that are getting bigger and bigger, giving us the functions we are familiar with today: WiFi, Bluetooth, high data throughput. This "higher, faster, further" of chip development is made possible on the design side by the high degree of automation without which successful and, above all, safe chip development is no longer conceivable.

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Verification of complex integrated circuits has so far been largely experience-based and manual

Again, safety is the key word. While EDA is advancing design automation with amazing methods, complex and difficult-to-verify circuits remain a major challenge for quality control and management. Verification engineers must not only ensure that the circuit can perform its intended function. They must also ensure that unforeseen conditions do not occur during operation and that design errors are avoided. If the camera in the smart refrigerator fails because of a system failure, it can be annoying. But with network technology, digital steering controls in cars, or pacemakers, system failures can be catastrophic.

However, verification has become a bottleneck in the ASIC design process because it has been difficult to automate the human experience and intuition required for efficient debugging. To solve this problem, and to support verification by at least partially automating debugging, it is worth looking beyond one's own nose - to so-called fuzzing, which has been successfully used in the field of software verification for years.

Drawing inspiration from software development

Basic principle of software-fuzzers – random inputs find random bugs

For software, the basic principle of fuzzing is quite simple and sounds banal at first: the application under test is bombarded with random inputs, without any detailed knowledge of the correct syntax or structure, in order to crash it. It is then possible to analyse how the inputs caused the error and how this can be avoided in the future. This approach is already used effectively to find security vulnerabilities in software. One of the most widely used software fuzzers is American Fuzzy Lop (AFL), which already has an impressive trophy collection: In addition to finding bugs in web browsers like Mozilla Firefox or Internet Explorer, it also finds hits in programmes like Adobe Reader and MySQL, as well as operating systems like Linux or iOS.

The great advantage of fuzzers is their high degree of automation. Once started, fuzzers run without further intervention until they find something or the search is aborted. For larger projects, such as the Linux kernel, multiple fuzzers are sent out on a parallel search over several days or weeks.

The idea of using this approach to verify electronic circuits is obvious. However, several approaches to integrate fuzzers into hardware verification have emerged only recently, e.g., [1].

Pure randomness does not work – the Infinite Monkey Theorem

In fact, fuzzing is not that simple. Rather, the idea that if you randomise the inputs to a system long enough, something meaningful will come out is reminiscent of the famous Infinite Monkey Theorem. It was originally stated by the French mathematician Émile Borel in 1913. He claimed that if a million trained monkeys each sat at a typewriter for 10 hours a day and typed randomly, they would produce the equivalent of the entire world's literature within a year. While the probability of this event occurring is not zero, it can be shown to be so small as to have no practical relevance. For fuzzing, this means that it is too unlikely that a random sequence of bits corresponds to, say, a corrupt JPEG file that causes an error in the software under test.

Building upon close misses – game principle of "Battleship" helps to find the bullseye

To solve this problem, most fuzzers like AFL use an approach called coverage-guided fuzzing. The underlying assumption is that a random input must also cause a response in the programme under test in order to provoke an error. Typically, software applications do not respond to input noise, but require certain file formats or communication protocols to start execution. If the programmes are not executed, they will not be able to exhibit the erroneous behaviour that is being sought. Programme coverage provides information about which parts of a programme were actually executed. Noise on the inputs of a software application is very likely to result in low coverage, while the input of, for example, a file with the correct file format will cover the execution of the corresponding function in the programme.

The information about the achieved programme coverage triggered by an input is used by fuzzers to avoid inputs that cannot cause an error. The problem can be illustrated by the game "Battleship". On an unknown and invisible playing field, a ship is hidden over several squares, and the player's task is to find and sink it. When the player announces the coordinates of a square, the opponent tells him whether he has hit it or not. The player now tries to hit the ship once by randomly calling out the coordinates, and upon a hit he tries to search the neighbouring squares and sink the ship by hitting the rest of the corresponding squares. If coverage-guided fuzzers happen to find an input that leads to a slightly larger programme coverage than simple noise, they try to search the "neighbouring" space by slightly modifying or mutating the original input.

Since each programme input is given a value for programme coverage, these values can be viewed as a landscape on a hyperplane in the space spanned by the inputs.

However, unlike common optimisation algorithms, the fuzzer here does not try to find local maxima, but rather searches for the peaks while avoiding the flat planes. Due to the similarity of the problem, "coverage-guided mutation-based" fuzzers, such as the AFL mentioned above, use algorithms from the fields of optimisation and genetics to search the input space and generate new inputs through mutations.

Fuzz-testing and chip design

Challenge: known approaches to transfer software fuzzers unsuitable for mixed-signal circuits

If fuzzing can be used effectively to debug complex software, why wouldn't it work for hardware development? Unlike software development, chips cannot be tested directly during design because they often do not yet exist as physical circuits. Therefore, they have to be emulated with programmable logic devices (FPGA) or simulated on the computer with appropriate software. This not only requires a lot of computing power. A hardware fuzzer also has to combine a variety of simulation software, data formats, and mathematical algorithms in a single workflow.

To address these challenges, several proposals have recently been published:

- Use software fuzzers and adapt them to hardware simulation software. This has the advantage of using already established and efficient fuzzers [1].
- Use of optimised simulation software for hardware or FPGA prototypes. This can speed up or even bypass the simulations, significantly speeding up fuzzing [2].

Unfortunately, both of these approaches have drawbacks that particularly affect the design of ASICs. Their function is often based on the interaction of analogue and digital circuit elements, which must be considered together. While optimised hardware simulators and FPGA prototypes can only simulate or emulate purely digital circuits, mixed-signal simulations are much more complex and cannot be directly replaced by FPGA prototypes.

In addition, adapting software fuzzers for hardware verification is very costly and inflexible. Furthermore, the approach published so far is limited to pure digital circuits.

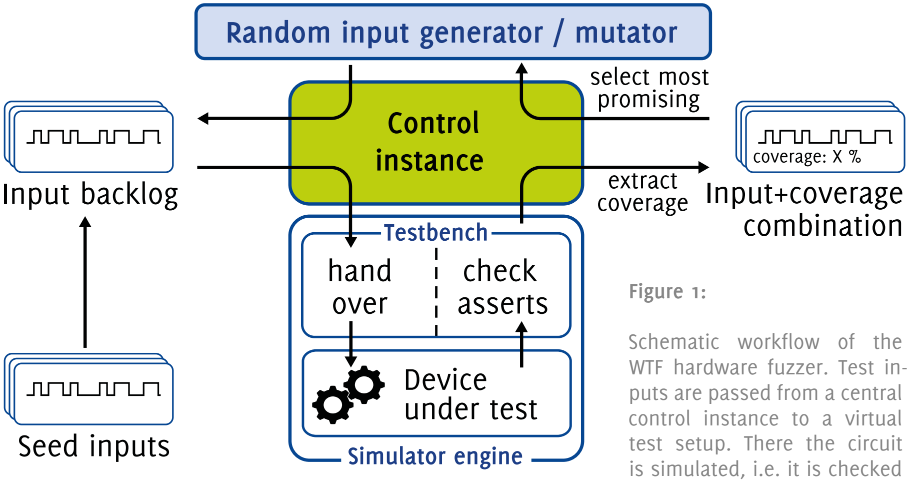

Figure 1:

Schematic workflow of the WTF hardware fuzzer. Test inputs are passed from a central control instance to a virtual test setup. There the circuit is simulated, i.e. it is checked whether the inputs can put the circuit into an undesired state. For each input, it is determined which parts of the circuit were active. With this information, new test cases are generated by mutating and selecting previous inputs. As a result, the fuzzer only generates test cases that actually trigger activity in the circuit. Source: IMMS.

„What the Fuzz“ (WTF) – the hardware fuzzer of IMMS for the development of mixed-signal chips

In the KI-EDA project, IMMS has developed a hardware fuzzer which, although it does not use proven software fuzzers, has a very modular design and is also suitable for the mixed-signal properties of ASICs (Fig. 1).

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The fuzzer consists of several interchangeable modules, which are coordinated by a central instance and cover all steps of the fuzzer:

- Input management
- Simulator
- Coverage readout
- Mutator and optimisation strategy

Like all fuzzers, WTF works iteratively. At the beginning, you have to define the unwanted error states of the circuit you want the fuzzer to search for. This can be, for example, the requirement that the circuit must not be in read and write mode at the same time.

A hardware simulation analyses the behaviour of the circuit for a particular input, checks for fault conditions, and then determines which parts of the circuit were ac-

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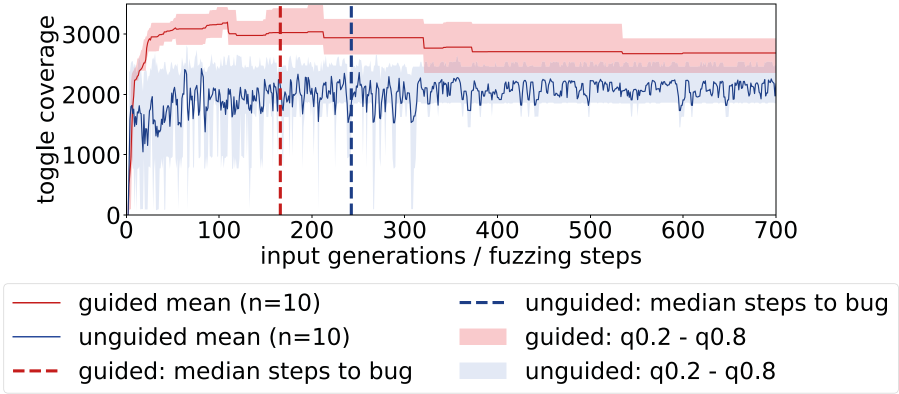

Figure 2: In this example, the fuzzer is presented with a sample circuit with an intentional fault built in to measure how quickly the fuzzer can find the fault. The data contains 10 runs of the fuzzer, each run automatically generating hundreds of test cases. Compared to unguided fuzzing (blue) with purely randomly generated test inputs, the guided fuzzer (red) finds the hidden defect much faster on average (dashed lines). It does not generate completely new inputs but mutates and selects previous ones. This allows it to generate evolutionary test cases that activate larger parts of the circuit (higher coverage), increasing the chance of finding the bug in each case. Source: IMMS.

tive during that input. This is the coverage achieved by that input. According to an optimisation strategy, a mutation is selected and a new input is generated. This new input is passed to a hardware simulation of the circuit, which checks for errors and determines the coverage achieved. To generate the next input, the two coverages achieved so far are compared. If the coverage was reduced by the last mutation, it is rejected and a new input is generated based on the original input. If the coverage was increased by the last mutation, the new input is mutated to generate the next generation of the input.

Whether mutations are accepted or not is decided by the optimisation strategy and can be stochastic, e.g. in a heuristic approximation method like simulated annealing. Typical genetic methods are used as mutations, which are easy to illustrate, especially for digital inputs. For example, input 1011 can be modified by replacing a single bit (e.g., 0011), or a position can be truncated (101), appended (10110), or inserted (10101).

Currently, WTF supports Cadence Xcelium and Icarus Verilog simulation software. However, due to the modular design of the fuzzer, the feature set can easily be extended. In particular, new optimisation strategies can be integrated.

The WTF hardware fuzzer is still in the development and testing phase, but has already proven its functionality on sample circuits [3]. The advantage of "coverage-guided fuzzing" over "unguided fuzzing", where the test inputs for the circuit under test are generated completely randomly, is well demonstrated (Fig. 2). In an experiment, WTF was tested on a sample circuit in which a defect was intentionally introduced at IMMS. Thanks to the feedback of the coverage achieved by the test inputs, WTF can efficiently generate test cases with higher coverage and thus find the fault hidden in the circuit faster.

Now that the fuzzer has demonstrated the general applicability of the fuzzing concept in the field of hardware verification, it is tested with industrial chips developed at IMMS. Approaches published by other research groups will now also be tested in practice. Since "coverage-guided fuzzing" has successfully established itself as a verification method in the software domain, it will be exciting to see whether it will also succeed in the hardware domain.

Contact person: Henning Siemen, M.Sc., henning.siemen@imms.de

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RESEARCH FIELD

SMART DISTRIBUTED MEASUREMENT AND TEST SYSTEMS

NOMINIERT

XXV. Innovationspreis Thüringen 2022

The scalable ultrasound and volume flow sensor platform for optimising energy efficiency in industry “sUSe” was nominated in the category “Industry and Material” for the 25th Innovation Award Thüringen. The sUSe project was funded by the Federal Ministry for Economic Affairs and Energy under the reference ZF4085709P08 on the basis of a resolution of the German Bundestag.

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

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.

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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 in order 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 in order 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) in order 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 2022 in our research on smart distributed measurement and test systems

IMMS nominated for the 25th Innovation Award Thüringen 2022: scalable ultrasound and volume flow sensor platform for optimising energy efficiency in industry

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On 30 November 2022 in Weimar, IMMS has been nominated in the category "Industry and Material" for the scalable ultrasonic and volume flow sensor platform "sUSe" for the Innovation Award "XXV. Innovationspreis Thüringen 2022". The platform is intended for the optimisation of energy efficiency in industry. The system will be prepared for market launch with the development partner SONOTEC GmbH from 2023.

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25th Innovation Award Thüringen 2022, 31 November 2022 in Weimar. Photograph: STIFT.

Dr.-Ing. Tino Hutschenreuther, Jonathan Josue Gamez Rodriguez and Sebastian Uziel (f.l.t.r.) with the "sUSe" sensor platform nominated for the XXV. Innovationspreis Thüringen 2022. Photograph: STIFT/GMM AG. **https://www.youtube.com/watch?v=B7tZ0f84J48**

Platform helps save energy for compressed air in industry

"Even before the energy crisis, industry was combating leaks in compressed air lines, as they cause the most energy losses and thus also unnecessary costs. In view of the current price development, it is even more important for companies to find such leaks, evaluate losses and initiate maintenance measures," explains Dr. Tino Hutschenreuther, Head of System Design at IMMS.

Up to 10% of electrical energy is used in a wide variety of industries to generate compressed air alone, for example to drive machines and cylinders, transport materials or small parts, cool molded or cast parts, flush gas tanks or operate exhaust, ventilation and drying systems. On average, 30% of this compressed air is lost due to leakage.

To significantly reduce such losses, IMMS has developed the sUSe electronics platform for an automatable solution for the sensors of the cooperation partners SONOTEC GmbH and Postberg+Co. GmbH. The sUSe system consisting of platform and sensors can be retrofitted in industrial compressed air systems to permanently monitor them, improve energy efficiency and save CO_2 emissions.

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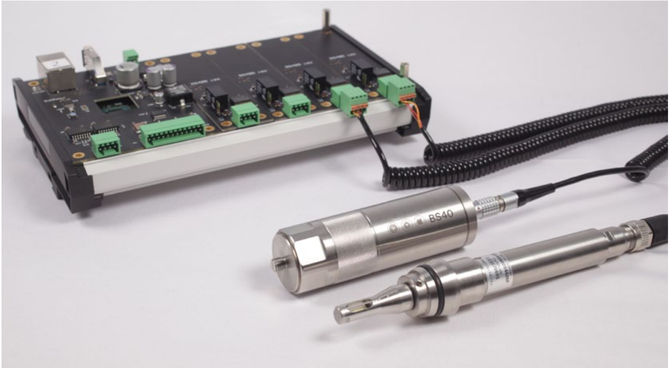
For the first time worldwide, the system combines hybrid sensor technology and data fusion in one device which allows for a holistic and continuous monitoring

Until now, leaks in compressed air systems have been measured, analysed, located and documented in reports by service technicians, usually commissioned externally,



The sUSe hardware platform for compressed air monitoring with ultrasonic sensor from SONOTEC (left) and volume flow sensor from Postberg (right).

Photograph: IMMS.

using individual sensors or various devices. Continuous monitoring usually does not take place and the data can neither be networked nor connected to ERP systems.

The sUSe platform developed at IMMS forms the basis of a worldwide novel, holistic monitoring system for compressed air systems. It consists of the platform and several ultrasonic and volume flow sensors that are distributed over a compressed air system, networked and permanently installed.

On the one hand, volume flow sensors from the partner Postberg measure the amount of compressed air flowing through at various points in the system. This is related to the quantity fed into the compressed air system. On the other hand, ultrasonic sensors from SONOTEC GmbH, which are also integrated in the system, acoustically locate leaks and evaluate their loss.

www.imms.de/distributed

With the sUSe platform, all data from a wide variety of sensors are merged and digitally processed. This data fusion enables a comprehensive evaluation, because now leakage points and total volume flow are considered together. As a result, the share of losses in the total consumption of compressed air can be precisely allocated. “With this completely new concept of evaluating compressed air losses holistically, companies can focus on the major leaks with the help of sound data,” Hutschenreuther continues. “After all, about 70 percent of compressed air losses can be attributed on average to about 10 percent of leaks, which you can now target and eliminate first with maintenance measures.”

Electronics platform, AI-based signal processing, communications solution, performance features

Since compressed air is supplied in varying quantities at changing points for many applications, such as for various actions of an industrial robot, the sUSe platform and all associated sensors must operate synchronously in terms of time. Therefore, IMMS has taken a modular approach to the design of the hardware components. The sensors acquire data simultaneously via a synchronisation mechanism to ensure the real-time capability of the system. The algorithms implemented by IMMS are used to evaluate the different channels within the system and provide an assessment. AI accelerators can be retrofitted via an expansion slot to significantly increase processing power.

This edge AI platform for decentralised data processing is used for each measuring point of the monitoring system. To be able to adapt the system very flexibly for different applications without having to make changes to the hardware, IMMS developed the signal processing components using a model-based design technology and configured the application algorithms for FPGA integration on this basis. Suitable communications interfaces and protocols were implemented for integration into maintenance systems and the corresponding communications capability of the platform was established.

In detail, the platform offers a completely digital data structure, sampling rates up to 400 kHz for synchronous and phase-accurate sampling for analogue and digital sensors, broadband measurements, exchangeable algorithms, scalable computing power, sensor data fusion, calibration function, cloud integration and networking via various techniques and protocols, and connectivity to ERP systems.

Market launch in 2023 and potential for further applications

"In view of the current dynamics on the subject of energy saving, the market launch planned for 2023 comes at the right time," says Michael Münch, Managing Director of SONOTEC GmbH. Beyond the monitoring of compressed air systems, he also sees versatile application potential in predictive maintenance, process monitoring and quality assurance. He adds that the modular platform architecture has been developed in such a way that very specific market requests can be effectively handled with different sensor combinations. "We assume that completely new market segments can be opened up with the technology," Münch concludes.

› *Integrated sensor systems*
› *Distributed measurement + test systems*
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Installation work at the end of June 2022 for the prototypical sensor nodes in Ilmenau for automatic lamp monitoring with radio communications as the first SmartCity test setup by IMMS in the thurAI project. Photograph: IMMS.

Streetlamps in Ilmenau on air with radio-based monitoring system: first SmartCity test setup developed by IMMS installed in the thurAI* project

www.imms.de/thurAI

IMMS has developed a first prototype of a retrofittable sensor system for automatic lamp monitoring with radio communications. At the end of June, the devices were installed on three streetlamps each with a different light source in the city on behalf of the city of Ilmenau.

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So far sporadic reports or expensive solutions

“At the moment, the city of Ilmenau mostly learns through reports of citizens when lamps flicker or are broken. In many cases, the failure of the corresponding lamps then lies some time back,” explains Dr. Silvia Krug from IMMS. Lars Strelow, the head of Ilmenau’s sports and operations department, also refers in this context to the defect report form on the city of Ilmenau’s website. However, one problem that has not been solved yet is the timely and automatic detection of defective and flickering streetlamps in the entire city area and the surrounding villages to enable quick reactions. Therefore, the city of Ilmenau is striving for an automated solution in the future that reports affected lamps directly in a timely way. “Existing solutions of the lamp manufacturers are very cost-intensive, as one would have to replace the lamps for it. Instead, the existing streetlamps should be equipped with an additional low-cost monitoring system,” Krug continues.

Sensor node prototype installed in Ilmenau for automatic lamp monitoring with radio communications as the first SmartCity test setup by IMMS in the thurAI project.

Photograph: IMMS.

Prototype of a retrofittable sensor system for lamp monitoring

IMMS, based in Ilmenau, has developed the first prototypes of a retrofittable sensor system for such lamp monitoring to address this problem in the thurAI project. The recently installed test system consists of two light sensors per lamp, which periodically monitor the function of the lamp itself and can also measure the lighting conditions of the surrounding environment. “This information is collected by a microcontroller on a local device, the sensor node. It is then processed and sent via radio to an existing so-called gateway, i.e. to a receiver,” explains Krug, who heads the thurAI project at IMMS. “We employ the modern transmission method LoRaWAN (Long Range Wide Area Network) as radio technology because it can be used independently from mobile network operators and still offers comparatively large ranges for communications.”

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AI to further improve the detection of defective lamps

The LoRa gateway is connected to the Internet via mobile communications and transparently forwards the sensor data it receives to a server. “The server processes the data and also provides initial diagrams of it. With this real data, we want to keep improving the existing algorithms that detect broken lamps,” Krug continues. The goal is to provide the operating status of all monitored lamps. If all the information is then displayed on a website, for example, it can also be made available to the public.

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About the thurAI project

In thurAI, the partners Technische Universität Ilmenau, Friedrich Schiller University Jena and IMMS are working on solutions in the three areas of SmartCity, healthcare and medical technology as well as production and quality assurance. IMMS and the Ilmenau TU are implementing a "LivingLab" in Ilmenau together with the city for the SmartCity topic. The focus here is data which is required for a wide variety of AI-based services in the SmartCity context.

ProQuaOpt* – productivity and quality optimisation for plastic injection molding processes with AI methods

There is hardly any time for process optimisation during traditional manual machines set-up

Injection molding is the most widespread process to produce plastic parts for practically all application areas. In this situation, high throughput and good quality parts are important for a manufacturer to survive on the market. For this purpose, machines are usually set up by skilled personnel to produce good parts at the beginning of a batch.

IMMS is developing an AI-based control system for resource-efficient online optimisation of injection moulding, the most widespread process for manufacturing plastic parts for practically all areas of application. Photograph: IMMS.

www.imms.de/proquaopt

To date, this happens once at the start of a batch and the machine then runs with constant parameters. However, if the ambient conditions change (e.g. the air temperature due to open gates), currently no reaction is possible and the risk of faulty parts increases. In addition, the settings are chosen based on experience. Whether these correspond to the optimum operating point in terms of resource consumption with good product quality is unclear.

The goal is to optimise the injection molding process through AI

In the ProQuaOpt project, we aim to apply AI methods for automated productivity and quality optimisation of the injection molding process. To achieve this, we plan to develop a product-process quality control loop that will consist of a subsystem to interact with the injection molding machine, a measuring element for quality inspection and an AI-based controller.

In addition to responding to changing environmental conditions, the control loop also enables continuous optimisation of the process in terms of resource efficiency. When necessary, the controller provides small adjustments to keep the process at the optimum operating point. Internal feedback is given to the controller via the quality inspection module. The adjustments will mimic steps that an expert would also perform.

IMMS develops AI-based control system

In the ProQuaOpt project, IMMS will combine its expertise in signal acquisition and processing for AI applications as well as the development of AI-based predictive models. We will develop a process-optimising control system for both inline and autonomous operation.

Depending on the input parameters, the control system will optimally adjust the settings of the injection molding machine without affecting quality of the produced parts. The system can also respond to external disturbances. This makes the injection molding process more efficient and results in less defective parts.

www.imms.de/embeddedai

www.imms.de/proquaopt

For processes, services and machinery that can be automated, IMMS is researching in HoLoDEC, among other things, energy-efficient edge AI systems with overall system energy modelling to be able, for example, to retrofit existing systems with wireless sensors for condition monitoring or level detection. Photograph: IMMS.

Start of HoLoDEC*: ultra-low-power architectures (ULP) and circuit concepts as well as energy-efficient edge-AI systems with overall system energy modeling

www.imms.de/holodec

Digitalisation and artificial intelligence enable many new applications by increasingly automating processes, services, and facilities. The key to this is the 'Internet of Things' (IoT) with a rapidly growing volume of data provided by a rising number of connected devices and sensors. This hardware is expected to operate more and more efficiently in terms of resources and energy while also responding quickly, especially in safety-critical applications. At the same time, it should be trustworthy from data acquisition to analysis. This is to be achieved by limiting the data traffic itself and processing data more and more near the point of origin through edge computing and thus less in the cloud.

For this purpose, IMMS is researching two issues in the HoLoDEC project: on the one hand, ultra-low-power architectures (ULP) and their efficient and automated design, and on the other hand, on edge AI systems that will enable energy-optimised power distribution between sensor and edge computing. Approaches from both focal points will be validated in two demonstrators, one for condition monitoring and one for an RFID sensor transponder IC with a ULP sensor frontend.

www.imms.de/ulp

www.imms.de/embeddedai

For design houses and chip developers, it is becoming increasingly challenging to develop optimal or energy-optimised integrated circuits and systems as these are becoming more complex and human resources are becoming scarcer. Therefore, IMMS is researching in close collaboration with Reutlingen University and Fraunhofer IIS/EAS to accelerate the development of analogue or mixed analogue/digital circuit blocks through generator-based, i.e., programmed processes.

As part of this, models should also be automatically generated to, for instance, consider non-functional properties such as energy consumption early in the system design. Both are necessary because with the currently common methods, the energy requirements of a system are only known towards the end of the design process and are therefore difficult to consider in the architectural design. At the system level, the lever for optimisations is the most significant. However, it can rarely be utilised since extensive changes in microarchitecture or topology would be required, sometimes in multiple iterations, and these, like the entire design of analogue components, would still have to be done manually.

IMMS is researching to reduce design times and uncertainties through automated designs and models. The goal is to accelerate the design process so that it can be iterated multiple times to optimise the energy consumption of a system early in the process.

With this new approach for automated design, IMMS will investigate and design particularly energy-efficient circuit concepts and validate them with a demonstrator for an RFID sensor transponder IC with a ULP sensor frontend. These results will be compared with manually designed chips. The demonstrator addresses a solution that enables the realisation of integrated sensor systems with very low energy budgets, ideally allowing for passive operation without batteries, and can be manufactured using cost-effective semiconductor technology.

www.imms.de/rfid

www.imms.de/ulp

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Energy-efficient edge AI systems with overall system energy modeling

To make optimal use of AI algorithms on resource-constrained devices for IoT applications, IMMS is researching energy-efficient edge AI systems with energy-optimised power distribution between as much close-to-sensor data processing as possible and minimal offloading of tasks to the wireless network in the HoLoDEC project.

IMMS takes the lead in cross-system optimisation of energy consumption in distributed sensor systems. The foci include hardware and software design, energetic modeling of embedded systems, concepts and procedures for sensor and overall system energy management, investigation and implementation of algorithms for anomaly detection on ultra-low-power components, as well as algorithms for automatic data extraction and reduction in terms of information content and energy consumption impact within the sensor. The algorithms will provide compressed sensor data, which will then be transmitted to the edge-AI platform. To combine data from different sensors, algorithms for data fusion are being explored and implemented. Additionally, IMMS is developing energy consumption models for individual sensor systems and the overall system.

To utilise AI algorithms as close to the sensors as possible without the need for extensive data transport to a cloud, IMMS is conducting research on optimisations of edge AI system architectures based on defined requirements. The background is that models and algorithms are no longer limited to running on powerful servers with ample storage space but are intended to be used on microcontrollers for which they were neither originally developed nor directly transferable, thus requiring adaptation. Current research often focuses on developing high-performance models on a server. The goal is to build upon initial investigations into optimisation for microcontrollers and energy-saving potential and to make AI algorithms accessible for resource-constrained devices. These approaches are being validated in a demonstrator for condition monitoring.

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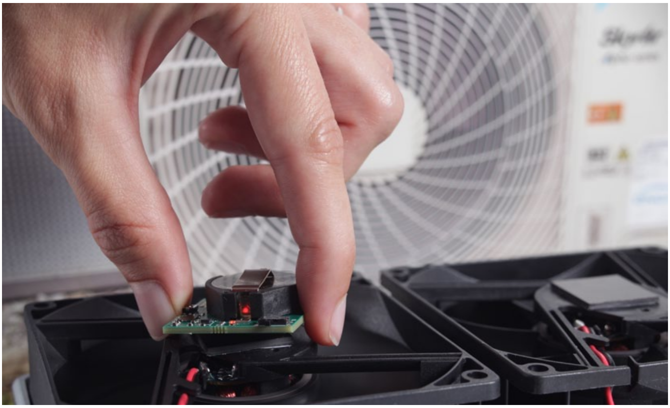


The retrofittable AI-based sensor for fan monitoring is a small sensor system that detects, classifies and visualises defects on fan blades or bearings. The sensor signal evaluation is made with an AI-based data processing implemented on a microcontroller.

Photograph: IMMS.

IMMS activities in the "SME Digital Centre Ilmenau"

Events and information for SMEs

www.imms.de/md

In 2022, IMMS alias "Smart Sensor Systems Model Factory" in the "SME Digital Centre Ilmenau" offered 10 lectures, 15 online seminars, 14 regulars' tables, and 5 specialist workshops as well as 49 informative talks and workshops on digitisation to support small and medium-sized enterprises in the introduction of digitisation and AI solutions. In addition, the model factories were present at 36 regional events of sector networks, at regional trade fairs, etc. There were further 30 activities in the nationwide "SME Digital" network. The offers work hand in hand with the partners Ilmenau TU, where the headquarters and the "Networking Model Factory" are located, the Ernst Abbe University of Applied Sciences Jena as the "Virtualisation Model Factory" and the Gesellschaft für Fertigungstechnik und Entwicklung e.V. in Schmalkalden as the "Process Data Model Factory".

The "SME Digital Centre Ilmenau" focuses on sustainability, platform economy and AI, in addition to the specialist foci reflected in the names of the model factories. As a model factory for smart sensor systems, IMMS is primarily dedicated to the topics of retrofitting, predictive maintenance, smart sensor systems, diagnostic solutions and AI-based sensor data evaluation. For example, retrofit solutions can be provided for machines with which the machine status is automatically recorded and visualised. Another core competence lies in the practical implementation of smart sensor systems with which machine tools are monitored by means of artificial intelligence, among other things. In addition, demonstrators show digital diagnostic solutions

Flexible data acquisition solution for AI-based industrial applications. With the electronics platform, multi-channel measurement and training data can be recorded in industrial manufacturing environments for various questions and evaluated with the help of AI.

Photograph: GFE.

that, for example, find cost-intensive leaks in compressed air systems with mobile measuring devices. Questions from SMEs about the use of AI are addressed by the AI trainers working for all the centre's partners.

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

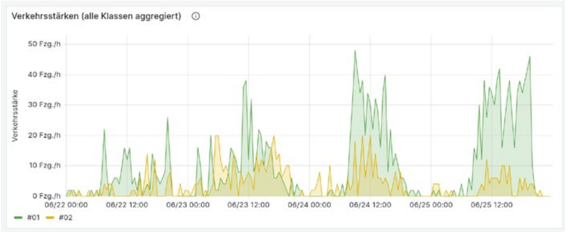
New demonstrators and digitisation projects

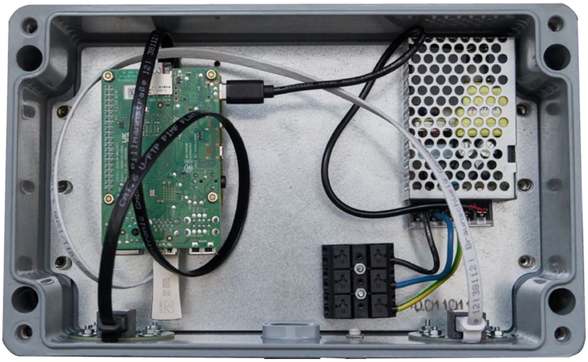
In addition to the various events, the "Smart Sensor Systems Model Factory" at IMMS is also working on demonstration and implementation projects.

www.imms.de/md

Possible applications of artificial intelligence (AI) in manufacturing SMEs were shown in various projects or demonstrators.

- The **retrofittable AI-based sensor for fan monitoring** is a small sensor system that detects, classifies and visualises defects on fan blades or bearings. The sensor signal is evaluated with AI-based data processing implemented on a microcontroller.
- The **flexible data acquisition solution for AI-based industrial applications** is an electronics platform for the flexible multi-channel recording of measurement and training data in industrial manufacturing environments, to which different sensor systems can be connected via various measurement channels and data interfaces. Signals from these systems can be evaluated using AI-based methods.





In the project, an intelligent audio sensor solution for 5 locations in Berger Feld in Gelsenkirchen was implemented together with comNET GmbH and the Fraunhofer Institute for Digital Media Technology. The system detects traffic flows and noise pollution and helps to improve public safety. The hardware setup was realised using low-cost components that are currently available. Diagram/photographs: IMMS/comNET.

- **RFID-based workpiece identification and localisation** in automatic feed systems, e.g. in milling machining centres, allows the automatic selection of suitable machining programmes, tools etc. In the project, different RFID tags and a compact RFID reader were tested to evaluate the technical feasibility and a high recognition rate depending on different manufacturing boundary conditions.
- **Intelligent networked sensor systems** were also used in an orchard to better plan care and irrigation measures for apple trees and to maintain or increase yield and quality despite climatic changes.
- With the **intelligent acoustic sensor units for smart cities**, noises in the city are recorded, evaluated based on AI and collected centrally. In the process, noise classes with assigned volume profiles are generated. They are used to record traffic flows and noise pollution as well as to improve public safety.

www.imms.de/md

Networked sensor systems in fruit cultivation: These enable better planning of care and irrigation measures as well as maintaining or increasing yield and quality despite climatic changes. Photograph: IMMS.

Networking with digitalisation key players expanded

Another important component of the work in the “SME Digital Centre Ilmenau” is the networking of the players involved in the digital transformation of companies. There was a regular exchange in the nationwide SME Digital Network, including in topic-specific working groups or at regional conferences of the participating centres. 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 Centre, 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 SME Digital Centres to companies. At the same time, the SME Digital Centres bundle the requirements of SMEs so that these are taken into account in basic and applied research.

digitalzentrum-chemnitz.de

scads.ai

ki-hub-sachsen-thueringen.de

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Mittelstand-Digital

Mittelstand-Digital Zentrum Ilmenau

Defective rolling bearings can be identified and analysed with the three-channel multi-sensor test device Trib.US developed by IMMS and SONOTEC. Photograph: IMMS.

Motivation and overview

Roller bearings are indispensable in any industrial sector. As ball or tapered roller bearings, they guide rotating or pivotally moving machine components such as shafts, axles, or wheels and transfer loads between components. They are used in engines and transmissions, or on pumps and shafts, among others, in consumer goods, wind turbines, industrial robots, or in conveyor belt transport rollers.

If a roller bearing is defective, it can lead to a complete system failure. Detecting wear on roller bearings and its causes in a timely manner is important to avoid downtime costs and consequential damage to equipment. The problem, however, is that roller bearings are often installed in a way that makes them difficult or very labour-intensive to inspect and maintain. In the Trib.US project, IMMS and SONOTEC GmbH have therefore developed an integrated mobile solution to assist in maintenance decisions for roller bearings during inspections. The result is a smartphone-like device with three sensor channels. This allows defects to be pinpointed more accurately and their causes to be determined more quickly, reducing or preventing production downtime.

www.imms.de/tribus

The device uses ultrasound, acceleration, rotational speed, and temperature sensors to detect deviations in signals that distinguish faulty roller bearings from those operating normally. Through correlation and sensor data fusion, conclusions can be drawn about defects, and this information is displayed directly in real-time on the device. This allows for on-the-fly assessment of which bearings are defective during machine operation. It enables a planned proactive replacement, preventing costly unplanned downtime and repairs.

For this purpose, IMMS has developed and implemented a real-time capable platform as well as algorithms for signal evaluation and correlation. The partner SONOTEC GmbH has provided the ultrasonic sensor technology, the user interface, and the associated maintenance management software.

Added value through more channels – the "three-channel SONAPHONE®" Trib.US

A roller bearing is typically monitored using an ultrasonic sensor. This allows for damage assessment through simple metrics. This capability is already achievable with the SONAPHONE® developed by IMMS and SONOTEC. This single-channel portable digital ultrasonic testing device is used for various applications, including air leak detection in compressed air lines, testing of condensate drains in steam systems, detection of electrical partial discharges, and increasingly for machine inspection. However, this device is only partially suitable for the analysis of roller bearing damage because it has only one sensor channel.

www.imms.de/sonaphone

To analyse damage patterns in roller bearings and their causes, a more complex data evaluation of the ultrasonic signals is required. Narrowing down the damage to specific components or areas of the roller bearing is immensely helpful in root cause analysis. The ultimate goal is not just to identify and replace the defective bearing but, above all, to determine its cause. Only in this way can measures be taken to rectify this issue and prevent future damage.

A multi-channel ultrasonic inspection is instrumental in harnessing untapped potential in data processing. In the Trib.US devices developed by IMMS and SONOTEC, three sensor channels are used to process data simultaneously, linking two ultrasonic data streams with a reference signal. For the first time, information from fault and damage detection is combined in a single device through two broadband ultrasonic

www.imms.de/tribus

channels and an additional multifunctional channel. Data collection occurs simultaneously, making it faster and facilitating analysis. Using multiple channels, for example, it's possible to determine whether an outer or inner ring damage is present in the roller bearing based on resonance frequencies in combination with rotational speed. This enables quicker maintenance decisions and corrective actions.

Integration and time synchronisation of the ultrasound channels

The time synchronisation of multiple ultrasonic sensors plays a crucial role in the accurate and precise correlation of ultrasonic signals for localisation and root cause analysis. Time synchronisation refers to the process by which various sensors or devices align their internal timekeepers, ensuring that they capture temporally coherent data to relate the sensor signals to each other. In the multi-channel SONAPHONE®, broadband sensors are used, such as BS10 for airborne ultrasound or BS40 for structure-borne sound. These sensors have their own clock sources, which can introduce phase differences during analogue-to-digital conversion.

www.imms.de/realtime

To ensure the synchronous sampling of signals, a synchronisation command was implemented in the real-time capable platform at IMMS. The handheld device sends this command to the sensors at fixed time intervals, thereby synchronising the timebase. Synchronisation occurs at a fixed time interval of 16 ms. To achieve this, the firmware of the sensors and the FPGA design were adjusted accordingly.

At IMMS, an analogue circuit for signal adaptation was developed for the integration of the reference sensors, and the connection of rotational speed and temperature sensors was implemented. SONOTEC handled the integration into the digital device. The internal AD converter of the programmable logic device (FPGAs) chosen for the hardware platform was used for analogue-to-digital conversion. Values provided by the sensor need to be processed differently depending on the sensor type. The respective processing algorithms were also integrated into the FPGA, and the interface to the measurement core was revised. Simultaneously, the corresponding data processing in the measurement core was implemented, and interfaces to the FPGA and the app were established.


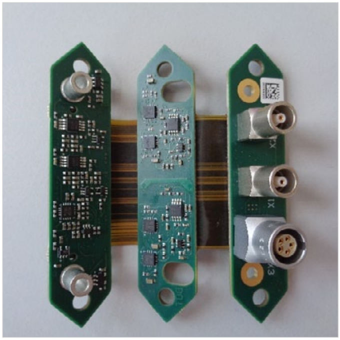

Figure 1: 3D representation of the three-channel extension boards for the SONAPHONE® and realised hardware. Diagram: IMMS, photograph: SONOTEC.

Correlation algorithms

Signal correlation refers to the process of analysing and evaluating two or more signals to gain insights into their similarity, phase shift, and temporal relationship. In the localisation of a sound source, two ultrasonic signals are captured, received by microphones or sensors at different positions. Correlating these signals allows the determination of time delays and phase shifts between the signals, which can be used to determine the source's position.

From the timing of the incoming signals, the time difference of arrival (TDoA) can be determined. This time difference can be calculated using cross-correlation. IMMS has explored several methods for cross-correlating ultrasonic signals and compared them in terms of implementability. The Generalised Cross-Correlation (GCC-PHAT) algorithm is a low-computational-cost method. The cross-correlation calculations of such an algorithm can be further improved by using signals in the frequency domain. Utilising Fourier transformation for signal convolution can further optimise the implementation. The selected algorithm was prototypically implemented and demonstrated to be suitable for localising a signal source.

www.imms.de/sonaphone

Implementation in a functional model

At IMMS, a new three-channel expansion board for the SONAPHONE® was designed to connect the sensors electrically. In a first step, the existing single-channel version was expanded. Interface electronics were implemented to connect two digital ultrasonic sensors and one reference channel.

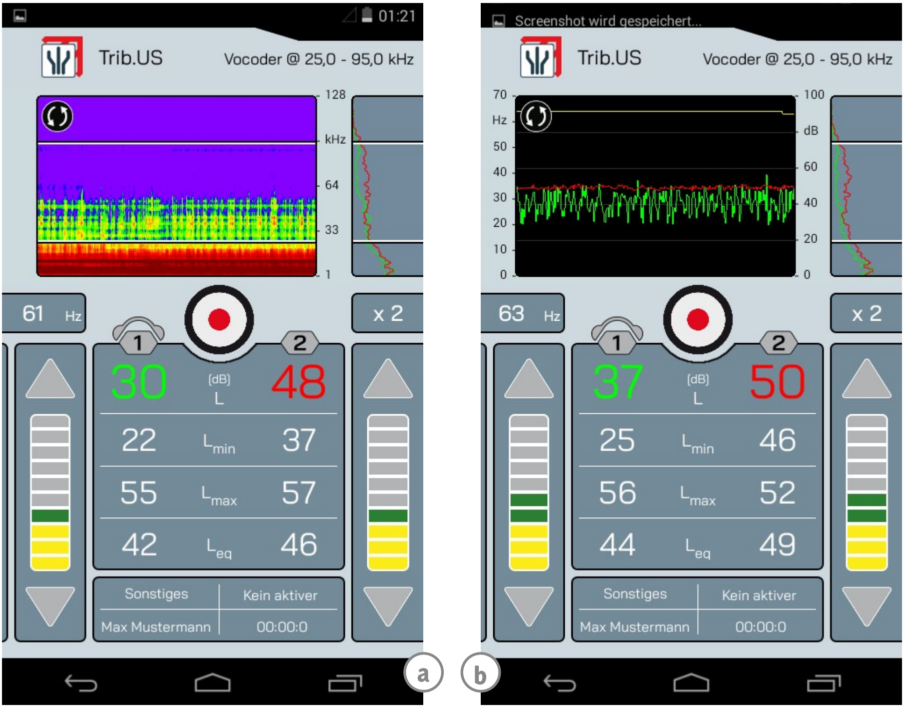

Figure 2: Trib.US app interface with (a) display of the frequency components in the ultrasonic range and (b) the level curves of two synchronous channels/sensors for test objects, e.g. roller bearings, as well as the third reference channel with the rotation speed. Source: SONOTEC.

In order to use compact analogue sensors, such as the T20 structure-borne sound probe or acceleration sensors, with the multi-channel testing device, a second step involved integrating the signal electronics of the digital sensors onto the expansion board. This includes aspects like analogue-to-digital conversion and filtering of the ultrasonic signals. By reducing the size, adapting the housing accordingly, and relocating processing logic to the expansion board, sensor usage is simplified, sensor costs are reduced, and the platform is opened up for a variety of other sensors (e.g., vibration sensors). Figure 1 shows the 3D design of the electronics, which includes signal processing, amplification, filtering, and analogue-to-digital conversion of the two analogue ultrasonic signals, as well as interface electronics for the reference channel including voltage generation. The challenge here was the placement and wiring of components in the limited space of approximately 70 x 20 x 10 mm³. To address this, a six-layer starflex board was designed, where three rigid PCB parts are connected for component placement using flexible areas. The board can be folded, as shown in Figure 1, to optimise the use of space.

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Figure 3: Multi-channel test device with two ultrasonic sensors and one rotation speed sensor on the bearing demonstrator. Photograph: SONOTEC.

The app for displaying the measurement values was developed by SONOTEC. Figure 2 shows the implemented interface of the Trib.US app. The current signal amplitudes are displayed in bar form at the bottom left and bottom right. In between, the level values of both channels are depicted. The channels are colour-coded: values from Channel 1 are in green, while values from Channel 2 are in red. In the middle of the interface, just above the green bar, there is a field displaying the values of the slow channel, such as the connected rotational speed sensor. At the top there is a display field in which the frequency spectra (purple background) or the level curves (black background) of the fast channels 1 and 2 as well as the reference channel can be visualised.

Demonstrator

To demonstrate and validate the multi-channel ultrasonic testing device, SONOTEC established a test and evaluation bench. This allows for the verification and validation of the proper functioning of individual sensors and the synchronous capture of the individual channels. Subsequently, the test bench can also be used to demonstrate the system's functionalities.

The demonstrator consists of a controllable electric motor that drives a shaft via a belt. The shaft, in turn, is mounted in two ball bearings. One of these ball bearings was intentionally prepared. A precisely defined (and precisely reproducible) damage was introduced into the raceway (outer ring) of the balls using a laser engraver at a specific location. This alteration resulted in a change in the ultrasonic emission and vibration pattern of the respective ball bearing. Reflective strips for the non-contact LED rotational speed sensor were also attached to the shaft. In the Trib.US app, the differences between defective and intact bearings can be seen in the amplitude values and waveforms (green and red), as shown in Figure 3.

Summary and outlook

In the Trib.US project, a mobile testing device with 3 sensor channels, consisting of 2 broadband ultrasonic channels and 1 additional multifunctional channel for locating damaged components in roller bearings, was developed. IMMS has realised hardware for connecting 3 sensors as well as the preprocessing and correlation of ultrasonic channels to enable the system's functionality for locating and analysing sound sources. SONOTEC is preparing the prototype for mass production, expected to commence around mid/late 2024. The device, due to its standalone operation, can also be used for other applications, such as testing valves or conveyor rollers. These applications are planned to be demonstrated in the next phase.

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by the German Bundestag

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Sensor system for online monitoring of membrane reactors for dialysis processes and in-vitro protein synthesis of large sample volumes

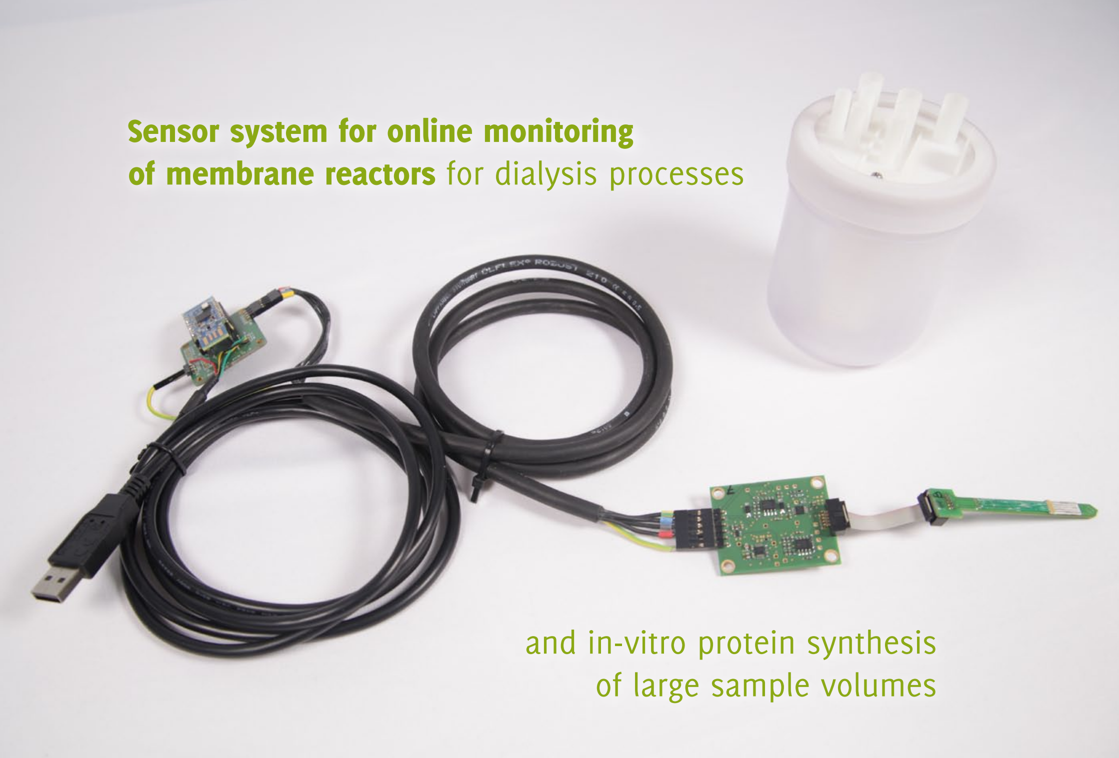

Figure 1: In the SensoMem project, IMMS developed a prototype for a system that allows to monitor biochemical reactions, such as dialysis or protein synthesis, while they are running. Multiple sensors observe the reaction in the laboratory and thus help avoiding process repetitions. Photograph: IMMS.

Motivation and overview

Biochemical reactions, such as dialysis, protein synthesis or the cultivation of cells, play a major role in e.g., patient-specific therapies. The production of these proteins within laboratories happens in membrane reactors under given environmental conditions. Reactors with large volumes of more than 20 ml per batch are still relatively new. Currently, mostly small volumes are produced. In addition, the processes are slow and can take up to a week to complete. So far, quality checks to assess whether the desired results were achieved happen by analysing the samples afterwards. If the results are not good, the process must be repeated, which leads to undesired delays.

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In the SensoMem project, IMMS worked on a sensor-monitored membrane reactor, which can evaluate whether everything is ok during the reaction. To achieve this, various sensors combined into a panel are introduced either into the reactor itself or the surrounding buffer solution and monitor the corresponding parameters there. This enables laboratory personnel to detect deviations in the reaction process at an early stage. To build the system, several challenges have to be handled. On the one hand, there is limited space in the reactor, so rather small sensors have to be used. On the other hand, the sensors have to be in contact with the liquid, but must not be damaged by it or negatively influence the reaction. The small installation space also means that many commercially available devices cannot be used here, as the probes are too large for containers with a volume of 20 ml.

In the project, IMMS developed the electronics for the panel and the corresponding measuring circuit to interface the sensors. One focus was the energy-optimised operation of the electronics, to potentially enable a battery powered system. Our concept allows to operate several measurement circuits in parallel and thus to analyse several reactors with several measured variables at the same time.

Sensor system for online monitoring of reactions in membrane reactors

We selected the sensors for the membrane reactor together with the partners scienova and Fraunhofer IZI. Specifically, temperature and conductivity were identified as important parameters. In addition, Fraunhofer IZI supported us by testing the materials for biocompatibility to ensure that the materials and the reactor design have no influence on the reaction.

Challenges

IMMS developed concepts to measure the mentioned quantities with the corresponding sensors. This step was particularly necessary for the conductivity measurement, since the system has to operate with a high resolution and cover a large measuring range. The challenge was to deal with both extreme points of the measuring range, since the resulting electrical signals can be very small in amplitude.

In addition, the energy supply in a small installation space posed a further challenge. To build a system that does not place constraints on the laboratory routines, the entire sensor system including battery / accumulator had to be kept as small as possible. However, button cells, as the smallest option, were infeasible due to the energy required for the measuring circuit. Here, IMMS used its expertise in the ener-

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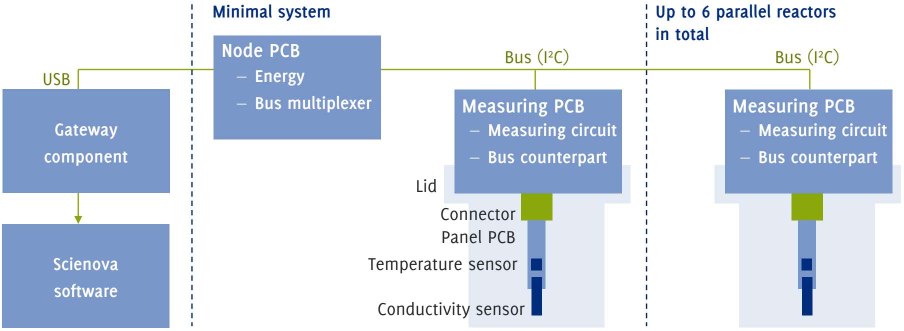

Figure 2: Concept of a sensor system for online monitoring of reactions in membrane reactors. Diagram: IMMS.

getic optimisation of embedded systems and trimmed the circuit so that it required as little energy as possible. These adjustments enabled a saving of 30% compared to the initial version and of 60% compared to commercially available alternatives.

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Solution

On the conceptual side, the system developed by IMMS consists of 3 components. For each reactor to be monitored, a measurement PCB with all the necessary components for measuring the conductivity and a sensor panel on which the sensors are located are employed. These are connected via an I²C bus to the base board, which provides the power and controls the measurement PCBs. Figure 2 shows this schematically.

It is important to note that there are special requirements for the panel. To ensure that the electronics are not damaged when in contact with the liquid within the reactor, the panel must be coated without affecting the sensors and the connections. The coating material has also to be biocompatible, i.e., it must not have a negative effect on the reaction to be carried out. In addition, the panel needs to be sterilisable to ensure that the reactor contents are not contaminated by the panel.

On the software side, IMMS developed a concept that sequentially addresses all connected modules and includes automatic measurement range switching for the conductivity measurements. To minimise energy consumption, all measuring groups can be switched on and off individually.

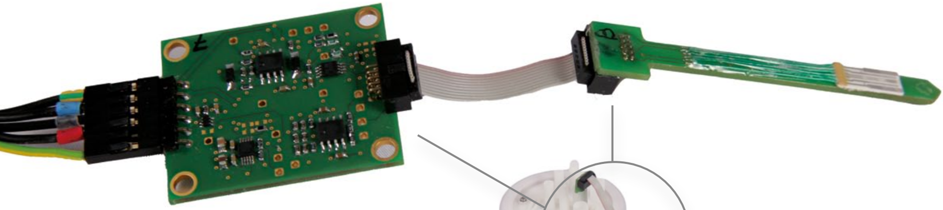

Figure 3:

above: measurement PCB to be attached to the outside of the membrane reactor,

below: panel with sensors to be in direct contact with the sample for measurements.

Photographs: IMMS.

Prototype and characterisation

The project worked with various prototypes to investigate different aspects of the system in parallel. This included tests whether the electronics are influenced by the magnetic stirrers operating in the membrane reactor or buffer solution as well as tests with the system within a climatic chamber. The results showed that the sensor system can be used with the laboratory equipment without any restrictions.

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After integrating all three system components into a prototype, we extensively characterised it and made appropriate adjustments to the software where needed. Figures 1 and 3 show the prototype as it is installed in a reactor with the panel inside of the reactor, the measurement PCB on the outside of the container and the base board, which can be positioned anywhere within cable reach. This also allows the actual measurement within the climatic chamber, while the base board is placed outside. Instead of a battery power supply, a USB interface was implemented for the prototype, providing both data transmission to the PC and power supply.

Commercial conductivity standard solutions were then used to evaluate and calibrate the system. For this purpose, a commercial conductivity measuring device provides a baseline for comparison. The measurements showed that different combinations of measurement PCB and sensor panel have slightly different ADC values for conductivity and therefore each combination requires its own specific calibration. However, this can be mapped on the software side. For the prototype, the required adjustments were made manually.

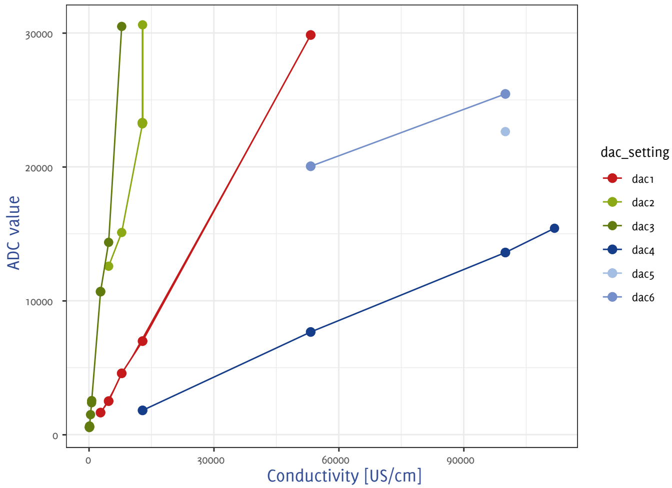

Figure 4:

Averaged results of the tests performed for different settings. The circuit goes into a nonlinear behavior for some settings or when the values are too high. These results provided the basis for the choice of settings.

Diagram: IMMS.

The calibration is required for each measuring range, since the configuration of the measuring circuit differs with respect to stimulation voltage and measuring resistors depending on the measuring range. IMMS experimentally determined these measuring ranges with the help of several reference solutions and selected the reference points carefully to allow an area where the ranges overlap without reaching the recognition limits. Figure 4 shows the averaged results of the experiments carried out for different settings. This shows that the circuit changes into a nonlinear behaviour at some settings or when vales are too high. During operation of the system, these areas should be avoided. Therefore, the corresponding settings were not used. Instead, ranges were chosen to ensure linear behaviour over the entire measurement range.

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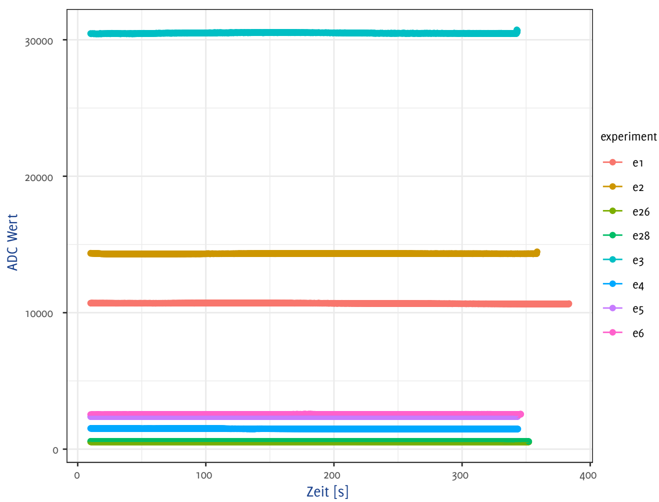

Figure 5:

These constant values of conductivity for corresponding reference solutions show the successful functional proof for live monitoring of reactions after system calibration.

Diagram: IMMS.

Evaluation of the system

After calibration the circuit provides constant values for the corresponding reference solutions (see figure 5). Thus, the functional verification was successful. This makes it possible for the first time to follow a reaction live and observe both the course of conductivity and temperature. This is a first step towards a continuous monitoring of certain reactions.

Future Work

The developed system is capable of monitoring and evaluating two critical variables related to biochemical reactions in a membrane reactor during the reaction. The resulting prototype therefore demonstrates the potential of such solutions.

The system is still at the prototype stage. Further adaptations are therefore necessary to turn it into a product. In particular, a method for self-calibration of the conductivity measurement using test solutions should be included. This is standard for commercially available devices. To achieve this, a function needs to be integrated into the system that performs a corresponding measurement based on a reference solution and adjusts the calculation coefficients accordingly.

Regarding protein synthesis, other variables are important. These are especially the pH value of the liquid and oxygen saturation in the liquid. Therefore, an extension of the system to include these variables should be the goal in the future. In the current project, this was not covered because the required small sensors for these variables were not available.

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Single-photon counting and picosecond-accurate measurements for research in quantum technology

The SPAD-EvalKit developed in QuantumHub Thüringen 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 or medical technology to be developed. Photograph: IMMS.

For quantum technology from Thüringen, Germany, IMMS is researching CMOS-based single-photon detectors

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Quantum technology is considered to be a key technology of the future. It enables the development of highly efficient technology that can far surpass the performance of conventional systems. By controlling individual quanta, i.e. the smallest light and energy building blocks, disruptive applications are made possible, for example quantum computers, tap-proof communications or quantum sensor technology. For this purpose, IMMS is researching the use of commercially available, silicon-based single-photon detectors, so-called SPADs (single-photon avalanche diode). They can be produced cost-effectively in a standard semiconductor technology (CMOS) and therefore enable highly integrated, miniaturised solutions. The SPADs are used to convert single photons into electrical signals and allow operation at room temperature without large and complex cooling systems.

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IMMS has developed a SPAD evaluation kit in collaboration with X-FAB. The low-cost, hand-sized USB device called SPAD-EvalKit requires no additional power supply and is illustrated in Figure 1. It is based on the time-correlated single-photon counting

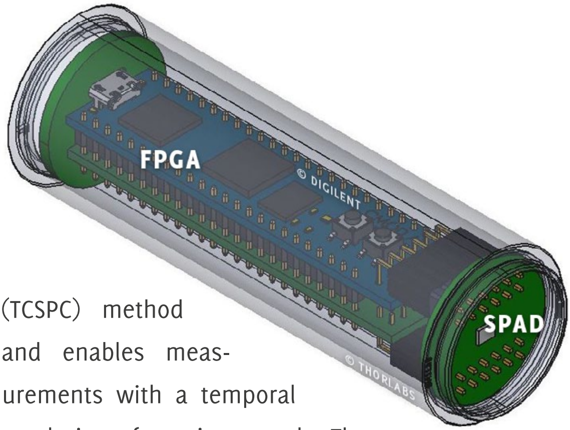

Figure 1:

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

Diagram: IMMS/Digilent/Thorlabs.

(TCSPC) method and enables measurements with a temporal resolution of 20 picoseconds. The TCSPC method used for this purpose and presented in this article makes it possible to assess the temporal course of the intensity of light pulses. It can be used to set up single-photon sources, characterise light pulses with very small light powers or distances and thus lay the foundations for quantum-based applications. Among other things, the method can be used to develop new solutions for in-vitro diagnostics or medical technology, such as miniaturised luminescence and fluorescence measurement technology.

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To interpret the sensor signals statistical evaluation is required. For the first SPAD evaluation kit, this is taken over by a programmable logic device (FPGA). This component is an intermediate step for later chip development. The FPGA can be used to specify the processes for sensor signal processing, but primarily to map the desired circuit structure, which can still be flexibly adapted for tests and optimisations.

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This laid the foundation for the integration of such an optical sensor element in conjunction with the necessary evaluation electronics in a microelectronics chip, which will flow into application developments of other research projects.

Very fast light pulses cannot be characterisied adequately with conventional methods

Fast light pulses are necessary for many applications down to the nano- or picosecond range. Light sources that generate these pulses must therefore be characterised. Without certainty about the nature of the excitation signal, a meaningful evaluation of the reaction of an optical system to it is often only possible with considerable limitations or no longer possible at all. This knowledge is essential, especially for fluorescence-based bioanalytical methods in medical technology or for time-of-flight applications such as in the automotive sector. For measurements where a very fast light source is used, the light source itself must therefore first be characterised.

Fast photodiodes are traditionally used for this purpose. The signal then recorded with an oscilloscope allows pulse widths down to the nanosecond range to be evaluated in the temporal amplitude progression. However, the basic noise of the oscilloscope greatly limits the achievable dynamic range. Therefore, the impulse response of the photodiode is often distorted non-linearly.

Time-correlated single-photon counting technique avoids undesired effects

To avoid these effects, the SPAD-EvalKit developed at IMMS in cooperation with X-FAB uses a fundamentally different method – time-correlated single photon counting (TCSPC). Here, the impulse response of the light source is not considered to be continuous, but discrete. Furthermore, the impulse response is not measured in a single run, but accumulated through repeated excitation and statistical evaluation of the results of many measurement runs. The TCSPC method is fundamentally based on the fact that the light emission of any light source is by no means a continuous and deterministic process, but is instead the stochastically distributed emission of individual photons. The impulse response of the light source is simply the probability density of the times at which photons are released from the light source. The measurement – or more correctly from a statistical point of view: estimation – of a probability density is carried out by means of a histogram of the times at which photons are released from the light source.

Characterisation of fast pulsed light sources using FPGA and SPADs

A system for measuring a light source by means of TCSPC therefore requires a single-photon detector, which collects the photons emitted from the light source. Secondly, it needs a sufficiently accurate time-to-digital converter (TDC). This measures the time difference between the excitation and the incidence of the first photon and increments the corresponding histogram class. After a sufficient number, i.e. several hundred thousand, of TDC values have been accumulated, the histogram

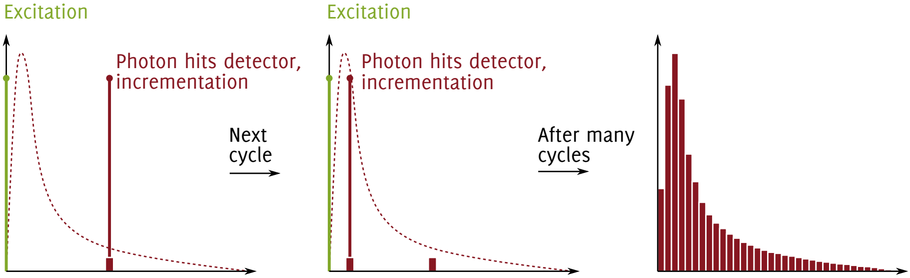

Figure 2: Cycles of the TCSPC procedure to create the histogram. Diagram: IMMS.

corresponds to the actual impulse response of the light source. This method is not a recent invention, but was described in the form used today as early as 1961.[1] For a long time, however, very bulky equipment was required to put such a setup into operation. At IMMS, with the help of the now commercially available silicon-based single photon detectors (so-called single-photon avalanche diode, SPAD) in X-FAB technology, it was possible to develop an extremely compact device that performs TCSPC measurements. The time-to-digital converter (TDC) is currently implemented in a field programmable gate array (FPGA). This programmable logic device maps all the structures of the envisaged integrated circuit, with which the system consisting of SPAD sensor and evaluation electronics can be further miniaturised and thus opened up for new quantum-based applications.

Gate delays allow cost-effective FPGA application

Since the highest reasonable clock frequency of current FPGAs is in the range of a few hundred megahertz, it is not possible to implement a TDC with a temporal resolution of about 20 picoseconds using simple counter logic. However, the following approach offers a solution that achieves this accuracy: certain basic hardware components of the reconfigurable FPGA logic are used as dead time elements, i.e. digital structures with a known propagation delay. The number of delay elements the start signal could pass through before the stop signal was set is measured. Thus, the time resolution of the TDC is not dictated by the reference clock, but by the propagation delay of these hardware components serving as delay elements.

Results

This enables the system to measure the impulse response of the light source, i.e. the intensity distribution over time. With a temporal resolution of approximately

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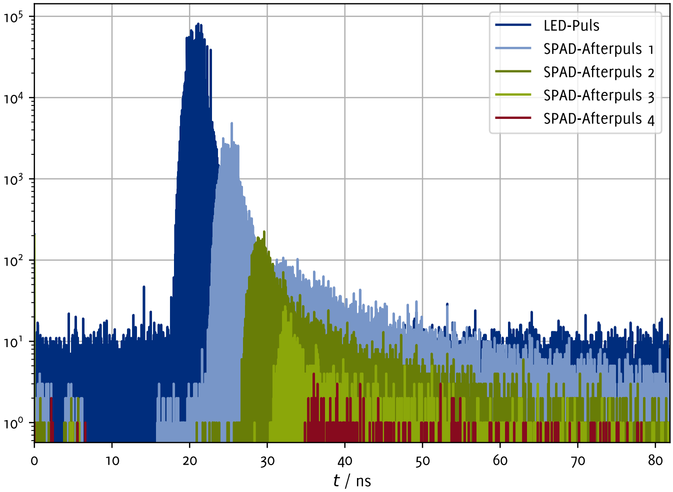

Figure 3:

Example histogram for the measurement of impulse responses of an LED light source by the TCSPC method. The unwanted effect of SPAD afterpulsing can be filtered out. It is shown here separately for SPAD afterpulses 1 to 4.

Diagram: IMMS.

20 picoseconds, even very short light pulses in the nanosecond range can be characterised. The dynamic range of the accumulated histogram is 80 dB after a moderate integration time and is thus significantly better than the dynamic range of a GHz oscilloscope – the latter is at most 40 dB at a typical resolution of 7 bits (ENOB) due to noise. To be able to exploit the high dynamic range, the ordinate axis of a TCSPC histogram is usually scaled logarithmically.

With the developed SPAD-EvalKit, unwanted effects of the light source and the detector can also be observed and quantified. For example, the afterpulsing of the SPAD can be filtered out by suitable correlation, see figure 3. This unwanted effect is caused by the detector: After it has sensed a photon, further pulses can be emitted immediately due to the charge carriers enclosed in a semiconductor layer, but these pulses cannot be assigned to a photon. This effect is called afterpulsing. With the SPAD-EvalKit, this afterpulsing can either be suppressed for normal operation or specifically extracted for characterising the detector.

In addition, interference effects of the light source can be investigated that are significantly below 1% of the peak value of the impulse response. One effect is the spontaneous emission of a stimulated laser diode. When measuring with a fast photodiode and an oscilloscope, this effect would only be measurable to a limited extent due to the limited dynamic range of the oscilloscope. This is especially critical for in-vitro diagnostic applications in which the laser diode is to be used to excite a biologically or chemically induced fluorescence. The reuse and further development

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of the system in the FluoResYst project already showed that this can also be characterised with the SPAD-EvalKit.

Cost-Effective, hand-sized USB device with the potential of further miniaturisation

The TCSPC method is excellent for characterising fast light sources and reveals effects that would not be visible when measuring the impulse response through means of a photodiode and oscilloscope. The system developed together with X-FAB allows the measurement of <1 nanosecond wide light pulses with a dynamic range of 80 dB. The combination of FPGA TDC and CMOS SPAD allowed the TCSPC measurement setup to be scaled down from what was previously an extremely bulky measurement setup to a low-cost, hand-sized USB device that requires no external power supply. The system is fully housed in a one-inch diameter lens tube. This also allows it to be complemented by a variety of commercially available optical components (e.g. lenses, filters).

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The measurement system has already been used to characterise fast laser light sources as part of the FluoResYst research project. Through this, a feasibility evaluation for the development of a SPAD-based ASIC for the detection of tuberculosis could be successfully provided.

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1 L. M. Bollinger, G. E. Thomas. Measurement of the Time Dependence of Scintillation Intensity by a Delayed-Coincidence Method. Rev. Sci. Instrum., Jan. 1961.

Testbench in hardware: AMS ASIC Scope for validation of AI-based simulation methods in chip design

Figure 1: AMS ASIC Scope with plug-in modules developed at IMMS. The analogue/mixed-signal test platform (AMS) for application-specific integrated circuits (ASICs) is the core of a novel validation environment that can generate and measure analogue and digital parameters. Photograph: IMMS.

Hardware testbench for chip design: introduction and overview

IMMS develops AI-based methods for the design of complex circuits

Microelectronic systems consisting of analogue and digital components record, amplify, digitise and transmit electrical, mechanical, optical, chemical or biological parameters. Thus, they enable a wide variety of applications, such as novel intelligent, autonomous production systems or sensor systems for in-vitro diagnostics. The design of such mixed-signal integrated circuits is becoming increasingly complex, as new applications require an increasing number or more precise analogue components to be combined on one chip. Design errors must be avoided as best as possible before a design is handed over to time-consuming and cost-intensive semiconductor production.

IMMS is therefore researching various methods for AI-based design and test automation to make the development process of integrated sensor systems more reliable and cost-effective. For example, with the help of AI, efficient simulation models are created that reproduce the behaviour of the circuit much better than with conventional methods and thus enable corrections and optimisations to the design before

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production. With neural networks, for example, non-functional properties are integrated very effectively into existing behavioural models, which thus become part of the software-based simulation environment, the testbench. They already increase the confidence of the design very effectively.

Feedback from test to simulation: new platform for failure analysis and prevention

Despite all this, after chip fabrication, errors are found during testing and characterisation, whose causes are sometimes difficult to identify. This is because software-based simulation and hardware-based characterisation can usually only be combined manually at the moment. Reasons for this are incompatible data formats and high complexity of the real circuit behaviour, which can only be simulated with a lot of effort.

To be more effective in preventing design errors through simulation, the methods of simulation must be validated and optimised with regard to their applicability. For this purpose, IMMS has developed the AMS ASIC Scope. It is an analogue-mixed-signal test platform (AMS) for application-specific integrated circuits (ASIC). This is the core of a novel validation environment that can generate and measure analogue and digital signals. A modular approach enables a configuration tailored to the ASIC. With physical test structures, the measurement environment reflects the requirements and parameters of the simulative test bench from the design software. The new platform thus enables not only automated test sequences on real circuits, but also a combined specification of test cases and parameter variations, in other words a feedback loop between simulation and test. The results of these tests are comparable with simulation and test data from the design environment. They can therefore be used to validate and improve simulation models from the design. When weaknesses occur, the search for the cause is simplified because simulation data and measurement results are directly comparable.

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Testbench in hardware for improvements in test and design

With the AMS ASIC Scope, simulations and tests from the design environment can be applied to real circuits for most test cases. The developed hardware implements this concept through a modular system with a main control unit for controlling different modular single boards for individual specific tasks. The system is intended to support the design of new ASICs in the future.

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The compatibility of simulation and real measurement that the test system brings provides great advantages in both test and design:

– Greatly simplified test development, since simulation stimuli can be reused
– Evaluation of models from development environment through direct comparability
– Identification of failures is simplified, deviations between simulation and test can be fed back into the design environment

Requirements

To use learning algorithms with the AMS ASIC Scope in simulation and characterisation context, several requirements for data acquisition and storage are met. The data sets are acquired using the same conditions and stored in compatible formats. The measurement system and simulation environment thus have identical interfaces and data structures.

For comparable results between development and physical environment, the AMS ASIC Scope fulfils the following requirements:

– Generation and measurement of analogue voltages and currents
– Input and output of digital signals
– Reading and writing of data via digital communication protocols
– High timing accuracy
  . Parallel sequence control / test-specific configuration of each module
  . Module synchronisation
  . No timing delays due to operating system
– Fast data connection between control unit and modules (>10 MBit/s)

Platform concept

To meet the requirements regarding circuit and simulation parameters, circuit-specific voltages and currents must be provided and signalling must be generated. The IC-specific functionality is is represented by its output values. Depending on the test object, the values to be investigated can be output and measured digitally or analogue. For this purpose, IMMS has developed a flexibly configurable test platform with analogue and mixed-signal input and output functions (AMS).

The behaviour of the ASIC is evaluated simultaneously by stimulating it with input signals and observing its output signals. This measurement represents the

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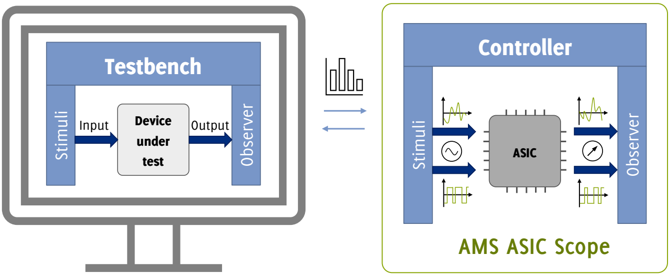

Figure 2:

Compatibility scheme between Testbench (left) and AMS ASIC Scope (right).

Diagram: IMMS.

equivalent of the behavioural description of a test bench. With this procedure, tests can be emulated in hardware comparable to simulation. To do this, it is necessary to stimulate a circuit with both analogue and digital signals.

The developed AMS ASIC Scope fulfils these functions through a modular approach. A configuration tailored to circuit and test is thus easy to realise. Modules of the measurement system are interchangeable and adaptable to the respective measurement requirements of an ASIC. Embedded in a plug-in desktop housing, the modules in Eurocard format can be mounted and secured easily. The components of the measuring system are controlled via a main module. It can be connected to a PC via a network cable to control the measurement system, see figure 2.

The electrical connection to the modules of the system is created via a passive backplane. This carrier board with connectors for the plug-in modules provides connections for data, signalling and power. All modules are operated with a fixed voltage of 24 V. Specific voltages for the circuitry of modules are generated locally for each module.

A parallel sequence control is realised by programmable logic devices (FPGAs) on the modules. These receive their module-specific measurement sequences from the main module and can be synchronised with each other via existing signals. After a measurement run, the results are read back from the main module. Each module is therefore customisable for a specific measurement task. The following module implementations are possible for this purpose:

- Digital signal generator and logic analyser
- Analogue voltage generator / logger
- Oscilloscope functionality
- AWG (arbitrary waveform generator)
- Power supply with high-dynamic current measurement function
- Source measurement functionality

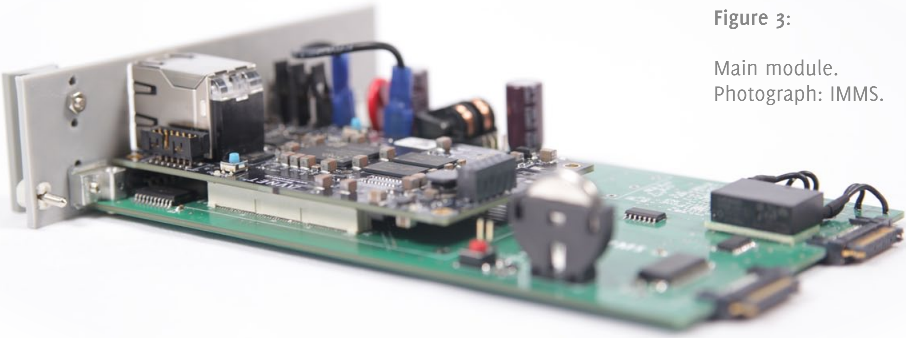

Figure 3:

Main module. Photograph: IMMS.

Platform components

Main module

This module is a fixed component and the central element for powering and controlling the measuring system.

A computing unit provides an interface to control components of the measurement platform and is used to create individual measurement sequences for the functional modules to perform a test. During a test, the main module is responsible for the time synchronisation of the modules. Results are then collected from modules and processed.

The power supply of the AMS ASIC Scope is realised with a 24 V DC power supply unit via a connection on the main module. Filters and fuses on the main module serve as protection to prevent damage to other system components in the event of reverse polarity, short circuits and other disturbances.

A system on module (SOM) in the form of a ZYNQ controller, which combines FPGA and PC, is used for data processing and system control. An interface for configuring and controlling the system is given via an Ethernet communication interface to other IT systems.

The FPGA part of the ZYNQ implements the interface for digital data transmission to the function modules in the form of a QSPI master. Communications speeds › 10 MB/s are achieved through four parallel data lines. Several slave select signals enable the targeted addressing of individual modules. In addition, clock and trigger signals are generated in the FPGA part to synchronise the function modules.

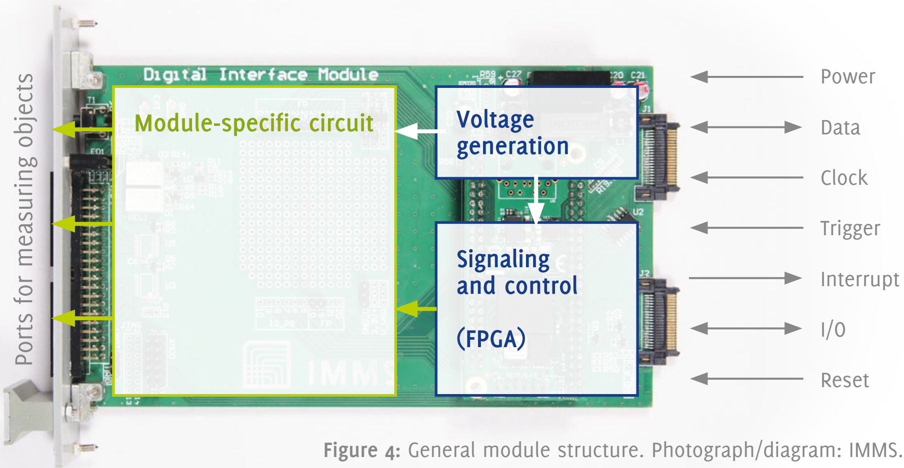

Figure 4: General module structure. Photograph/diagram: IMMS.

Functional modules

The functional modules of the AMS ASIC Scope provide the system with its actual functionality by enabling inputs and/or outputs of digital and analogue signals.

A consistent structure of hardware and FPGA designs of modules standardises the digital connection to the main module and the module control within the test system. This minimises development effort, as large parts of hardware, FPGA design and software can be reused. The fundamental hardware design of all modules follows a uniform structure, see figure 4.

Voltage genaration

Starting from a 24 V DC input, all module-specific voltages are generated. A 3.3 V regulator is always present. It provides the voltage for the FPGA. Depending on the functional circuit, one or more additional voltage regulators are required.

Signaling and control

A logic component in the form of an FPGA represents the connection to the backplane and thus to the main module. With this digital connection, measurement sequences and results are exchanged with the main module. The digital control of circuits, which take place for conversion from analogue to digital and vice versa, is controlled from this SOM. A timing synchronisation to the measurement sequence of several modules is done by synchronisation lines from the main module via the backplane.

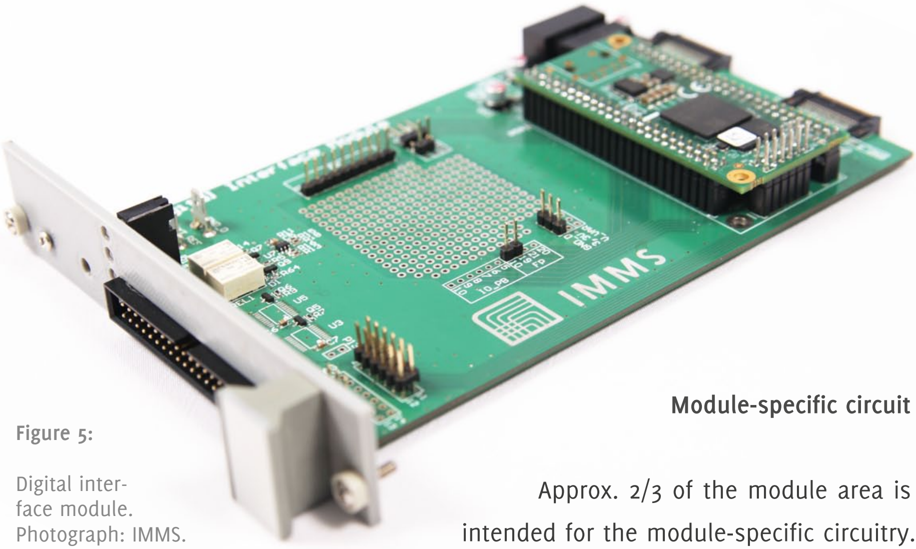

Figure 5:

Digital interface module. Photograph: IMMS.

Module-specific circuit

Approx. 2/3 of the module area is intended for the module-specific circuitry. The actual circuitry for stimuli and observers is provided in this area. This contains the analogue circuit plus the conversion of the signals between the analogue section and the digital data of the FPGA.

Digital-IO with level-shift input/output

This module was created to generate and record digital signals. This allows a module implementation that is highly versatile in terms of digital signal generation and recording:

– Generation of predefined sequences of digital signals (pattern generator)
– Recording of digital signal sequences (logic analyser)
– Generation of standardised bus signals (e.g. I²C, SPU, USART) for digital data transfer with circuits

The module has 16 digital channels, which can be freely configured according to the respective application. In addition, the high-level voltage of the digital signals can be defined. This is done either by an external voltage reference signal or alternatively by a digital-to-analogue converter on the module, which is controlled by the FPGA. The logic voltage can be configured in the range of 1.2 V to 5.5V.

In addition, there is a development area on the module that allows setups for debugging the system itself as well as developing circuit components for new modules.

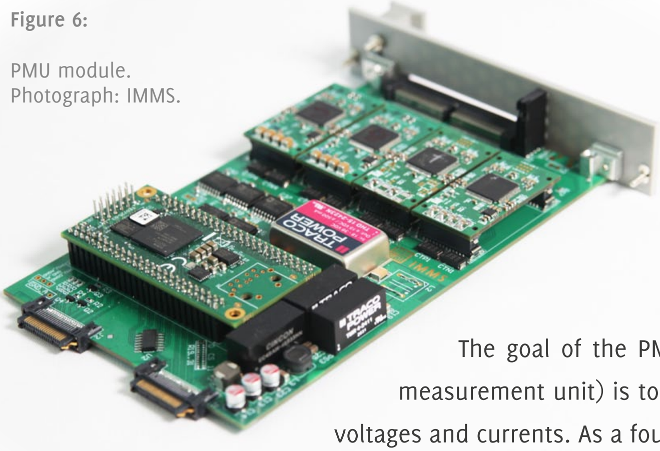

Figure 6:

PMU module.
Photograph: IMMS.

PMU module

The goal of the PMU module (parametric measurement unit) is to generate and measure voltages and currents. As a four-quadrant source, this module can also be used as an electronic load.

The module contains four SOMs with PMU ICs. One of these PMU channels allows the generation of voltages and currents with optional constraining of the complementary parameter. The measurement of the voltages and currents is realised by built-in measurement amplifiers and ADCs. Other features of these SOMs are:

- Voltage
  - Range = –11 V to +11 V
  - DAC – accuracy 16 BIT & ± 10mV
  - ADC – 24-bit resolution (± 10 µV)
- Current
  - 5 selectable current ranges (±5 µA to ±50 mA)
  - Range = –50 mA to +50 mA
  - Accuracy depending on current range ± 2.5 nA (5 µA range) to ± 0.5 mA (50 mA range)
- Channels configurable as four-quadrant sources and sinks with options for limiting current and voltage

In total, a PMU module contains 16 channels, which can be individually configured according to the above-mentioned characteristics. This AMS ASIC scope module is therefore ideally suited as an analogue module for applying sources or sinks from the simulation environment to a real IC tests.

› Integrated sensor systems
› Distributed measurement + test systems
› Mag6D nm direct drives
› Contents
* Funding

Measuring the current consumption of a digital circuit often turns out to be a serious challenge because different operating modes usually represent very large differences in power consumption. Depending on the type of circuit, it is also rarely possible to put ICs into static operational states with constant power consumption over time.

The aim of the power supply module is to solve these challenges by measuring the current consumption of a DUT over a very large measuring range. However, the operating voltage of the measured object must not be influenced by the current measurement. With this module, it is possible to record and digitise the current consumption of circuits in different states.

Two different methods for current-voltage conversion were researched and characterised for this module. This resulted in two analogue measuring adapters with different methods for amplifying the current for measurement.

A logarithmic measurement amplifier enables digitalisation of current consumption with very high dynamics without the need for range switching. Artefacts caused by switching times between measuring ranges can thus be completely avoided, because logarithmic amplification with subsequent digitisation does not require range switching.

A linear conversion with several measuring ranges avoids additional inaccuracies that occur due to non-linear effects. However, all ranges must always be digitised, since the valid measuring range of the current measurement is only obtained after digital conversion. Switching the analogue measuring ranges is also not necessary in this circuit concept.

The module allows a measuring range of 10 nA to 10 mA with a sampling rate of up to 10 MS/s with the created measuring amplification. The various measurement units can be placed very close to the test object to reduce unwanted influences.

Figure 7:

Power supply module.

Photograph: IMMS.

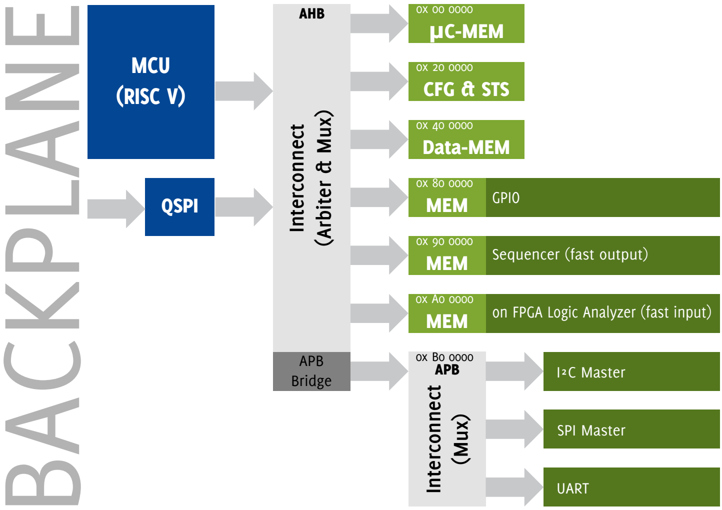

Figure 8: FPGA structure. Diagram: IMMS.

FPGA concept

A uniform FPGA design with a modular structure is to unify the different modules at the level of the hardware description language. The implemented design has similarities to a microcontroller design and implements an address-based bus system (AHB = advanced high-performance bus) in the same way.

On the master side of the bus there is a microcontroller core and a protocol converter for external access from the main module of the AMS ASIC Scope. These bus masters have access to memory areas, configuration registers and other module-specific components.

The protocol converter is a QSPI slave to AHB master converter. It provides direct bus access to slave components of the AHB. For example, the microcontroller's programme memory or measurement sequences and results can be transmitted via this.

The microcontroller receives its programming via a defined memory area, which is accessible from the AHB. It can operate the functions by accessing the registers of slave components and, in this way, carries out a measurement sequence that has been assigned to the module.

In addition to the predefined memory areas, the following components are available as bus slave components:

- GPIO registers
  . direct control of GPIO pins (General Purpose Input / Output)
  . Control of parallel interfaces
- Serial communications protocols (SPI, UART, I²C, ...)
- Sequencer for fast GPIO interactions
- Timer for synchronisation by signalling from main module
- Logic analyser for fast logging of digital inputs

Summary and Outlook

In the KI-EDA project, a novel and modular test system was developed that will support the development of new ASICs in the future by applying simulations and tests from the design environment to real circuits. The hardware developed implements this concept through a modular system with a main controller for controlling various modules for specific tasks. Their combination results in a setup that is specifically configured for the respective application. This fulfils the requirements for tests and enables the coverage of most test cases on the real circuit by:

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- Generation and recording of digital signals
- Digital communications via serial bus systems
- Analogue power supply with measurement of the supply current (up to 10mA at 10MS/s)
- Four-quadrant sources with up to ±10 V and ± 50 mA with measurement of current and voltage

During the KI-EDA project, the entire hardware of the AMS ASIC Scope was designed, developed and built. In addition, a modular hardware design for the logic components of the modules (FPGAs) was created. The further development of the AMS ASIC Scope in the follow-up project HoLoDEC will include the software implementation to realise the goal of “a testbench, but in hardware”.

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RESEARCH FIELD

MAGNETIC 6D DIRECT DRIVES WITH NANOMETRE PRECISION

The integration of actuation in all spatial directions, including the respective rotational axes, creates manifold and complex challenges for the developers of various disciplines working on ultra-precise positioning platforms. While the respective solutions of mechanical design, drives and metrology are still at least partially visible as shown, the results from controller design and electronics development remain mostly invisible. IMMS has nevertheless been advancing its research on magnetic 6D direct drives in all related disciplines in 2022. The most “visible” development was the new generation of vertical lifting and actuating modules presented in a specialist article. Photograph: IMMS.

Research field
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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Highlight of 2022 in our research on Magnetic 6D direct drives with nanometre precision

PTB and IMMS receive iENA bronze medal for new seal configuration for more precise displacement measurement in high-tech applications

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On 17 May, Physikalisch-Technische Bundesanstalt (PTB, Germany's national metrology institute) and IMMS were honoured with a bronze medal for their development "Seal configuration for an interferometer route partially arranged in vacuum" in the competition of the inventors' fair iENA at the Thuringian awards event of PATON – Patent Center Thüringen at Technische Universität Ilmenau. More than 350 inventions from 17 countries have already been presented at iENA from 4 to 7 November 2021. Due to the pandemic, PATON, which had presented the work at iENA and entered it into the competition, created the festive setting for the inventors to receive their personal awards and present their contributions in May 2022.

Dr Jens Flügge (left), PTB, and Steffen Hesse (right), IMMS, were honoured with a bronze medal in the competition of the iENA inventors' fair for their new sealing for more precise displacement measurement in high-tech applications. Photograph: IMMS.

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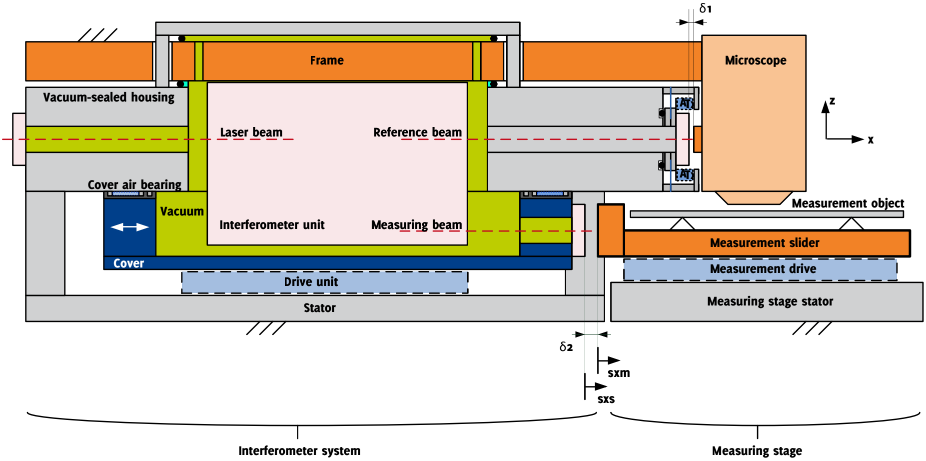
Dr. Jens Flügge, head of the department "Dimensional Nanometrology" at PTB, and Steffen Hesse, specialist for precision drive systems at IMMS, presented their solution on behalf of the team of inventors. This solution will help to make it easier to manufacture high-tech products with nanometre precision in the future, for example in semiconductor production. In contrast to other approaches, the invention allows the actual production process to be kept out of the vacuum while at the same time providing higher measurement accuracy.

Demand for precision machines is growing

The progressive miniaturisation of technical products is leading to a growing demand in many industrial sectors for precision machines with which the smallest structures and objects can be measured and processed with high precision. Many such objects have spatial dimensions in the millimetre to centimetre range, while surface features and functional elements are only a few micro- or nanometres in size. One example of this is exposure masks, which are used in semiconductor manufacturing to create structures for microelectronics chips with nanometre precision.



Simplified sectional view of the interferometer system with an exemplary embodiment of a sealing arrangement and a coupled measuring stage. Diagram: IMMS.

Interferometers enable high-precision measurements, but should operate in vacuum

Interferometers are used for precision measurements on these objects, especially for length measurements in the nanometre range. For the measurement, interferences are detected that occur when light waves are superimposed.

With high-precision requirements, even minimal changes in the refractive index in air due to temperature, pressure and humidity have a negative effect. To avoid this dominant source of error, it is of advantage to arrange the interferometers in a vacuum.

However, many measurement objects and processes are only suitable for use in a vacuum to a limited extent. For this reason, interferometers have long been used whose beam path runs largely in a vacuum and are encapsulated by metal bellows for this purpose.

New sealing arrangement separates vacuum for interferometer from drive and enables more precise measurements

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The alternative sealing arrangement developed by IMMS and PTB features an interferometer housing with an air-guided cover. ”By using suction channels and sealing gaps, we were able to seal the vacuum in the cover without contact”, explains Steffen Hesse from IMMS. As a result, the cover and housing can be moved frictionlessly in relation to each other – not only in the direction of measurement, but also transversely. “In this way, the cover, which encapsulates the measuring beam, can be tracked to the movement of the target very precisely, which is absolutely essential for highly accurate detection of the target position.”

Like the conventional bellows solution, the novel sealing arrangement thus reduces the measurement uncertainty of an interferometric measurement system without also having to operate the drive system with the object to be moved in a vacuum.

Compared to known solutions, other interfering influences on the measurement result can also be significantly reduced. “The completely differentially designed interferometer optics also contribute to this”, says Dr Jens Flügge from PTB. “We have additionally shortened the dimensions of the coupling between the measurement object, sensor system and interferometer by means of the interferometer arrangement, which reduces the sensitivity to variations in the ambient conditions such as vibrations and temperature. By carefully accommodating the forces created by the vacuum, we avoid unwanted deformations of the optics and the metrology frame that could distort the measurements.” The system can also be easily used in two-dimensional applications. A fully differential interferometer adapted to the design with sub-10 picometre noise and non-linearities was successfully commissioned.

German patent: DE 10 2019 117 636 B3, **Patent applicant/owners:** IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH); Physikalisch-Technische Bundesanstalt (PTB), **Inventors:** Steffen Hesse, Michael Katzschmann, Hans-Ulrich Mohr, Dr. Christoph Schäffel (IMMS); Dr. Jens Flügge (PTB)

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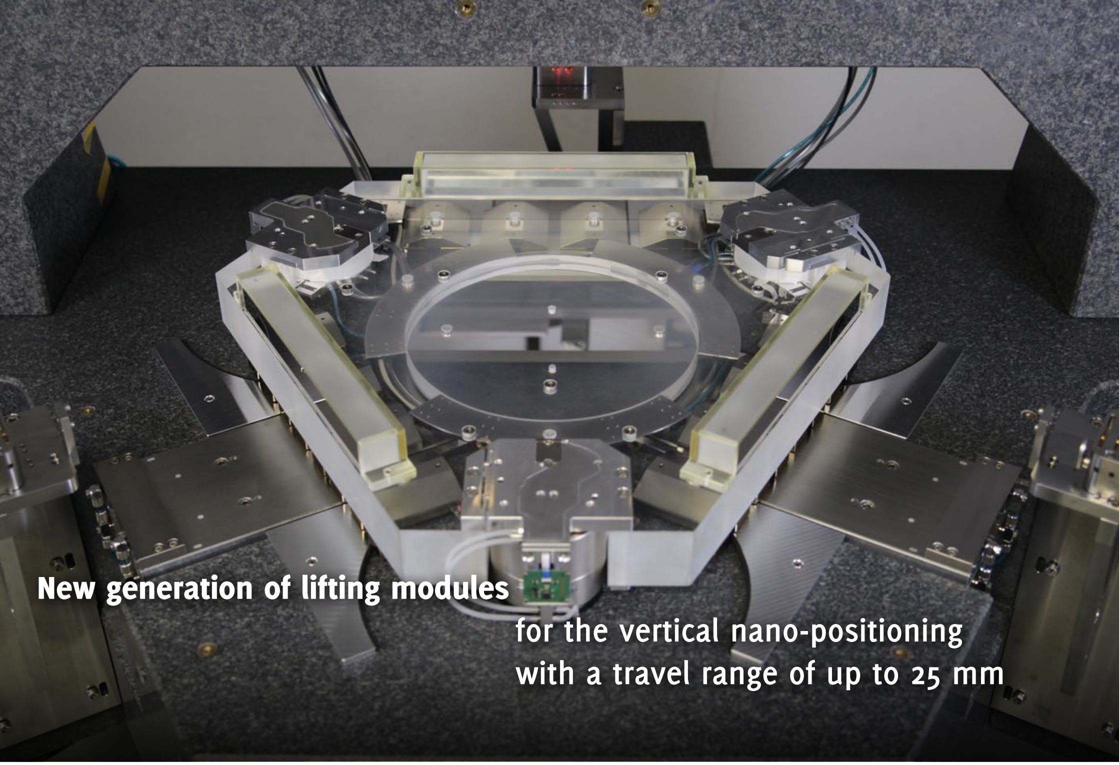

New generation of lifting modules for the vertical nano-positioning with a travel range of up to 25 mm

At IMMS, new lifting modules for up to 15 kg load capacity and 25 mm stroke each have been developed and integrated into a 6D drive system as vertical nanopositioners that combine a practically powerless carrying of the payload with nanometre positioning capability. Photograph: IMMS.

Introduction and motivation

For positioning systems with nanometre positioning accuracy, there has been a steadily growing number of applications in recent years. In semiconductor manufacturing and many related high-tech areas, positioning resolution in the sub-nanometre range is now being sought. Also, in the precision manufacturing of mechanical components, optical inspection, or in the qualification of sensor systems, the requirements are increasingly shifting from a few tens of nanometres to the lower nanometre range. Compared to the lateral movement of the object, vertical positioning once again takes on a special role, since here the quite considerable moving mass must be carried permanently, but as far as possible without heat emission. At IMMS, new lifting modules for up to 15 kg load capacity and 25 mm stroke each have been developed and integrated as vertical nano-positioners into a 6D drive system, combining practically powerless carrying of the payload with nanometre positioning capability.

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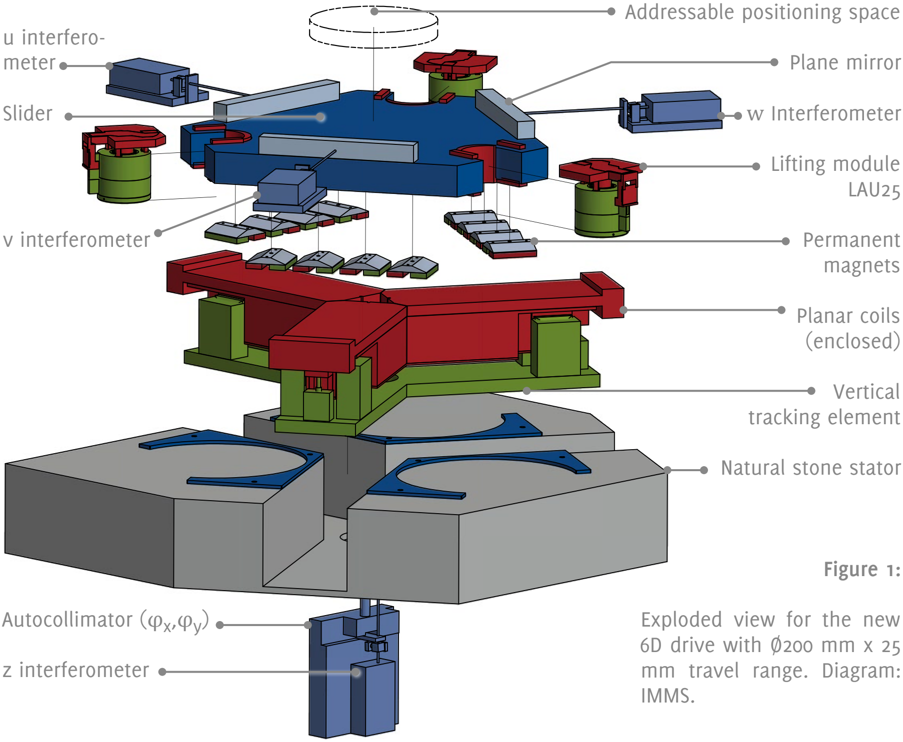

Figure 1:

Exploded view for the new 6D drive with Ø200 mm x 25 mm travel range. Diagram: IMMS.

6D direct drives for even greater travel ranges

In current research work, IMMS is realising a novel nano-positioning system with a drastically increased working range compared to *previous drives*. The planar range of motion grows to Ø 200 mm, while the available vertical stroke increases from formerly 10 to 25 mm. This creates a 6D drive system that can position even larger objects, such as wafers, masks, or optical lenses, with high precision in space as part of a fabrication or inspection application in the three spatial axes and the respective rotation around these axes.

www.imms.de/inpos

Figure 1 and figure 2 show the realised nano-positioning system: The moving object, the slider, is a large central body made of quartz glass with lateral mirror surfaces. The position of the slider is measured in all six degrees of freedom by laser interferometers and autocollimators without contact and with nanometre precision. Permanent magnets are mounted on the underside of the slider, to which the horizontal drive forces can be applied by planar coils. By a star-shaped arrangement of these drive units, the slider can be positioned contactless and field-guided in the xy-plane. For vertical positioning in the z-direction, a new generation of lifting modules

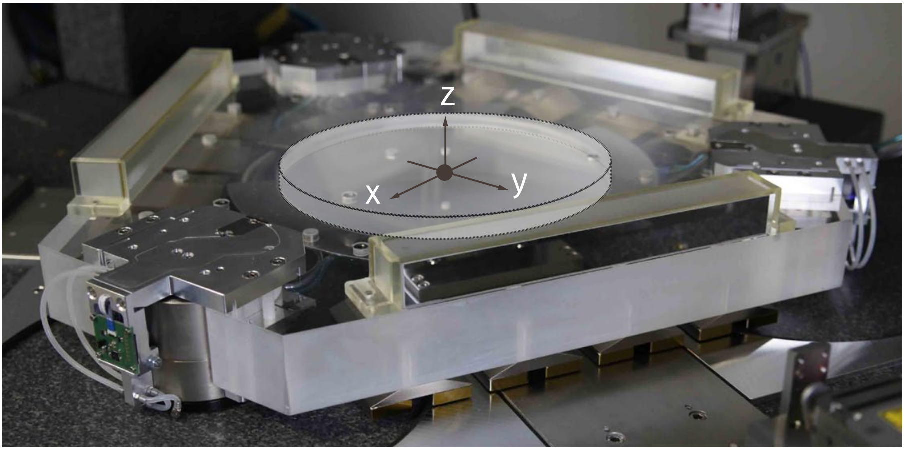

Figure 2: Photograph of the constructed drive system; the addressable positioning space is marked accordingly. Photograph: IMMS.

has been developed, which are placed at the three corner points of the slider, where they allow frictionless planar guidance of the slider and at the same time its sensitive vertical adjustment, too. In this way, the z-position and the angular positions of the slider are adjusted with high precision by the three lifting modules. In addition, for large vertical strokes, the planar drive coils follow the slider movement to maintain its efficiency over the entire stroke by keeping the air gap constant. In addition to the integrated planar drive system, the specially developed lifting modules represent the core functional components of this 6D drive concept. The integration of several functions (carrying, guiding, driving, measuring) in a highly integrated and compact design enables the step from a planar system (3D) to a controlled 6D positioning of the slider.

Novel lifting modules for increased load and stroke

The design know-how for the new generation of lifting modules is based on many years of IMMS' research activity in this field and a development guide that has emerged from this. This enables a fast and targeted design of the positioning modules for new stroke and load specifications and changed boundary conditions. For the present concept, the rotor mass of approximately 40 kg and the payload of 5 kg are distributed nearly equally over all three lifting modules, so that each is loaded with approximately 150 N. Along with the increased load and the longer stroke, a larger installation space (approximately ∅ 85 mm x 90 mm) is also available compared with earlier applications. This allows better adaptation of the included actuator elements to the load situation and better integration of the other functional components.

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The core elements of each lifting module are the two actuators working in parallel: A pneumatic cylinder primarily and quasi-statically compensates the weight force and an electromagnetic actuator generates the precise and dynamic positioning forces. The pneumatic actuator is located concentrically inside the electromagnetic actuator. As a result, both actuator forces are on the same effective axis, thus an extremely compact design is possible.

In the first step of the new design, the pneumatic weight compensation is adapted to the load to be supported and the frictionless vertical guide is structurally integrated into it. The design and production of the air bearing components is carried out here together with IMMS' long-standing development partner, the air bearing specialist AeroLas. The surrounding design space is divided among the components of the electromagnetic drive using an optimisation algorithm and finite element magnetic field simulations contained therein. The goal of the optimisation is to minimise the heat input during operation to keep thermal disturbances to the machine metrology low. The result of the simulations in Figure 3 shows the final geometry of the coil, the back iron parts (Fe) and the permanent magnets (M). This dimensioning results in the magnetic field lines penetrating the range of motion of the coil (white frame) very uniformly.

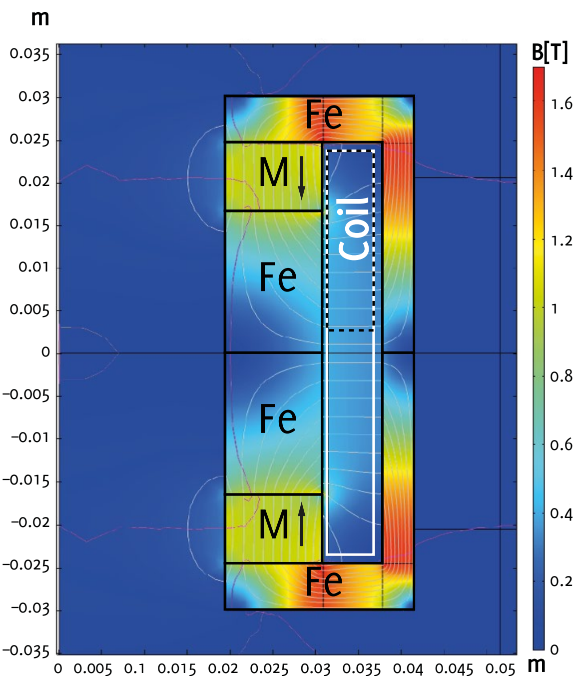

Figure 3:

Magnet field simulation (M: magnet, Fe: back iron, white frame: travel range of the coil, coil exemplarily at the upper end of the travel range).

Diagram: IMMS.

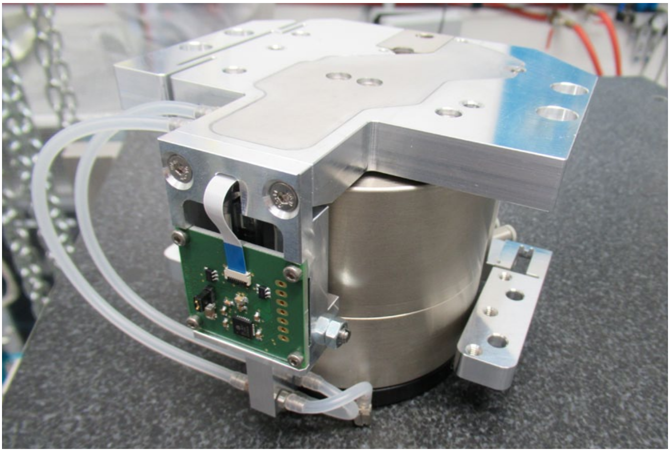

Figure 4:

Assembeld lifting unit for 25 mm travel range and 15 kg load capacity.

Photograph: IMMS.

In addition to the pneumatic and electromagnetic design, the electrical and pneumatic supply and return lines are largely relocated to the inside of the mechanical system and merged to a single interface during the design process. When the lifting modules are mounted on the slider, all the necessary supply lines are connected via this universal interface.

Implementation and validation of the lifting modules as vertical nano-positioners

Mounted on the slider and implemented in the control periphery, the three lifting modules are able to position the slider vertically (z-direction) and in the two tilting axes (r_x, r_y). Figure 5 shows the first results for the control deviation at constant

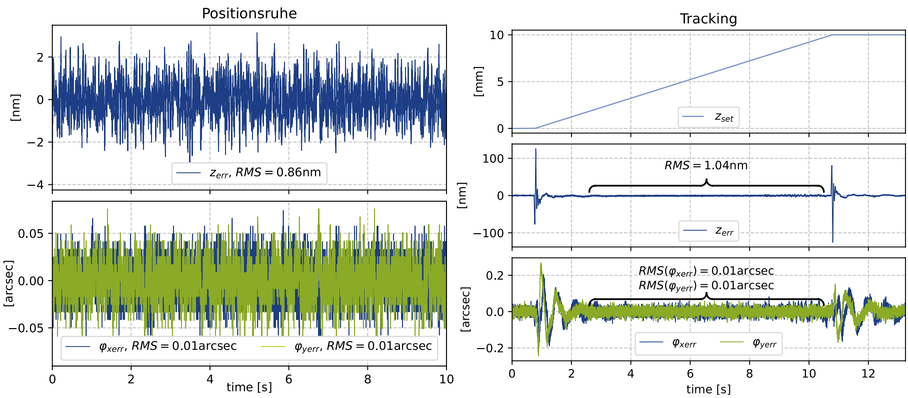

Figure 5: Measurement results for the vertically controlled operation with three lifting modules attached to the slider. Left panel: control deviation of the vertical position (z_{err}) and two tilting angles (φ_{xerr}, φ_{yerr}) at constant setpoint; Right panel: target trajectory and related control deviation while traversing a trajectory. Diagrams: IMMS.

target position (left panel) as well as during the traversing of a target trajectory increasing in z-direction (right panel). During standstill at a target position, the control deviations of the vertical position (z_{err}) and the tilt angles (φ_{xerr}, φ_{yerr}) are very small. The root mean square (RMS) of these error signals is only 0.86 nm and 0.01 arc seconds, respectively. During vertical motion from 0 to 10 mm with constant velocity (Figure 5, right panel), the RMS value of the z-control deviation increases only marginally to 1.04 nm. Only in acceleration and braking phases appreciable deviations from the nominal trajectory occur, which are smaller than 150 nm in the current configuration and can be further reduced by additional control measures (feedforward control, jerk limitation, etc.).

Progressive development towards a 6D nano-positioning system

Right off, nanometre-level position control was achieved with the newly developed vertical drives. This confirms the chosen design approach and the suitability of the integrated solution found as a combined drive and guide element for vertical nano-positioning. At the same time, this work also further extended and refined the development guide for the design and optimisation of such vertical actuators and added a successfully realised design variant for 25 mm stroke.

The lifting modules and the partial results already achieved with them are thus an important intermediate step on the way to commissioning the complete system controlled in 6D.

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Such a 6D nano-positioning system, with its large planar and vertical travel range, thus represents an excellent basis for the implementation of high-tech probing or manipulation systems, such as atomic force microscopy, and opens up completely new application scenarios for such high-tech applications.

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SERVICES

FOR RESEARCH AND DEVELOPMENT

Idea / Concept → Design / Development → Characterisation / Test → Production transfer

Compliance with industry standards and qualification

Risk and quality management

IMMS supports its partners in the development from the idea to series production. The picture shows an example of one of the embedded systems that has been developed and supported through to series production by IMMS: the intelligent current measuring clamp EMCheck® ISMZ I. Photograph: IMMS.

Services for research and development

We provide support during the entire R&D process from concept to product development ranging from the design of mechanical and electronic devices and modules to hardware and software system integration services, prototype construction and transfer to industrial production. We support our customers from concept to series production with a complete offer or with the following partial services for

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- IC design methods: **www.imms.de/eda**
- Test and characterisation: **www.imms.de/test**
- Development of embedded systems: **www.imms.de/embedded**
- Development of mechatronic systems: **www.imms.de/mechatronics**
- MEMS – simulation, design and test: **www.imms.de/mems**
- Finite Element Modeling: **www.imms.de/fem**

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Example: Service offering for MEMS – simulation, design and test

As a design house for the open technology platform XMB-10 from X-FAB, we develop acceleration sensors according to customer specification in a semi-automated design process. For the testing of MEMS, we focus on the vibrometric investigation of sensors. This includes functional tests, e.g. of resonators up to 1.2 GHz, as well as indirect parameter identification. From vibrometric measurement data and FE parameter calculations, material stresses of beam- and membrane-based sensors can be determined.

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We have been supporting research institutes in the field of MEMS for a long time. In recent years, we have already been able to successfully transfer some of the research results into products of our industrial partners.

Steffen Michael was honoured with a bronze medal for his invention "Micro-electromechanical acceleration sensor" in the competition at the iENA inventors' fair.

Photograph: IMMS.

IMMS receives iENA bronze medal for microelectromechanical acceleration sensor

On 29 November 2022, IMMS was honoured with a bronze medal for the development "Microelectromechanical acceleration sensor" in the competition of the inventors' fair iENA for the Thuringian awards event of PATON – Landespatentzentrum Thüringen at Technische Universität Ilmenau. PATON had presented the work on behalf of the inventor Steffen Michael at the iENA in Nürnberg, Germany, at the end of October and entered it in the competition.

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The novel design of this microelectromechanical acceleration sensor is optimised in terms of process tolerances and achieves high sensitivity on the smallest possible surface for the XMB10 process family from X-FAB. Both of these features enable manufacturers, e.g. from the automotive or communications sectors, to integrate chip-sized MEMS sensors, which can be produced with low-cost standard technology, into their systems. Microelectromechanical sensor systems (MEMS) are used to measure acceleration with miniaturised measurement technology. The patent enables the design of efficient z-acceleration sensors in XMB10 technology, which make it possible to measure accelerations from the sensor plane.

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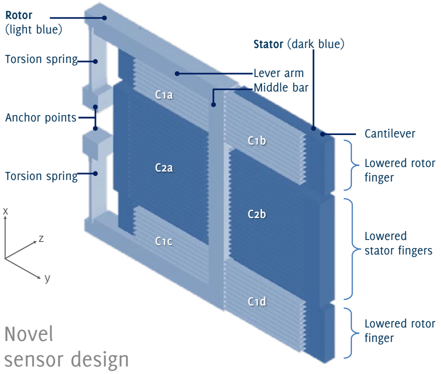
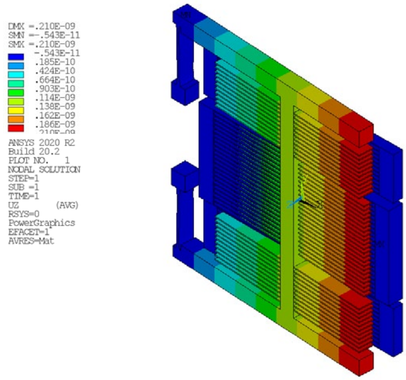
Comb structures are used for this purpose, with which accelerations are detected out of the sensor plane via a capacitive measuring method. Capacitive MEMS acceleration sensors consist of comb electrodes with interlocking finger structures. Accelerations are detected by the displacement of a rotor electrode (seismic mass) hung on a spring relative to a stator electrode. This causes a change in capacitance, which can be evaluated electronically either directly or differentially.



Novel sensor design of the z-acceleration sensor. Diagram: IMMS.



It is achieved in the XMB10 technology for the measurement of accelerations vertical to the sensor plane via thinned finger structures for rotor and stator fingers. Torsion springs are used to achieve high sensitivity with minimised sensor area. The rotor electrode consists of a frame with two parallel lever arms and a centre bar running between the lever arms. The lever arms are each suspended from one of two torsion springs. The centre bar runs parallel and at a distance from the torsion springs. In this design, the change in capacitance is achieved by changing the area of opposing electrodes.

With the new design, accelerations can be measured out of the sensor plane with a high sensitivity and on a small sensor surface. At the same time, the sensor plane itself has a high stiffness in the x-y direction and the sensor has a low susceptibility to errors. Due to the design, the acceleration sensor can be manufactured in high quantities using cost-efficient MEMS technology. In addition, the design can be combined with other components or acceleration sensors, e.g. to form a 3D sensor.

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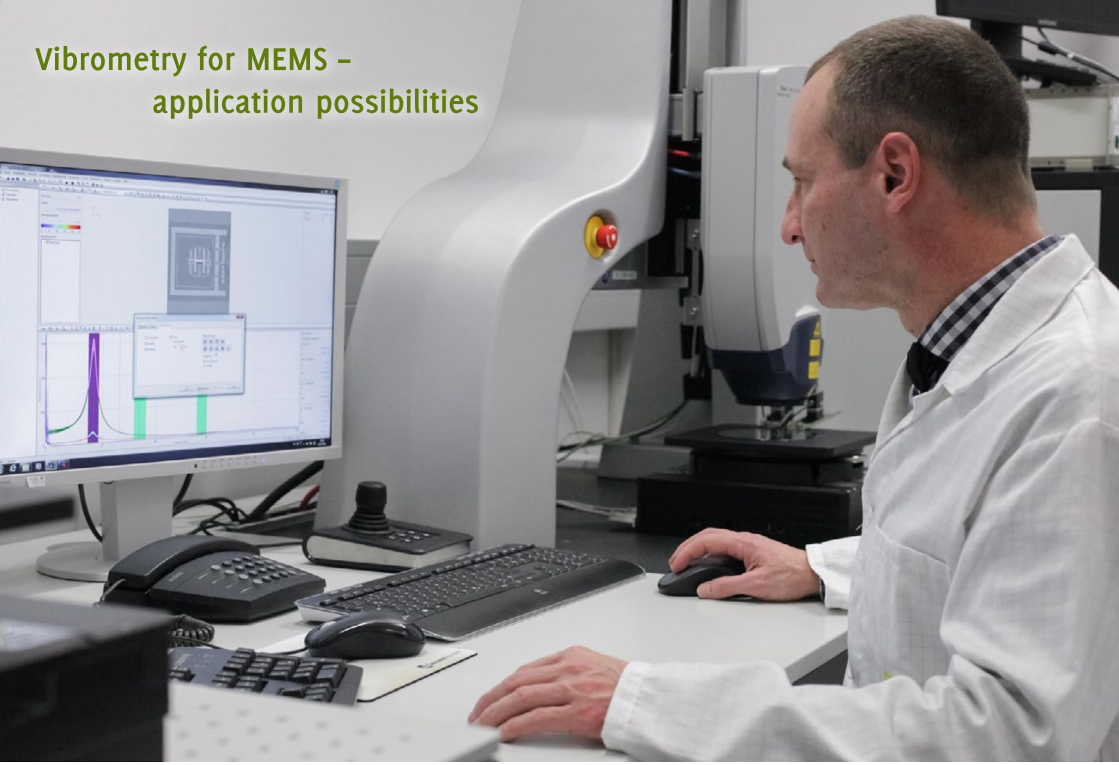
The patent allows different sensor designs that can be manufactured with the same MEMS technology. Thus, for example, the seismic mass can be optimised, momentums occurring at the torsion springs can be distributed more evenly and parasitic influences can be reduced. A system adapted to the design was successfully put into operation.

www.imms.de/patent

German patent: DE 10 2020 119 371 B3, **patent applicant/owner:** IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH), **inventor:** Steffen Michael

Vibrometry for MEMS – application possibilities



Measuring workstation for the acquisition of 3D vibrations on MEMS. Photograph: IMMS.

Motivation and overview

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Microelectromechanical systems (MEMS) have been increasingly penetrating many areas of daily life as sensors for several years. They can be found, for example, in cars as tyre pressure sensors or acceleration sensors for airbags and navigation devices as well as in smartphones with MEMS-based microphones and acceleration sensors.

Such applications will continue to advance in the coming years. The corresponding high growth in the sensor market goes hand in hand with great cost pressure on the one hand and high quality requirements on the other hand for MEMS that are manufactured similarly to microelectronic chips at wafer level. Their quality is usually tested as early as possible to minimise reject rates of assemblies or even finished systems such as smartphones.

For quality inspections in sensor production, non-destructive optical measuring methods are an important tool in addition to electrical measuring methods. With these it is possible to examine the micrometre-small and very sensitive MEMS structures without probing and thus without destruction. Microscope-based methods can

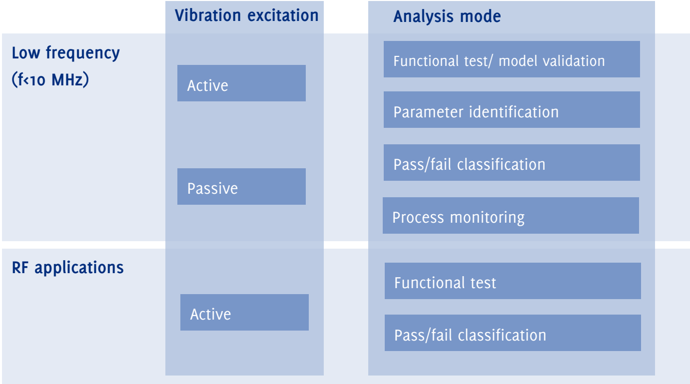

Figure 1:

Classification of different vibrometer applications for MEMS testing.

Diagram: IMMS.

be used, for example, to determine lateral dimensions and thus evaluate manufacturing processes. Classical optical measurement methods, however, do not allow the detection of material parameters such as material stress or local inhomogeneities such as inner membrane cracks below closed cover layers. Vibrometry measures the natural frequencies of the MEMS structures without contact, which are set into vibration and examined with a laser. The frequencies in emitted and reflected laser beams that are characteristic of each MEMS structure are analysed using the Doppler effect. This makes it possible to determine inhomogeneities or material stresses by evaluating the measured natural frequencies. The short measurement time of less than 0.1 s with optimised test setups also predestines vibrometry for quality control in sensor production over the entire production cycle from wafer production to packaged sensors, also for cost reasons. An overview of the possible applications of vibrometry in the field of MEMS is shown in Figure 1.

IMMS has many years of expertise in the field of vibrometry and, with the available measurement equipment consisting of several vibrometers as well as semi-automatic test stations, offers customers the possibility to carry out vibrometric measurements both accompanying the design process of sensors and for the quality assurance of entire wafers. Finite element (FE) simulations for parameter identification and for determining the functional dependence of parameters of interest on the natural frequencies can also be carried out at IMMS.

Three areas are relevant when using the vibrometric measurement method:

– the vibration excitation of the sensor structures, which are often passive, i.e. without functional elements for vibration excitation,

- the application-specific post-processing of the measurement data of the vibrometer as well as
- the process monitoring of the relevant sensor parameters across the various manufacturing steps, including the detection of process errors such as membrane cracks.

In the following, these three components and the application possibilities will be discussed in more detail.

Excitation of the natural frequencies

A prerequisite for the vibrometric measurement of natural frequencies is their excitation. While vibration excitation is an inherent feature of sensors such as resonators or inertial sensors due to functional elements such as piezoelectric layers or capacitive comb structures, a large number of e.g. membrane-based sensors have no functional elements for generating mechanical forces. With such passive sensors, the vibration excitation must be external. There are two different methods for this. On the one hand, vibrations of sensor structures can be thermally excited by means of a laser, on the other hand, electrostatic excitation is possible in a frequency range of up to 10 MHz. For this purpose, an electrode connected to a high-voltage amplifier is positioned at a distance of a few micrometres above the sensor surface. The electrode is made of transparent material (ITO – Indium Tin Oxide) and is mounted on a glass carrier to achieve the greatest possible electrostatic force without interfering with the beam path of the vibrometer.

Application possibilities of vibrometry

Vibrometry offers a wide range of applications beyond the obvious ones, such as functional tests of sensors where frequencies are part of their functionality (e.g. resonators). In addition to the detection of manufacturing defects such as membrane cracks, this is above all the indirect identification of geometry and material parameters by means of measurement and simulation data. Especially in the determination of material parameters like Young's modulus and material stress, vibrometry has a unique selling point compared to other non-contact, non-destructive measurement methods. Another advantage of vibrometry is that it can be used for quality control during the entire process, from wafer production to packaging.

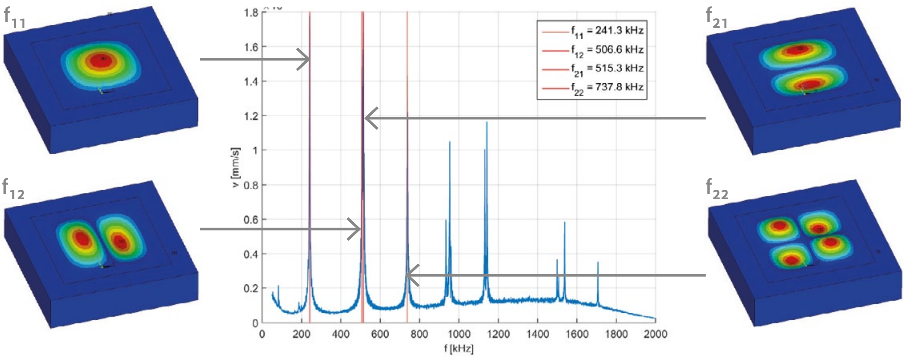

Figure 2: A frequency response function (FRF) with split frequency peaks. Diagram: IMMS.

Good/bad classification

A simple application is the good/bad classification of sensors based on a "learning phase" with good and bad reference sensors. If the natural frequencies of functioning and defective sensors differ, the standard deviation can be determined from the measurement of a significant number of good reference sensors as a criterion for good/bad classification in sensor production.

Due to this symmetry, nominally symmetrical sensor structures such as circular or square membranes have a large number of natural frequency pairs that are out of phase with each other at the same value. In the case of asymmetries, these frequency pairs split. Such split frequency pairs can be used to detect defects such as membrane cracks or the occurrence of asymmetrical material stresses, as can occur, e.g., as a result of packaging processes. IMMS has developed a frequency response postprocessing tool that detects split frequencies.

Parameter identification

The method of indirect parameter identification is based on the one hand on the vibrometric measurement of the natural frequencies and on the other hand on the simulation data of a modal analysis to determine the dependence of the natural frequencies on the geometry and material parameters of interest. By means of an optimisation, the sensor parameters are then determined from the measured data.

Depending on the structure to be investigated, the procedure allows the identification of one to, as a rule, a maximum of three parameters. The minimum number of natural frequencies to be measured is then derived from the number of parameters to be identified. If more natural frequencies can be measured than necessary, an estimated identification error (EIE) can be determined from these.

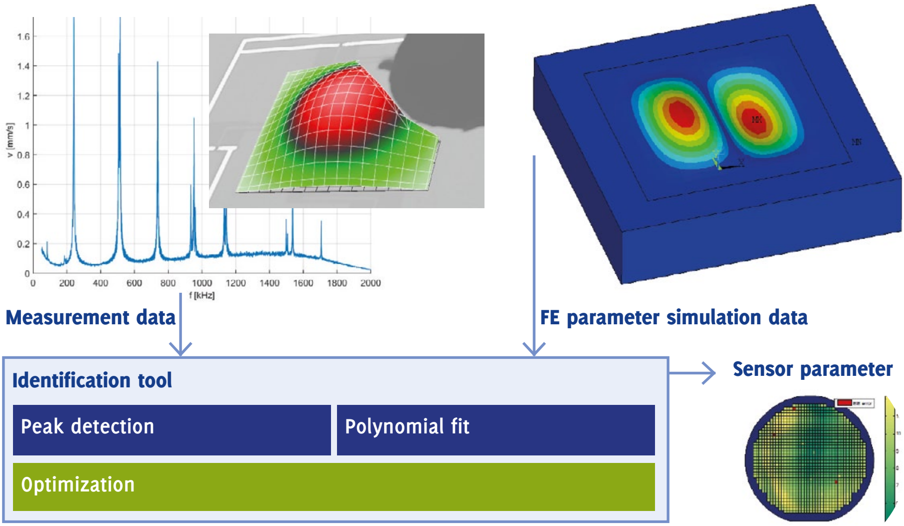

Figure 3: Structure of the parameter identification. Diagram: IMMS.

From the measured frequency response, the parameters natural frequency value, amplitude and quality factor can be extracted, and in the case of several measuring points, also the natural form. The natural frequency value is always used for parameter identification. If the determination of the internal pressure of a cavity is of interest, the quality factor also flows into the parameter identification. The mode shapes are particularly considered at frequencies that are close to each other, as the influence of material stresses can lead to a changed sequence compared to the nominal one. All parameters of interest can be determined from the frequency value, quality and shape. Therefore, there is no need for additional consideration of the frequency amplitudes; moreover, a complex calculation of the vibration amplitudes depending on the excitation (especially if this is done externally) is avoided.

Phases of Identification

The parameter identification procedure can be divided into three phases. First, it must be investigated whether the parameters sought can be determined with the required resolution using the procedure. Accordingly, prior to parameter identification, a sensitivity analysis is performed to determine the sensitivity of the natural frequencies versus the parameters of interest. For simple structures or for basic investigations, analytical formulas can be used; for more complex structures, FE programs like ANSYS are suitable for such a sensitivity analysis. If the structure to be investigated does not have the desired sensitivity, the desired parameters can be determined using specially designed test structures.

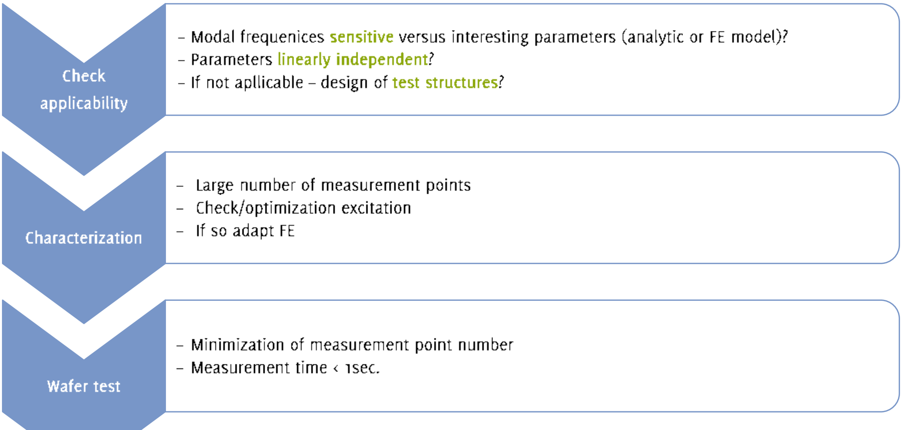

Figure 4: Phases of the parameter identification. Diagram: IMMS.

To get to know the sensor, the characterisation phase is followed by frequency measurement using a dense network of measuring points. This is accompanied by the selection of suitable frequency modes for identification as well as validation and, if necessary, adaptation of the FE model. In the final third phase, the process is optimised for use in wafer production by, among other things, minimising the number of measurement points with regard to a short measurement time, which is usually significantly less than one second.

Example – parameter identification of quadratic membranes

Examples for parameter identification can be well illustrated by the formula for the calculation of natural frequencies of fixed quadratic membranes with material stress (the simplified clamping conditions compared to real sensors do not change the basic statement on parameter dependencies)

$$f_{m,n} = \frac{1}{2a\sqrt{\rho}} \sqrt{(m^2+n^2)\sigma + \frac{Eh^2(m^2+n^2)^2\pi^2}{12a^2(1-\nu^2)}}$$

with Young's modulus E, density ρ, Poisson's ratio ν, membrane thickness *h* and size *a* as well as the intrinsic stress σ. The ratio of the geometry term to the stress term under the root is relevant for the possibilities of parameter identification. If the ratio of the geometry term to the stress term is very large, as in the case of pressure sensors, it is possible, for example, to determine the membrane thickness for a given membrane size. With very thin membrane-based sensors such as microphones or thermopiles, the ratio is reversed. Due to the very large stress term compared to the geometry term, the method is predestined for an exact identification of the material stress.

Development of test structures

For the use of measured natural frequencies for the determination of material or geometry parameters, the prerequisite must be fulfilled that the natural frequencies have a functional dependence on the sensor parameters of interest. If several parameters are to be identified, they must also be linearly independent of each other. If these prerequisites are not fulfilled with the given sensor structures, however, there is the possibility of parameter identification by means of test structures specially designed for vibrometric measurement or the combined evaluation of two different structures.

An example of linearly dependent parameters are the thickness and size of stress-free square membrane structures – by means of the natural frequency values, only the ratio of thickness to size can be determined, but not the values themselves. The nominal identification of a parameter (e.g. membrane thickness) is also a de facto identification of several parameters, if the process-related tolerances of the model input variables (e.g. membrane size in KOH etching) mean that a sufficiently precise determination of the parameter of interest is no longer possible. A solution approach to identify the membrane thickness here is the combined evaluation of two rectangular test structures of different dimensions. By measuring the first three natural frequencies of two rectangular membranes of different sizes, membrane thickness and sizes can thus be determined.

The identification of Young's modulus and material stress by means of beam-based structures is another example of the solution approach of combined evaluation of measurement data from different structures. Since the Young's modulus and material stress cannot be identified simultaneously with high accuracy in a beam clamped on both sides, the Young's modulus is first determined on the cantilever, which is stress-free per se, and then the material stress in the beam clamped on both sides.

As already shown in the examples for parameter identification, tensile stresses can be identified with high accuracy by means of vibrometric measurements, especially for very thin membrane and beam structures. In the case of compressive stresses, however, identification is only possible as long as the buckling stress has not yet been exceeded, because when structures are buckled out their natural frequencies are quasi-constant. The solution to still enable the use of the method at such high compressive stresses is the design of test structures with segments in which a tensile stress is established by using relaxation processes during the release. An example of such a test structure is a rhombus with a central web. The pressure-braced outer legs of the rhombus lead to a tensile stress of the central web, which can be used for vibrometric measurement or identification of the material stress.

Summary

Thanks to its expertise and the software tools developed, IMMS enables customers to apply vibrometry in the field of MEMS. This includes the vibration excitation of passive MEMS through a device-specific setup as well as the “translation” of the measured frequency response into parameters relevant for development and processing such as the material stress by means of extraction of frequency peaks and subsequent parameter identification. The developed FE library modules also allow efficient modelling of membrane and beam based membrane structures for the design of process-specific test structures for the identification of geometry and material parameters.

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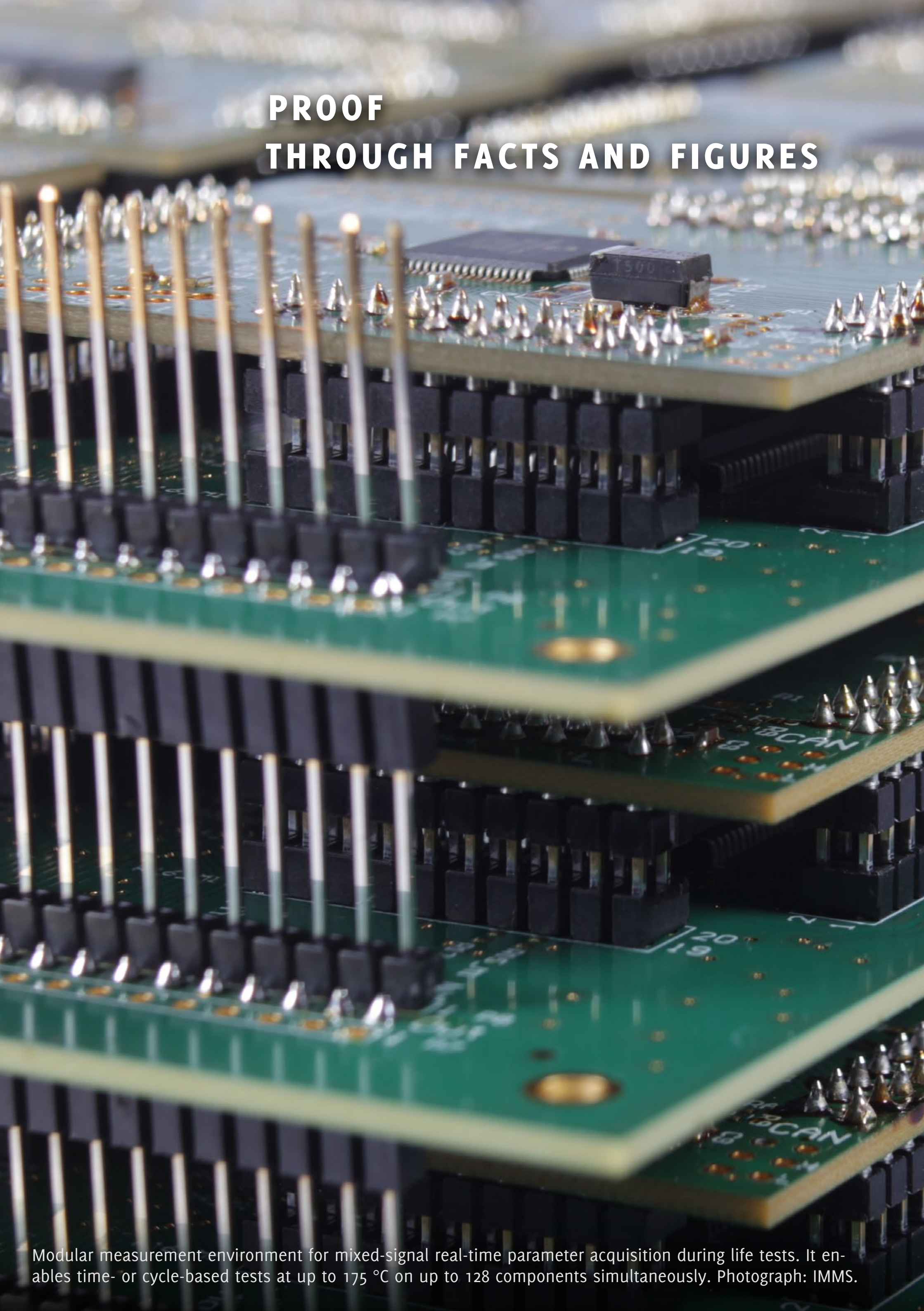
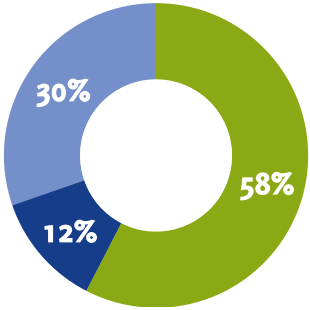
Contact person: Dipl.-Ing. Steffen Michael, steffen.michael@imms.de

PROOF THROUGH FACTS AND FIGURES



Modular measurement environment for mixed-signal real-time parameter acquisition during life tests. It enables time- or cycle-based tests at up to 175 °C on up to 128 components simultaneously. Photograph: IMMS.

Staff structure



Scientists | administration | students

At the end of the 2022 financial year, 99 employees of various nationalities and disciplines were working at IMMS. Of these, 57 scientists and 30 students were employed in research and development. This corresponds to a share of around 88 % of all **employees**. In addition, 4 of the 12 employees assigned to administration were directly appointed to support science.

As part of their training in practice-oriented research, a total of 56 students were supervised at IMMS during the 2022 financial year, including 8 Bachelor's theses and 7 Master's theses, and 6 members of staff were enrolled as doctoral students at a university.

Despite the noticeably increasing competition for the outstanding minds, it was possible to recruit even more researchers to work at IMMS in 2022, but the planned demand for scientists could not be completely covered.

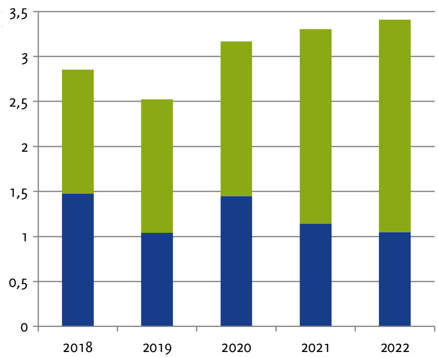
As in previous years, the financial year was characterised by the work on public research projects and the transfer of research results to industry (industrial contract research). The growth of the previous years could be continued, so the **third-party funding earnings** (project earnings) increased by around 3 % in 2022 compared to the previous year.

The publicly funded project business (funded projects) was further expanded compared to the previous year. Earnings from public project grants were 9% higher than in the previous year.

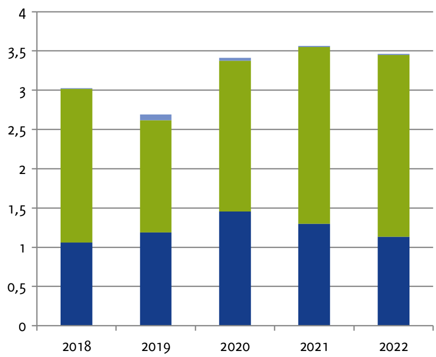
In 2022, 2 publicly funded research projects were started. In the 2022 financial year, earnings from industrial contract research (industrial earnings) were about 8% lower than the high earnings of the previous year. As in previous years, industrial

1 *As the employment figures given are actual numbers for 31.12.2022 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 €



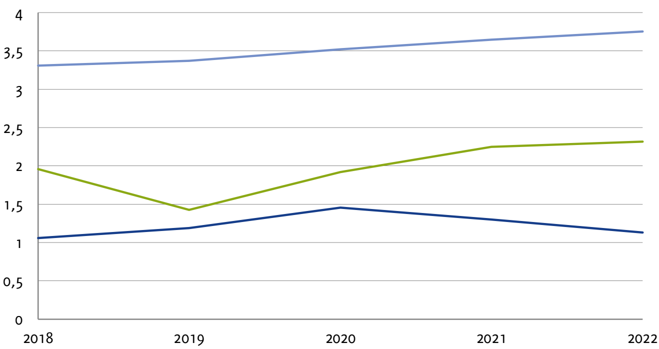
contract research was predominantly shaped by a large number of small-scale contracts with SMEs in Thüringen (approx. 50%).

Overall, project revenues were around 3 % below the previous year's value. The distribution of total **third-party funding revenue** (project revenue) between revenue from funded projects and revenue from industrial contract research largely corresponds to the distribution of earnings.

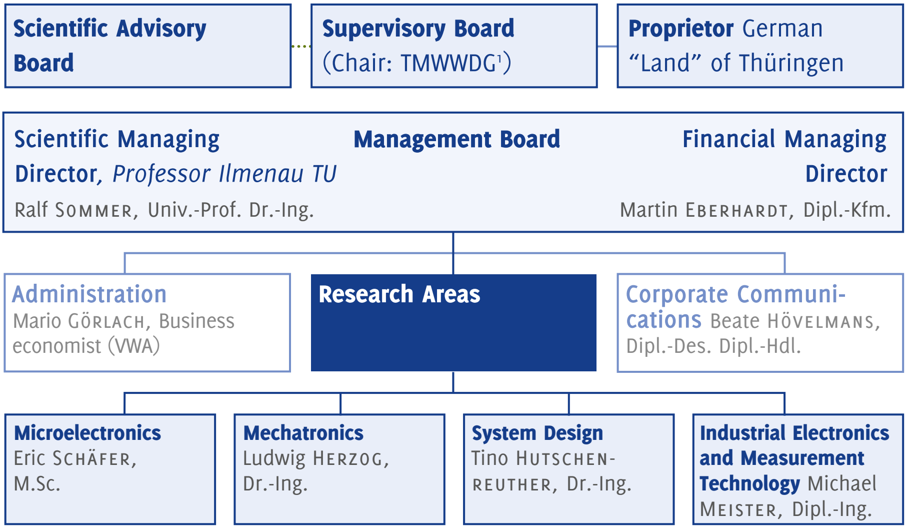
In 2022, the internal research groups funded by the German Land of Thüringen were again able to pursue important research topics for the strategic further development of IMMS. **Institutional funding** (basic funding) from the Land of Thüringen continued to be an essential precondition for the innovative strength of the institute.

www.imms.de/funding

Pillars of financial support in million €



Organisation*



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* as of 31 December 2022

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› Distributed measurement + test systems
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› Contents
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* as of 31 December 2022

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 sensor technology, lecture
- Technical electrodynamics, lecture
- Superconductivity in information technology, lecture
- Project seminar ATET

Events

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Conferences / events with contributions by IMMS

27/02/2022 – **TuZ 2022**, 34th ITG/GI/GMM workshop on Test methods and reliability of circuits and systems, *talk*, online

09/03/2022 – **Vertrauenswürdige Elektronik**, BMBF Digital Conference on Research and Innovation for Technological Sovereignty, *2 talks*, online

10/05/2022 – **21. ITG/GMA Fachtagung Sensoren und Messsysteme 2022**, accompanying conference of the SENSOR + TEST 2022 trade fair, *talk*, Nürnberg

30/05/2022 – **EUSPEN 2022**, euspen's 22nd International Conference & Exhibition, *talk*, Genf

12/06/2022 – **SMACD 2022**, International Conference on Synthesis, Modeling, Analysis and Simulation Methods, and Applications to Circuit Design, *talk*, Villasimius, Sardinia, Italy

15/06/2022 – **CIVEMSA 2022**, The IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications, *talk*, Chemnitz

28/06/2022 – Silicon Saxony Day, Future technology and business solutions from the areas of hardware, software and connectivity, *talk, exhibition booth, demo*, Dresden
22/08/2022 – CCTA 2022, 6th IEEE Conference on Control Technology and Applications, *2 talks*, Trieste / hybrid
15/09/2022 – FGSN 2022, expert meeting on wireless sensor networks 2022 of the GI/VDE-ITG specialist group on communications and distributed systems, *talk*, Berlin
22/09/2022 – Regulars' Table Predictive Maintenance of the Smart System Hub Dresden, *talk, moderator*, online
27/09/2022 – elmug4future, Technology conference on "Energy supply – a complex growth market in transition", talk, exhibition booth, Friedrichroda
29/09/2022 – FED Conference, 30th Conference of the Professional Association for Design, Printed Circuit Board and Electronics Manufacturing (FED), *talk*, Potsdam
09/11/2022 – Künstliche Intelligenz heute und morgen, a VR-Bank Rudolstadt event on AI topics with SMEs, *talk*, Rudolstadt
15/11/2022 – EUSPEN 2022, Euspen Special Interest Group Meeting: Precision Motion Systems & Control 15th – 16th November 2022, *talk*, 's-Hertogenbosch, Niederlande

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Workshops / IMMS as host, organiser or co-initiator

11/01/2022 – AI Developers' Round Table, *talk, organisation, moderator*, online
25/01/2022: – Retrofitting, event series of the Smart Sensor Systems Model Factory (IMMS GmbH) of the SME Digital Centre Ilmenau (Mittelstand-Digital), part 1/3: Data acquisition through retrofitting, *co-organiser, talk*, online
08/02/2022 – Retrofitting, SME Digital event series, part 2/3: Data connection through retrofitting, *co-organiser, talk*, online
10/02/2022 – Regulars' Table Predictive Maintenance, Smart Systems Hub, *talk*, online
08/03/2022 – Retrofitting, SME Digital event series, part 3/3: Data processing through retrofitting, *co-organiser, talk*, online
16/03/2022 – BarCamp @ DATE 2022, BarCamp on electronic design automation (EDA), microelectronics and (embedded) systems design, *workshop*, online
17/03/2022 – Decarbonisierung der Wirtschaft, expert panel of Ilmenau TU, ELMUG eG, PolymerMat e.V. & SME Digital on decarbonisig economy, *co-organiser*, Ilmenau
13/09/2022 – AI Developers' Round Table, *co-organiser, co-moderator*, online
15/09/2022 – Fachkräftemangel, expert panel of Ilmenau TU, ELMUG eG, PolymerMat e.V. & SME Digital on kills shortage, *co-organiser, co-moderator, talk*, IMMS Ilmenau

05/10.2022 – Ersti-Woche Freshers' Week at Ilmenau TU, *city rally station*, IMMS Ilmenau

11/10/2022 – AI Developers' Round Table, *co-organisator and Co-moderator*, Ilmenau

10/11/2022 – Mikro- und Nanotechnologien, expert panel of Ilmenau TU, ELMUG eG, PolymerMat e.V. & SME Digital on micro- and nanotechnology for SMEs, *co-organiser*, Ilmenau

06/12/2022 – Regulars' Table Smart Sensor Systems, SME Digital event series, *co-organiser, talk,* IMMS Ilmenau

07/12/2022 – Networking evening of SME Digital und BVMW Ilm-Kreis, *co-organiser, 2 talks,* IMMS Ilmenau

14/12/2022 – Regulars' Table Smart Sensor Systems, SME Digital event series, *host, talk und moderator*, Ilmenau

Trade fairs and exhibitions

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08/04/2023 – elmug4you – Exhibition of the ELMUG members, *exhibition booth*, online

28/06/2022 – Silicon Saxony Day, Future technology and business solutions from the areas of hardware, software and connectivity, *talk, exhibition booth, demo*, Dresden

29/06/2022 – Neue Wirtschaft Mitte, Thuringian Economic Conference, *exhibition booth*, Erfurter Kreuz

06/07/2022 – Info event of the high-performance centre InSignA, *exhibition booth, demo*, Ilmenau

12/10/2023 – 6. Thüringer Maschinenbautag, 6th Thuringian Mechanical Engineering Day, *exhibition booth, demo*, Erfurt

26/10/2022 – inova2022, Career Forum at Ilmenau TU, *exhibition booth, demo*

27/10/2022 – iENA 2022 International trade fair on ideas, inventions and innovations, presentation and inventor competition via PATON | Landespatentzentrum Thüringen, *exhibition booth*, Nürnberg

04/11/2022 – Thüringer KI-Forum, Thuringian forum on AI, *exhibition booth*, Erfurt

Video productions for demonstrators / online events

www.imms.de/videos

– ***New IMMS webseite is online: www.imms.de****, videoclip for LinkedIn and YouTube for the IMMS website relaunch, https://www.youtube.com/watch?v=jo5YHIC66M4*

– ***CMOS image sensor platform for time-resolved fluorescence measurements with europium.*** *The video is intended to support communication for the goal of opening up further applications in in-vitro diagnostics in future research and development projects beyond the exemplarily demonstrated quantitative reading of lateral-flow test strips. https://www.youtube.com/watch?v=pEXdMNZZkPA*
– ***Internships/Jobs/Bachelor's/Master's Theses****: IMMS students with an overview. Start of the video series aimed at arousing interest in working at IMMS from a student perspective; extensive filming in 2022 for interviews for the student video series. https://www.youtube.com/watch?v=cAlv_HAk1ZE*

Publications

Reviewed Publications

www.imms.de/publ

An IoT-based Sensor System to Capture Flower Bud Growth in Spring, Silvia Krug[1,2]. Tino Hutschenreuther[1]. *19. GI/ITG KuVS Fachgespräch Sensornetze (FGSN 2022) 15. September 2022, Berlin, Germany, pp. 37-40,* **DOI: https://doi.org/10.34702/mncp-qb18.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH), 98693 Ilmenau, Germany. [2]Mid Sweden University Sundsvall, Sweden.

Robust Tracking Control with L1 Adaptive Augmentation for a Long Stroke Vertical Nanopositioning System: Part II, Alex S. Huaman[1]. Johann Reger[2]. 2022 IEEE *Conference on Control Technology and Applications (CCTA), 2022, pp. 621-627,* **DOI: https://doi.org/10.1109/CCTA49430.2022.9965993**, *22 - 25 August, 2022, Trieste, Italy.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH), 98693 Ilmenau, Germany. [2]Control Engineering Group, Technische Universität Ilmenau, P.O. Box 10-05-65, D-98684, Ilmenau, Germany.

Robust Tracking Control with L1 Adaptive Augmentation for a Long Stroke Vertical Nanopositioning System: Part I, Alex S. Huaman[1]. Johann Reger[2]. 2022 IEEE *Conference on Control Technology and Applications (CCTA), 2022, pp. 614-620*, **DOI: doi.org/10.1109/CCTA49430.2022.9966103**, *22 - 25 August, 2022, Trieste, Italy.* [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH), 98693 Ilmenau, Germany. [2]Control Engineering Group, Technische Universität Ilmenau, P.O. Box 10-05-65, D-98684, Ilmenau, Germany.

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Abbreviations

ADC *Analogue-digital converter*
AFL *American Fuzzy Lop (software fuzzer)*
AHB *Advanced high-performance bus*
AI *Artificial intelligence*
ASIC *Application-specific integrated circuit*

CMOS *Complementary metal–oxide semiconductor*
DAC *Digital-analogue converter*

EDA *Electronic design automation*
ERP *Enterprise resource planning*

FPGA *Field programmable gate array*
FRF *Frequency response function*

GPIO *General-purpose input/output*

I²C *Inter-integrated circuit*
IC *Integrated circuit*
IEEE *Institute of Electrical and Electronics Engineers*
IoT *Internet of Things*
IP *Intellectual property*
ITO *Indium tin oxide*

LFA *Lateral-flow assay*

MEMS *Microelectromechanical systems*
MLP *Multilayer perceptron*

PCB *Printed circuit board*
PMU *Parametric measurement unit*

QSPI *Quad-SPI (serial peripheral interface)*

RFID *Radio-frequency identification*
RMS *Root mean square*

SiCer *Silicon (Si) ceramic (Cerium) composite substrate*
SME *Small and medium-sized enterprises*
SoM *System on module,*
SPAD *Single-photon avalanche diode*

TCSPC *Time-correlated single-photon counting*
TDC *Time-to-digital converter*

ULP *Ultra-low power*
USB *Universal serial bus*
UV *Ultraviolet radiation*

WTF *What the Fuzz, Hardware fuzzer, verification procedure developed at IMMS*

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