IMMS

ANNUAL REPORT

2021

Contents

Annual reports for other years: www.imms.de

Cover photo: IMMS is developing the real-time capable platform and AI algorithms for such a mobile multi-sensor testing device for preventive maintenance in industry. Photograph: IMMS.

Foreword

Univ.-Prof.-Dr.-Ing. Ralf Sommer and Dipl.-Kfm. Martin Eberhardt. Photograph: IMMS.

Dear Readers,

In the second pandemic year, despite the challenges associated with it, we were again able to manage the Institute's business operations together with our staff in such a way that our anniversary year became a successful business year. However, 2021 was also overshadowed for us by the sudden death of our esteemed colleague and head of department Dr.-Ing. Christoph Schäffel, who had helped shape IMMS since 1995. We will all miss his excellent technical expertise and also the personal conversations.

We have positioned ourselves for the future with the numerous newly acquired projects (12), with which we can consistently pursue our strategic orientation. This shows that the research topics we are pushing continue to be highly relevant for society and business. With the project starts of KODIAK, SensInt and FluoResYst in the research field of **Integrated Sensor Systems**, we are researching the challenges of individual, decentralised health monitoring for all with electronic rapid tests. With the results, we aim to improve and expand one of our lead applications *"Sensor systems for in-vitro diagnostics"*. We have also started project work on trustworthy electronics using AI-based chip design methods with VE-VIDES and VE-ARIS and are contributing to the BMBF initiative on Germany's technological sovereignty.

Annual reports for other years: www.imms.de

In the research field **Smart Distributed Measurement and Test Systems,** we have started projects such as ViroGraph, QuantumHub, thurAI, edgeCam, Trib.US and Eco-Harvester in 2021. There, we are working on a novel technology platform for detecting SARS-CoV-2, CMOS-based single photon detectors for quantum technologies from Thüringen and sensor technology for SmartCity, among other things. For our lead applications *"Adaptive edge AI systems for industrial applications"* and *"IoT systems for cooperative environmental monitoring"*, we have achieved results that enable machine learning on resource-constrained microcontrollers for edge AI and IoT applications and address the challenges in agriculture in times of climate change with sensor systems for optimised irrigation.

In the research field of **Magnetic 6D direct drives with nanometre precision**, we have set the course for precision manufacturing of the future. Our work on picometre positioning was recognised with the Best Paper Award at the IEEE International Conference on Mechatronics 2021.

These and other solutions are made possible by commitment and funding. We thank the German Land of Thüringen for its institutional funding, which makes our transfer work and cooperation with Thuringian SMEs possible in the first place. We thank our committees for supporting and advising us in all matters. We thank all our research partners for their manifold impulses, which we transfer into application-oriented solutions. We would also like to thank our business partners and sponsors as well as all the people who encourage us in our work.

We thank our employees for their commitment, their creative ideas and their skills, without which all the innovative solutions would never become reality. You can find examples of innovative solutions in this report. We wish you much pleasure reading it.

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

Dipl.-Kfm. Martin Eberhardt
Financial Managing Director

Annual reports for other years: www.imms.de

OBITUARY

Dr.-Ing. Christoph Schäffel, *25 July 1961, †16 May 2021

We are shocked and very saddened by his sudden death.

Christoph Schäffel has shaped our subject area of mechatronics since the founding of IMMS. He never wanted to be the centre of attention, de facto he was the centre. With his outstanding technical expertise and ideas, he as head of the subject area has made mechatronics at IMMS what it is today: it determines the global state of the art for nano- and now picometre-accurate precision drives. Throughout his 25 years there, he has led numerous research and development projects to success and he has been author and co-author of numerous publications and patent specifications. In addition, he has accompanied our young scientists.

We will miss his cordial manner and his humour. We will miss him personally as a colleague and we will remember him with the best of memories.

Our deep and special sympathy goes to his wife and his children.

In deep mourning and on behalf of the staff

Prof. Dr.-Ing. Ralf Sommer (Managing Director), Martin Eberhardt (Managing Director), Robert Fetter (Chairman of the Supervisory Board)

Dr.-Ing. Frank Spiller has taken over as interim head of the Mechatronics Department.

Video on 25 years of IMMS – transfers from basic research to industry

https://youtu.be/o2ks-ks298s

25 years of IMMS

From one of the world's first USB hubs to AI – transfers from basic research to industry

At the end of its 25th anniversary year, the IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH) has published the video "From one of the world's first USB hubs to AI". In it, some people from the past and present bridge the gap from one of the first transfer projects launched in 1996 to current solutions from IMMS. From the beginning, IMMS has been committed to advancing Thüringen, Germany, by transferring the results of basic research into applications and products. Today, the Land-owned company of the German Land of Thüringen and associated institute of Ilmenau TU supports companies in launching internationally successful innovations for health, the environment and industry and provides solutions from the feasibility study to series production.

More on 25 years of IMMS: www.imms.de

"Everyone probably knows USB. This is also due to developers from Thüringen."

This explains Dr.-Ing. Karsten Pahnke, Managing Director of emsys Embedded Systems GmbH, who worked at IMMS until 1998 and was responsible for the USB developments. "1996 Intel, Microsoft and IBM came up with the idea, to define a standard that would be universally used for the PCs. In Thüringen, we have early understood

that this meant equipping not only PCs, but also devices with USB, and that this requires intelligent hardware and software in the device.“ The basis was the USB chip for PC mice from Thesys GmbH in Erfurt, which later became X-FAB and MELEXIS. Such a chip serialises the data between PC and mouse and this is exactly what is even more complicated if you want to connect several devices, Pahnke continues.

The multiple distributor needed for this, the USB hub, was developed by IMMS: „We were one of the first in the world who dared to do this.“ Initiated by requests from globally operating computer accessory manufacturers who used the USB hub development for their devices, and after numerous USB workshop series and the publication of the first German USB book, the developers around Pahnke from IMMS founded emsys Embedded Systems GmbH, which was dedicated to customer-specific development projects for hardware, software and technology around USB.

Even today, the focus there is still on USB, especially on sophisticated software developments for e.g. high data transfer rates with the lowest possible power consumption for battery-powered devices. In addition, emsys also develops its own products in other areas, such as the current network analyser for the new 450 megahertz network, which supports service technicians in the installation of smart meter gateways. The cooperation with IMMS is still ongoing. Currently, both partners are working on edge AI solutions for virtual security zones and their connection via mobile communications. “Again, it’s about the greatest possible performance in a very small system” Pahnke summarises.

Today‘s transfers – SONAPHONE® as example for miniaturisation and intelligent solutions

In 1998, IMMS passed the further developments of the USB standard into the hands of the spin-off companies emsys and Thesycon. Since then, IMMS has been developing solutions for miniaturisation and for intelligent systems, which are the key to new applications and products, especially for small and medium-sized enterprises. One of these solutions is the SONAPHONE®, a new type of digital testing device that can detect leaks in industrial machinery using ultrasound and that can be used for predictive maintenance. The smartphone-like industrial measuring device, which has been launched on the market in 2016, was jointly developed by IMMS and SO-

NOTEC. IMMS developed the digital components of the hardware and, among other things, software that makes the ultrasound data audible.

Prof. Dr. Peter Holstein, responsible for strategic development at SONOTEC GmbH, especially emphasises the research cooperation with IMMS for the success of the device so far, from which companies can benefit: "Usually, small and medium-sized enterprises are extremely busy with everyday problems. At the same time, however, there is also the task of developing new products and of doing preliminary development, so that cooperation with research institutes is absolutely necessary to activate additional know-how." For the SONAPHONE, thanks to the joint development, many frequencies can be measured and evaluated simultaneously with only one device. In the past, measurements were similar to listening to the radio on only one frequency, Holstein continues. „You wouldn't get much pleasure from the music there. We have, so to speak, brought the hi-fi system into the ultrasonic world."

Fit for the future – AI and intelligent systems for industrial applications and beyond

Today, IMMS and its partners are working on ultrasound monitoring devices with AI, among other things. „We are now trying to integrate these AI algorithms into the SONAPHONE. With this, we are now making the SONAPHONE AI-capable and fit for the future" says Dr.-Ing. Tino Hutschenreuther, Head of System Design at IMMS. The device will soon operate with three channels to enable the ultrasound source to be located. „We use AI to do that. This is also our goal beyond the SONAPHONE: to put AI into practice for microcomputers in industry and here especially for adaptive edge AI systems." Then and now, the focus is on ever more powerful and smaller systems. Today, the chips developed at IMMS are only a fraction of the size of the former USB chip and are only a few square millimetres small on average. With miniaturised systems and intelligent software, IMMS aims to open up many new applications for the future, e.g. in the fields of environmental monitoring, smart city and life sciences.

More on 25 years of IMMS: www.imms.de

Short video summary of all greetings. **www.imms.de/25jahre**

https://youtu.be/*iJLEio8EsMw*

Greetings and congratulations for our 25th anniversary

We have received numerous greetings and congratulations for our 25th anniversary. Many of them pick up on current projects and results of the last few years and thus illustrate from different perspectives how we at IMMS transfer research results into applications and products together with our partners from science and industry.

Our anniversary coincided with a phase in which, despite all difficulties, we have intensified our efforts to support companies with research and development for the challenges of the future. We are all the more pleased that our partners and supporters have taken the time to talk about joint successes in videos and text contributions and to jointly look into the future with us.

We would like to express our sincere thanks for this. These words make us proud of what we have achieved together and spur us on to continue working with you on cutting-edge innovations!

More on 25 years of IMMS: www.imms.de

Interview with Dr.-Ing. Karsten Pahnke, Managing Director of emsys Embedded Systems GmbH **www.emsys.de**

https://youtu.be/o2ks-ks298s

Greetings by Prof. Dr.-Ing. Karlheinz Brandenburg, Managing Director of Brandenburg Labs GmbH **www.brandenburg-labs.com**

https://youtu.be/9tqWAt8FRB8

Greetings by the Managing Directors Thomas Brock and Prof. Dr. Thomas Ortlepp, CiS Forschungsinstitut für Mikrosensorik GmbH, **www.cismst.de**

https://youtu.be/Lmq6S8uBvDc

Greetings by Jörg Doblaski, X-FAB CTO, and Dr. Gabriel Kittler, X-FAB CEO Site Erfurt, **www.xfab.com**

https://youtu.be/v2fxcwhm530

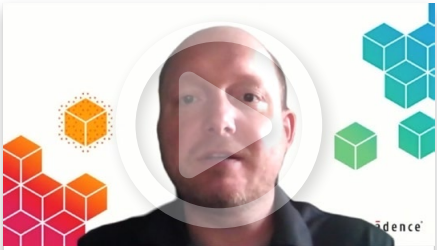
Greetings by Dr.-Ing. Carsten Emde and Andrea Ruf, Open Source Automation Development Lab (OSADL eG), **www.osadl.org**

https://youtu.be/vzkp_8tbueg

Greetings by Hans-Christian Fritsch, Managing Director of Ilmsens GmbH, Ilmenau, **www.ilmsens.com**

https://youtu.be/fftiaqGL1Jw

More on 25 years of IMMS: www.imms.de



Greetings by Anton Klotz, Cadence GmbH, Germany, **www.cadence.com**

https://youtu.be/zomtlfu4JuU

Greetings by Judith Liebetrau, Group Leader Industrial Media Applications, Fraunhofer IDMT, Ilmenau, **www.idmt.fraunhofer.de**

https://youtu.be/o2Xwc8v4Jqc

Greetings by Prof. Dr.-Ing. Jens Müller, Presidium Ilmenau TU, **www.tu-ilmenau.de**

https://youtu.be/zY5FUxBdlC8

Greetings by the Prime Minister of Thüringen, Bodo Ramelow, **www.staatskanzlei-thueringen.de**

https://youtu.be/fT2jaQ1PmkE

Greetings by Rene Rodigast, Business Manager Acoustics, Fraunhofer IDMT, Ilmenau, **www.idmt.fraunhofer.de**

https://youtu.be/wl1YPAve5n8

Greetings by Dr. Peter Schneider, Managing Director of Fraunhofer IIS EAS, Dresden **www.eas.iis.fraunhofer.de**

https://youtu.be/xR0TE2gQ60k

More on 25 years of IMMS: www.imms.de

Greetings by Prof. Dr.-Ing. Axel Sikora, Hochschule Offenburg, **www.hs-offenburg.de**

https://youtu.be/Vi7Ej42oWQU

Greetings by the team of Indu-Sol GmbH Schmölln in Thüringen, **www.indu-sol.com**

https://youtu.be/RpeRj059hNw

Greetings by Wolfgang Tiefensee, Minister for Economic Affairs, Science and Digital Society in Thüringen, TMWWDG **www.wirtschaft.thueringen.de**

https://youtu.be/bEfu8KiWowo

Greetings by Prof. Dr. Ingolf Voigt, Deputy Managing Director and Site Manager Fraunhofer IKTS, Hermsdorf **www.ikts.fraunhofer.de**

https://youtu.be/4MxOZg_INfA

More on 25 years of IMMS: www.imms.de

Uwe Ahnert, Managing Director BioTeZ Berlin-Buch GmbH and Steffens Biotechnische Analysen GmbH

Congratulations IMMS and Prof. Dr. Sommer ...

... on 25 wonderful years full of creative energy for research, education and innovation. BioTeZ and Steffens Biotechnische Analysen would like to thank you for the good cooperation and hope for many new joint projects in the future, where we may rely on the competences of IMMS in the field of microelectronics and mechatronics to bundle them with our expertise in protein chemistry and molecular diagnostics for new solutions.

All the best, luck and success, dear IMMS and dear Prof. Dr. Sommer.

Uwe Ahnert, Managing Director BioTeZ Berlin-Buch GmbH and Steffens Biotechnische Analysen GmbH, **www.biotez.de, www.steffens-biotec.com**

Judith Binzer, Managing Director DFAM, and Johanna Schreiner, VDMA Micro Technologies

A quarter of a century in the service of science in the field of microelectronics and mechatronic systems. We would like to thank IMMS for its cooperation with both DFAM (Deutsche Forschungsgesellschaft für Automatisierung und Mikroelektronik e.V.) and the VDMA Micro Technologies Department. For us and for our member companies, the connection with research institutes means a considerable added value, because only through the cooperation of research and industry new innovations for mechanical and plant engineering can be created. We would like to wish IMMS every further success and look forward to the next 25 years!

Judith Binzer, Managing Director DFAM, **www.dfam.de**
Johanna Schreiner, VDMA Micro Technologies, **www.micro.vdma.org**

More on 25 years of IMMS: www.imms.de

Managing Director Dr. Denis Dontsov, SIOS Meßtechnik GmbH, Ilmenau – Jointly research, develop, solve

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

For many years, IMMS and SIOS Messtechnik have been united by their enthusiasm for exciting research projects and challenging technical solutions in the application of mechatronic systems for nanopositioning of the highest precision.

We have been able to demonstrate this in numerous funded projects and joint developments over the past 25 years.

In our cross-team collaboration, we often move towards the limits of what is technically feasible. However, our collaboration is not about developing exclusively theoretical approaches; rather, it is always about finding practical solutions and ultimately transforming them into innovative high-end solutions and products. This is the foundation for mutual success. We appreciate IMMS' technical competence combined with the extremely high quality standards as well as the systematic and targeted way of working of the IMMS colleagues and, last but not least, the very communicative and uncomplicated nature of our cooperation.

Most recently, we were able to share a success with the joint research work "Picometer-scale positioning of a linear drive system via feedforward feedback control", which was awarded the Best Paper Award. In this research project, the positioning is carried out in the picometre range with the help of the ultra-stable differential interferometer developed by SIOS.

Projects of this kind motivate us to continue the cooperation with our colleagues from IMMS in the coming years.

Managing Director Dr Denis Dontsov on behalf of the SIOS Meßtechnik staff wishes IMMS inspiring ideas and innovative solutions, which will jointly drive us to new technological developments and also bring us forward in the future.

More on 25 years of IMMS: www.imms.de

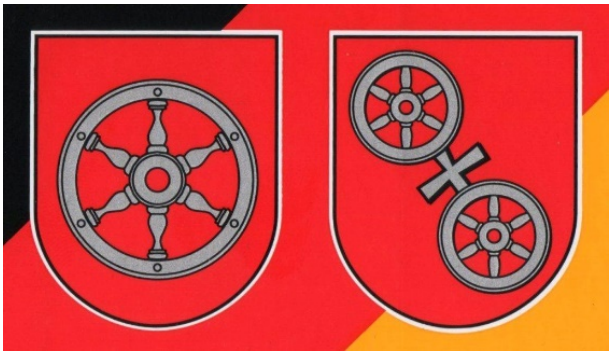
www.sios.de

IMMS iC-Haus

Historische Beziehungen Erfurt - Mainz

- Über 1000 Jahre war die Geschichte Erfurts eng mit dem Erzbistum bzw. Kurfürstentum Mainz verbunden
- Seit 1988 sind Erfurt und Mainz Partnerstädte
- Seit 2019 besteht die Forschungskooperation zwischen der iC-Haus GmbH (Bodenheim bei Mainz) und der IMMS gGmbH (Erfurt)

… mit sichtbarer Bewegung auch in den Stadtwappen von Erfurt und Mainz



Wir gratulieren herzlich zum 25-jährigen Bestehen des IMMS und freuen uns auf die Partnerschaft in inzwischen drei mit Bundesmitteln geförderten Forschungsprojekten zur Schaltkreisintegration mit den Themen Künstliche Intelligenz, Kopierschutz und Medizin-Laser.

Dr. Heiner Flocke
und das iC-Haus Team

More on 25 years of IMMS: www.imms.de

Univ.-Prof. Dr. Matthias A. Hein. Photograph: private source, Matthias Hein.

Univ.-Prof. Dr. Matthias A. Hein, Head of the RF and Microwave Research Group, Director ThIMo, Technische Universität Ilmenau

"Innovation and economic value creation result essentially from a competent and efficient transfer of university preliminary research into solutions suitable for industry. Right here, IMMS has established itself as a reliable R&D partner in its 25 years of existence. We warmly congratulate the entire IMMS team and look forward to further successful cooperation!"

Univ.-Prof. Dr. Matthias A. Hein, **www.tu-ilmenau.de**

Prof. Dr. Doris Heinrich, Director iba, Institut für Bioprozess- und Analysenmesstechnik e.V., Heilbad Heiligenstadt

Prof. Dr. Doris Heinrich, Director iba, Institut für Bioprozess- und Analysenmesstechnik e.V., Heilbad Heiligenstadt. Photograph: iba.

Dear Prof. Dr.-Ing. Sommer, dear IMMS team,

On behalf of all colleagues of the Institute for Bioprocess and Analytical Measurement in Heilbad Heiligenstadt and as a member of the Scientific Advisory Board of IMMS, I would like to send you my warmest greetings on the occasion of your 25th anniversary.

In these years you have successfully pursued application-oriented research and have always been a reliable partner in the search for new innovative solutions for the automation, control and regulation of processes in research and industry. In doing so, you have always faced the great challenges of data acquisition and processing in complex environments of life science applications. In this exciting environment, we were able to advance highly interesting research projects together with you.

The results of the INSPECT project with the development of an optoelectronic in-situ detection of the vitality of cells in a three-dimensional microhabitat speak for themselves. The current joint research on the application of an integrated circuit for the analysis of bioimpedimetric data from biotechnological processes in the BICCell

More on 25 years of IMMS: www.imms.de

project as well as iba's involvement in the project-accompanying committee of your ViroGraph research project are also witnesses of a grown collegial cooperation.

I hope that we, as affiliated institutes of Ilmenau TU with a complementary research profile, will continue to be a strong and successful axis of applied research in the German Land of Thüringen in the future.

I wish you and your staff successful years in a strong scientific environment.

Yours Doris Heinrich
on behalf of the Institute for Bioprocess and Analytical Measurement Technology e.V.
www.iba-heiligenstadt.de

Frank Helbing, Head of Traffic Department, Civil Engineering and Traffic Office, Erfurt City Administration

Installation of wireless sensor nodes in the road surface as part of the sMobiliTy field test in Erfurt. Photograph: IMMS.

The civil engineering and traffic department of the Thuringian capital Erfurt works intensively on the sustainable handling of the mobility needs of the population. In addition to the use of strategic traffic control measures, activities in the field of traffic management are also being intensively pursued. The focus is on the systematic use of intermodal and integrated traffic and environmental management. Erfurt has one of the most modern traffic control centres in Germany, the core of which is the so-called traffic management platform with the subsystems traffic computer centre, traffic situation analysis and forecast as well as traffic and environmental data management.

The Department of Civil Engineering and Transport has worked intensively with IMMS GmbH within the framework of the research project "Smart Mobility in Thüringen (sMobiliTy)" (duration 01.10.2012 to 30.09.2015). In the 3-year project to promote electromobility, the "Tactile Street" sensor platform developed by IMMS GmbH was tested in the urban area of Erfurt and served as a valuable data source for recording traffic and environmental data. The insights gained from this were a precondition for forecasting the range and travel times for electric vehicles.

More on 25 years of IMMS: www.imms.de

"We have come to know IMMS GmbH as a very innovative, flexible and ambitious company," Frank Helbing, Head of the Traffic Department at the Civil Engineering and Traffic Office, elaborates. "We still remember the joint cooperation very well. Together we achieved unique and outstanding project results from which traffic management in Erfurt still benefits today.
We therefore wish IMMS GmbH only the best for the future as well as many more exciting and innovative projects."

Frank Helbing, Head of Traffic Department, Civil Engineering and Traffic Office, Erfurt City Administration, **www.erfurt.de**

Prof. Dr. Peter Holstein und Hans-Joachim Münch, SONOTEC GmbH

Matching IMMS's anniversary, SONOTEC's contacts with IMMS are also "celebrating" their 10th anniversary. SONOTEC has been supporting teaching at Technische Universität Ilmenau for a long time. Consequently, the contacts to IMMS also resulted from this. The performance and requirement profiles of both partners complement(ed) each other excellently. The increasing influence of digitalisation on device development and the related requirements for applications led to joint new considerations for a new class of testing devices for maintenance, for which IMMS was and is an ideal partner for us. From a jointly developed concept, for which there was no model on the international market, the SONAPHONE testing device, which has since become extremely successful on the market, was created as part of a joint development.

Award ceremony TÜV Süd Innovation Award 2019 (from left to right): Sebastian Uziel (Hardware developer, IMMS GmbH), Prof. Dr. Ralf Sommer (scientific managing director, IMMS GmbH), Michael Münch (Managing Director, SONOTEC GmbH), Christian Schreiber (International Sales Manager, SONOTEC GmbH). Photograph: SONOTEC GmbH.

More on 25 years of IMMS: www.imms.de

During the development, both sides were able to contribute their know-how and strengths and develop them further.

The cooperation between the two partners has become a success story. The demands of the market cannot be met by medium-sized companies alone. Conversely, the research institution benefits from its proximity to the market. The pressure from the market resulting from the requirements of I4.0 and digitalisation is immense. New requirements and opportunities are being developed together. So far, the IMMS' experience in areas such as electronics design, model-based development, embedded computing and the understanding of operating systems has been the main focus of the cooperation. Increasingly, data-driven developments around AI are playing an important role. IMMS has developed the digital hardware platform for this in the sUSe project, which enables the basis for a completely new approach in the stationary monitoring of leakages in compressed air systems. By connecting volume flow and ultrasonic sensor technology, appropriate measures can be initiated after AI-controlled processing and leakage evaluation.

The combination of cooperation structure, technological concept and consistent market orientation made it possible to develop further innovative devices for applications in maintenance, building on the basic development. Several joint research projects, publications, patents and also innovation awards won for the joint development are proof of this.

The successes of the past are at the same time our common basis for future cooperation.

Prof. Dr. Peter Holstein, Hans-Joachim Münch, SONOTEC GmbH., **www.sonotec.de**

Dr. Jens Kosch, Fellow – X-FAB Global Services GmbH, Erfurt

Congratulations on the 25th anniversary of the institute, combined with thanks and appreciation for 25 years of fruitful cooperation.

X-FAB, or Thesys in the past, was already involved in the founding phase as an important Thuringian industrial partner, as the aim of the foundation was to close the large gap in the industry-related research landscape for microelectronics and mechatronics manufacturers and users in Thüringen. I can say from an industrial perspective that this has been very successful, as IMMS is our most important external research partner.

More on 25 years of IMMS: www.imms.de

Personally, too, I have had the honour and pleasure of accompanying the Institute from the very beginning, not only in the role of industrial partner, but also as a former member of the Scientific Advisory Board and later and to this day as a member of the Supervisory Board.

Dr. Jens Kosch, X-FAB Fellow. Photograph: X-FAB Global Services GmbH.

Although the Institute is relatively small, it has succeeded in building up good competences in a rather broad spectrum. This and the close proximity have made it possible for IMMS to become the partner of choice for many projects, from industrial contract research to large-scale projects funded as European consortia such as ADMONT.

People make the difference. In every phase of the 25-year development, it has been the dedicated people, whether researchers, administration or managing directors, who have shaped the institute and understood very well the needs and demands of their industrial partners. Many IMMS scientists have also found their way into industry over the past 25 years. This impact of the Institute in attracting skilled experts to industry is also important.

25 years ago, only a few had really recognised the economic importance of microelectronics. Now the broader public is also aware of the leverage effect microelectronics has as a key industrial technology, how indispensable it is for Europe's technological sovereignty. But it is also becoming increasingly complex and is being combined with other fields such as mechanics, optics and bio-chemical processes. This also creates great opportunities and impulses for IMMS to link mechatronics and microelectronics research even more closely.

Reflecting on the 25-year history and successes is wonderful. It is also useful if one also gains the motivation, self-confidence and passion for shaping the future based on it.

I wish all IMMS staff all the best for the future and the Institute's committees fortunate guidance and support.

Dr. Jens Kosch – Fellow – X-FAB Global Services GmbH, **www.xfab.com**

More on 25 years of IMMS: www.imms.de

Andreas Krey, Managing Director Landesentwicklungsgesellschaft Thüringen mbH (LEG Thüringen)

Andreas Krey, Managing Director Landesentwicklungsgesellschaft Thüringen mbH (LEG Thüringen). Photograph: LEG Thüringen / Andreas Pöcking.

LEG and IMMS can look back on a quarter of a century of productive and close cooperation. From the first cooperations – I am thinking of the establishment of today's Arnstadt-Ilmenau technology region – to today, there has been continuous and successful cooperation. IMMS enriches the work of various networks and clusters with its wide-ranging expertise in a variety of technology fields and is thus a strong partner of our Thuringian Cluster Management (ThCM). IMMS was a founding member of the ELMUG eG. network, among others, and the institute has played a significant role in the successful development of this innovative cluster.

From the beginning, IMMS was an important R&D and transfer partner for innovative Thuringian companies; its work was particularly important for the many spin-offs and start-ups that took place in the Ilmenau region after reunification. The institute gave central input for the profiling of the Land of Thüringen in the field of various future technologies, exemplified here in the field of mechatronic systems by the conception and production of drive technology for nanopositioning and nanomeasuring machines.

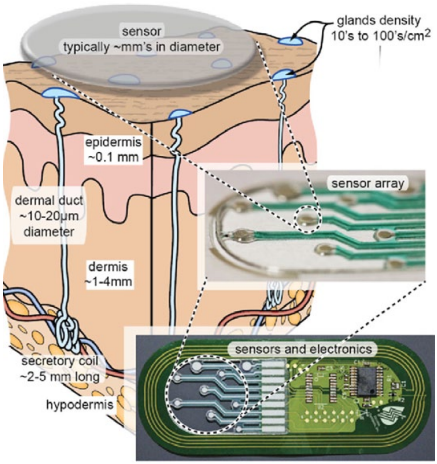
I would like to congratulate the IMMS team on its 25th anniversary and wish the institute continued success for the future!

Andreas Krey, Managing Director Landesentwicklungsgesellschaft Thüringen mbH (LEG Thüringen), **www.leg-thueringen.de**

More on 25 years of IMMS: www.imms.de

Dr. Andreas Laute, Product Manager Datacom, Melexis GmbH, Erfurt

Since its foundation 25 years ago, IMMS has always been a reliable partner in many funded projects as well as for development outsourcing activities. Therefore, the collaboration with IMMS is an important factor in supporting the R&D activities of Melexis. Throughout the years, most of our collaborations were addressing very demanding automotive electronics developments.



Sensor Patch for Monitoring of Sweat Electrolytes, Quelle: Melexis GmbH.

Melexis recently approached further market segments, for example Digital Health. In this context, we are very happy about IMMS's strong engagement in the funded project "Virograph". The goal of the project is the development of biosensor electronics based on graphene field effect transistors (G-FETs). Melexis is acting as a member of the advisory board. We believe that the results of "Virograph" can help us move faster towards integrated solutions for biosensors. Potential applications are rapid self-tests for viruses, sensing of environmental conditions, glucose monitoring and point-of-care services.

We are looking forward to further collaborations and wish IMMS all the best for their 25th year anniversary.

Andreas Laute
Product Manager Datacom, Melexis GmbH, Erfurt, Germany,
www.melexis.com

More on 25 years of IMMS: www.imms.de

Prof. Dr.-Ing. Wolfgang Nebel, Board of OFFIS e.V., Institute for Computer Science, Oldenburg

Prof. Dr.-Ing. Wolfgang Nebel, Board of OFFIS e.V., Institute for Computer Science, Oldenburg. Photograph: OFFIS e.V.

Dear Mr. Sommer,

Almost since its foundation, IMMS has been known to me as one of the strongest performers for topics in the connection of mechatronics and microelectronics and their applications in Germany. Together we have been able to initiate and implement exciting and highly relevant projects. As a member of the Scientific Advisory Board, I am particularly pleased to be able to accompany and advise IMMS very closely. I wish the Institute continued success for the next 25 years, its team much enjoyment in research and all of us important contributions from the Institute for our common technological future.

Prof. Dr.-Ing. Wolfgang Nebel, **www.offis.de**

Prof. Dr. W. Nebel, Prof. Dr. U. Schlichtmann und Dr. J. Haase, Vorstand des edacentrum

From the very beginning, IMMS, which is five years more “experienced”, has been a reliable partner for edacentrum in close and fruitful cooperation: supported by the good personal relationship of their “founding fathers”, Professors Rößler (IMMS) and Barke (edacentrum), IMMS has helped to shape the work of the edacentrum’s advisory board from the very beginning until today. Strategies for German microelectronics research were developed, which were subsequently also implemented in numerous projects with a very high degree of innovation in the technical solutions as well as creative cooperation concepts such as cluster research.

The numerous joint successful collaborative projects in the field of design automation for electronics (EDA) were a guarantee that IMMS and edacentrum could always benefit from each other. In projects such as ANASTASIA2, SpeAC, DETAILS, DIONYSYS, HERKULES, HONEY, SYENA, RAPIDMPSOC, ANCONA, MEMS2015, RoMulus or,

More on 25 years of IMMS: www.imms.de



edacentrum board: Prof. Dr. Ulf Schlichtmann, Faculty of Electrical Engineering and Information Technology, Chair of Design Automation, Technical University of Munich (TUM); Prof. Dr. Wolfgang Nebel, Carl von Ossietzky Universität Oldenburg, Fakulty II, Dep. of Computing Science, Embedded Hardware/Software Systems Group, Chairman of the Board of OFFIS – Institut für Informatik e.V.; Dr. Jürgen Haase, Managing Director of edacentrum GmbH. Photographs: edacentrum.

most recently, VE-VIDES, IMMS was a valuable partner who could benefit from the comprehensive network of the edacentrum and its connections to the microelectronics industry and its applications in return. IMMS has always taken on the role of the most shaping institute for MEMS and their applications and has come up with outstanding innovations. The excellence and practical relevance of IMMS research work is emphatically demonstrated by the fact that two IMMS scientists, Prof. Dr. Ralf Sommer and Georg Gläser, have received the annual EDA Achievement Award, which is presented by edacentrum for outstanding EDA research results with high practical relevance.

In addition to this successful cooperation in projects, IMMS and edacentrum have also taken new innovative paths together in the design of events. For example, IMMS and edacentrum, together with OFFIS – Institute of Computer Science, have launched the so-called “edaBarCamp” event series and held Germany’s first “unconference” organised as a “BarCamp” in the field of design automation for microelectronic and embedded systems. The new event format makes intensive use of new social media communication methods, which are the preferred channels for young scientists in particular. Thanks to the organisational and content-related support of IMMS, the first “edaBarCamp” was so successful that five such events have since been held at various locations in Germany, one of them at IMMS in Erfurt.

The edacentrum congratulates IMMS most sincerely on its 25th anniversary and wishes the institute with its highly competent and committed team continued suc-

More on 25 years of IMMS: www.imms.de

cess and skill in assessing and shaping the research topics of the future, as it has done so far and even a bit beyond. We look forward to at least 25 more years of successful cooperation!

Prof. Dr. W. Nebel, Prof. Dr. U. Schlichtmann, Dr. J. Haase,
Vorstand des edacentrum, **www.edacentrum.de**

Team of X-FAB Global Services GmbH, Erfurt

X-FAB says thank you & wishes all the best for the next 25 years!

The X-FAB team would like to congratulate you on your anniversary. The colleagues in the collage are representative of many others who have had the opportunity to work together with colleagues from IMMS on exciting research and industrialisation projects over the past quarter of a century. We are proud of what we have achieved together and glad to have such an innovative and reliable partner at our side. Go on like this!

www.xfab.com

Pictured from top left: Tina Zimmermann, Detlef Sommer, Markus Ackermann, Antje Zimmermann, Melanie Wilhelm, Jörg Doblaski, Uwe Schwarz, Klaus Heinrich, Roberto Gärtner, Lars Bergmann, Marc Schuchart, Daniel Gäbler, Anja Noack, Pierre Rollberg, Alexander Zimmer, Gabriel Kittler.

More on 25 years of IMMS: www.imms.de

IHK Industrie- und Handelskammer Südthüringen

GRUSSWORT

25 Jahre Institut für Mikroelektronik- und Mechatronik-Systeme

Ein guter Anfang

„Die beste Möglichkeit, die Zukunft vorherzusagen ist, sie zu erfinden." Alan Kay

Durch kontinuierliche Innovationstätigkeit sind Unternehmen in der Lage, sich in rasant verändernden Märkten nachhaltig zu behaupten. Innovationen sind der Motor wirtschaftlichen Fortschritts – heute mehr denn je – und bedürfen einer fundierten wissenschaftlichen Basis, auch in unserer vom Mittelstand geprägten Südthüringer Wirtschaftsregion. Hier, wo unternehmenseigene Entwicklungs- oder gar Forschungsabteilungen Seltenheitswert haben.

Und so freut es mich ganz besonders, Ihnen im Namen der Industrie- und Handelskammer Südthüringen zum 25-jährigem Bestehen Ihres Instituts gratulieren zu dürfen. 25 Jahre, in denen zukunftsfähige Forschungsergebnisse in markt- und margenfähige Anwendungen und Produkte überführt wurden und ein wesentlicher Beitrag zur wirtschaftlichen Entwicklung unserer Region geleistet wurde. Tatsächlich: ein guter Anfang.

Strukturwandel, Digitalisierung und Fachkräftebedarf: nur einige Herausforderungen, welche es in der Zukunft zu meistern gilt. Dabei wird die Brücke zwischen Wissenschaft und Wirtschaft eine elementare Rolle einnehmen. Hierfür wünsche ich Ihnen und Ihrem Team alles erdenklich Gute und viel Erfolg. Auf eine weiterhin sehr gute Zusammenarbeit.

Dr. Ralf Pieterwas
Hauptgeschäftsführer der IHK Südthüringen

1/1

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www.suhl.ihk.de

More on 25 years of IMMS: www.imms.de

Freistaat Thüringen Finanzministerium

Grußwort der Finanzministerin Heike Taubert anlässlich des 25-jährigen Bestehens der IMMS GmbH (Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH)

„Stolz, dass ein Teil Hightech auch aus Thüringen kommt!“

Sehr geehrter Herr Prof. Dr.-Ing. Sommer,
sehr geehrter Herr Eberhardt,
sehr geehrter Herr Fetter,
sehr geehrte Mitarbeiterinnen und Mitarbeiter der IMMS GmbH,

ich gratuliere Ihnen herzlich zu 25 Jahren IMMS in Thüringen und danke Ihnen für Ihre großartige Forschungsarbeit in den vergangenen Jahren. Ich bin sehr stolz, dass ein Teil Hightech auch aus Thüringen kommt. Sie entwickeln Techniken, die zukunftsweisende Impulse setzen und moderne Forschung voranbringen. Das zeigt ganz aktuell zum Beispiel Ihr großes Engagement für die Entwicklung von miniaturisierter Messtechnik für eine neue Technologieplattform zum Nachweis von SARS-COV-2. Das IMMS ist nicht nur Wegbereiter für neuartige Automatisierungstechniken für die Fertigungs- und Metallverarbeitungsindustrie, KI-Verfahren oder Chip-Design, sondern vor allem auch ein zuverlässiger Partner für kleine und mittlere Unternehmen im Freistaat.

Die Entwicklung von Fahrzeug- und Maschinensystemen, Industrie- und Telekommunikationsanlagen oder die intelligente Vernetzung von Mess- und Testsystemen wird immer anspruchsvoller. Unternehmen wollen heute kosten- und energieeffizient, sicher und funktional arbeiten. Dafür benötigen sie Ihre Hilfe, denn Sie kennen sich aus mit der digitalen Transformation von Unternehmensprozessen für den Mittelstand. Ihre Arbeitsergebnisse kommen in der Praxis an. Durch Ihr Knowhow und mit Ihrer Technik können die Unternehmen komplexe Automatisierungslösungen realisieren und Unternehmensprozesse effizienter gestalten.

Als Finanzministerin freue ich mich besonders, dieses Jubiläum mit Ihnen feiern zu können. Ich danke Ihnen für Ihre starken Leistungen in den vergangenen 25 Jahren und wünsche Ihnen für die Zukunft alles Gute, weiter frische Ideen und Begeisterung für Ihre innovative Arbeit.

Herzlichst Ihre

Heike Taubert
Thüringer Finanzministerin

www.finanzen.thueringen.de

More on 25 years of IMMS: www.imms.de

Team Micro-Sensys GmbH, Erfurt

Founded in Erfurt in 1991, microsensys GmbH is now one of the most innovative and flexible RFID companies in Europe. The wide range of smart ID products and the existing large vertical range of manufacture from sensor transponders to gateways, system software to data assembly open up efficient access to the IoT world. We have been working closely and constructively with the IMMS research team for years in the context of several projects. In the course of our cooperation, we have come to know the IMMS team as a competent partner and appreciate their innovative spirit, which provides an excellent basis for technologically sophisticated developments. For us, the IMMS research institute represents an innovative regional technology partner that can support us in the implementation of development tasks in the field of ASIC design, but also in a coordinating role in the implementation of industrial and publicly funded projects. We are looking forward to continuing to solve challenging problems together in the future, building on our development successes to date. We congratulate all employees and our project colleagues from the Institute of Microelectronics and Mechatronics Systems on their 25th anniversary and are pleased to take this as an opportunity to thank you for the many years of cooperation as well as the great commitment in the implementation of several successfully completed projects. We wish you continued success on the path you have chosen, as well as innovative strength for future developments and public research projects that enable an efficient and rapid transfer of knowledge between science and industry, and thus positively influence social life.

microsensys team, **www.microsensys.de**

More on 25 years of IMMS: www.imms.de

Prof. Dr Andreas Tünnermann, Director of the Fraunhofer Institute for Applied Optics and Precision Engineering IOF

Prof. Dr. Andreas Tünnermann, Director of the Fraunhofer Institute for Applied Optics and Precision Engineering IOF. Source: Max Planck School of Photonics.

Light is a versatile tool. Its potential to contribute to the solution of relevant future questions as the basis of innovative technology is far from being exhausted. To the contrary: the so-called "second quantum revolution", which uses the targeted manipulation of individual light particles as its most essential tool, is developing an ever stronger dynamic and is drawing ever wider circles in its relevance for society, industry and the economy.

Here, photonics, as the science of light, sees itself as the central pioneer for the step of fundamental quantum experiments out of the laboratories and into market-ready applications. In order to be able to successfully follow this path, close interdisciplinary cooperation between many research fields is needed. The complexity and demands placed on quantum applications by end users cannot be mastered by one scientific discipline alone. For this reason, research institutions such as the Fraunhofer Institute for Applied Optics and Precision Engineering IOF in Jena need strong partners for the development of application-oriented quantum systems.

An important companion for us here has been the IMMS Institute for Microelectronic and Mechatronic Systems from Ilmenau for many years. Over the past 25 years, the institute has established itself as a stable bridge between science and industry, helping to transfer research into concrete applications for business and industry. With its know-how in the fields of microelectronics, systems engineering and mechatronics, IMMS is an ongoing catalyst of the transfer process, which the applications of the second quantum revolution are also striving for.

More on 25 years of IMMS: www.imms.de

The Fraunhofer IOF is therefore looking forward with confidence to the next major joint project, which the two institutes will realise in cooperation with other Thuringian institutions: As part of the "Quantum Hub Thüringen", a Thuringian research network for quantum technologies, a feed-forward system for high-

ly secure quantum communications will be created. Here, IMMS is contributing its expertise in the development of optoelectronic sensor technology, thus contributing not only to the success of this particular project, but also, in the long term, to the development of relevant quantum technology on a global scale. Without the IMMS' wealth of experience from more than 850 successfully completed projects, such groundbreaking joint projects would not be possible. Fraunhofer IOF therefore warmly congratulates IMMS and its staff on its 25th anniversary and thanks them for the consistently good and successful collaborations! We are looking forward to the next 25 years of joint cooperation.

Prof. Dr. Andreas Tünnermann
Director of the Fraunhofer Institute for Applied Optics and Precision Engineering IOF

www.iof.fraunhofer.de

More on 25 years of IMMS: www.imms.de

Voices from industry and academia on current projects

Damir Redžepagić, IC Architect, ArtIC Solutions. Photograph: ArtIC Solotions.

Damir Redžepagić , ArtIC Solutions

”Developing integrated circuit designs and implementing solutions based on semiconductor material is a challenging endeavour. Semiconductor industries and technology evolve at incredible rate and keeping up with the changes can be a daunting task. To increase the chance of success, the semiconductor companies are forced to create the right solution for the market fast and that solution must be made first time right.

How does one create the right solution for the market? The answer to this question is quite straightforward: by listening and understanding the customers’ needs. How does one create the solution first time right? The answer to this question is also quite straightforward: do not make mistakes. This requires experience.

IMMS is the company where we found both experience and focus on understanding the customers’ needs. Their experience in digital IC design, synthesis, place and route, verification and sign-off using the state-of-the art tools and methods makes IMMS a great partner to work with when developing mixed-signal integrated sensors. We also value and appreciate the proactive disposition, flexibility, fast responsiveness, and pleasant interaction that we found at IMMS and IMMS employees. Many thanks for the great cooperation.“

Services for integrated circuits: www.imms.de

More voices from industry: www.imms.de

www.art-ic-solutions.com

ARTIC
The Art Of Integration

Alexander Zimmer,
X-FAB Global Services GmbH, Erfurt

Alexander Zimmer, Master of Engineering, Principal Engineer Process Development OPTO, X-FAB Global Services GmbH, Erfurt. Photograph: X-FAB.

"For several years we have been active in the development of novel single photon detectors, so-called SPADs. The specification and characterisation of these detectors are a great challenge. IMMS was able to offer us valuable support due to its many years of experience in the field of measurement technology and circuit design for optical sensors. In addition to the possibilities for methodology development, system integration plays a major role in SPADs.

Together, it was possible to identify areas where joint development for this particular type of sensor could be applied. Thus, the know-how of X-FAB technology could be combined with IMMS expertise in circuit design and characterisation. The reliable work and the trusting partnership is a highly valued basis for the cooperation with IMMS. In the past, we have already had very good experiences in various projects with IMMS. For the SPAD sensors, we were thus able to quickly identify new fields and applications where joint development is worthwhile for both sides. In particular, the development of the SPAD evaluation kit represents a milestone in our cooperation.

Building on this success, we would like to continue the collaboration in the future. Beyond the single photon detectors, we have been able to identify further projects and interfaces in perspective, through which we would like to thematically go deeper into new solutions with IMMS.

In particular, the enthusiasm and the pragmatic and creative way of approaching new developments are qualities that I would like to emphasise. The intrinsic motivation to constantly develop things further, to drill down to the bottom of measurement methodologies and parameters, as well as to understand the interrelationships, are also positive qualities, from which our partnership benefits."

Services for test and characterisation: www.imms.de

More voices from industry: www.imms.de

Prof. Dr.-Ing. Patrick Mäder, Head of the Data-intensive Systems and Visualization Group (dAI.SY), Institute for Applied Computer Science, Technische Universität Ilmenau.

Photograph: arifoto UG.

Prof. Dr.-Ing. Patrick Mäder, Technische Universität Ilmenau

"Our Data-intensive Systems and Visualization Group (dAI.SY) at the Institute for Applied Computer Science at Technische Universität Ilmenau and IMMS have collaborated in the Thuringian IntelligEnt research group to improve design automation for integrated circuits and systems by applying machine learning algorithms.

More on the IntelligEnt research group: www.imms.de

Together with IMMS, we have implemented circuit processing by learning algorithms for the design of analogue/mixed-signal circuits. Integrated into the design software, algorithms are used to support the circuit designer with novel functions such as the recognition of untypical structures during the design process. The circuit representation and learning procedure developed for this purpose enable neural networks to learn the function of circuit blocks implicitly. In addition, IMMS has developed new solutions for modelling, layout, simulation and verification as well as for testing and characterising integrated circuits on the basis of our AI support.

Core topic AI-based design and test automation: www.imms.de

In addition to design automation, we have developed a method for machine-learning-based measurement data analysis for ASICs together with IMMS. Our developed method independently analyses extensive and numerous signal courses for potential and unknown faults and automatically creates groups of related fault types. Practical tests with industrial partners showed a ten- to 30-fold reduction in the otherwise enormously time-consuming and expensive effort for the analysis of measurement data.

It was a great pleasure for us to see the goal orientation and commitment with which the colleagues from IMMS worked with their sound application know-how to open up the methods and tools we researched and the immense potential of machine learning for microelectronics design. To do this, IMMS used requirements and data sets from industry that were contributed by companies on the project's advisory board. This enabled not only the validation of the methods, but also the successful demonstration of their great benefit. For us, the cooperation shows how important IMMS is for a transfer of results from basic research into practice. In our view, the solution-oriented, agile and collegial way of working contributes to this, in addition to the deep technical understanding.

In addition, we worked together with IMMS on the AnoPCB software project. There, students jointly supervised by us developed a plug-in for the PCB design software KiCad based on the IntelligEnt results for circuit layout. The solution was awarded the EDA Competition Award for young scientists by the IEEE Council on Electronic Design Automation (CEDA). This success in the competition on the occasion of the international conferences on methods for the design of integrated circuits SMACD 2021 and PRIME 2021 clearly shows the thrust with which IMMS combines the promotion of young scientists with research and development.

More on AnoPCB in this report

We count on continued good joint supervision of students and look forward to the next opportunity to collaborate on R&D topics on electronic design automation and AI."

More on the encouragement of young academics in this report

TECHNISCHE UNIVERSITÄT
ILMENAU

www.tu-ilmenau.de

Dr. Gerd Reidenbach, Head of Unit 33 – Horticulture and Horticultural Experimentation, Lehr- und Versuchszentrum Gartenbau (LVG, a teaching and research centre for horticulture), Thuringian Agency for Agriculture and Rural Areas, Erfurt Branch, Leipziger Straße 75a, 99085 Erfurt, Photograph: Reidenbach.

Dr. Gerd Reidenbach, Lehr- und Versuchszentrum Gartenbau (LVG)

"At the Lehr- und Versuchszentrum Gartenbau, a teaching and research centre for horticulture, we are primarily working on recommendations for action on how to use irrigation water sparingly and efficiently, and we are testing the regional suitability of cultivars in fruit and vegetable growing, among other things. The background to this is the climate change predicted in the Thuringian Climate and Adaptation Programme. It indicates that, in addition to the continuous search for adapted cultivars, new strategies in water management must be developed in order to supply people with high-quality food. For the economical, efficient use of raw materials and resources, water in particular is becoming increasingly important in the context of climate change, since slowly but continuously rising temperatures, a decrease in precipitation and extended vegetation periods are to be expected as an expression of climate change. In addition to new cultivation strategies, plant breeding and variety testing, supplementary irrigation is becoming more important for more and more crops in line with market and price developments.

With this in mind, we have found the ideal partner in IMMS to expand our experiments on drip irrigation with sensor technology. For example, a radio sensor system developed at IMMS was used for the irrigation of sweet cherries. The colleagues from IMMS installed and supervised the systems on our experimental fields for us. We were thus able to record air temperature and humidity, soil temperature and humidity, leaf moisture as well as air pressure and photosynthetically active radiation at different points for four different variants of irrigation and two variants of mulch

To the specialist article in this report

cover. IMMS provided us with the measurement data via a connection to our server for our experiments and processed them graphically. Even the sole use of soil moisture sensors provided us with decisive information to achieve savings compared to fixed irrigation intervals or irrigation according to the current standard model. For this purpose, IMMS also investigated the suitability of different soil sensors for this application. This is important for our recommendations for fruit growers, especially since there are also significant price differences for the sensors.

We have experienced IMMS as a reliable and proactive partner who has taken our perspective and implemented targeted solutions from it and is always open to new impulses. For example, in our meetings, which I always find very constructive and goal-oriented, we had discussed further potential savings that we could achieve if we could use information about the plant itself in addition to abiotic variables. As a result, IMMS has developed a sensor for measuring fruit growth in order to integrate it into the existing system in the future. This will enable us to recognise the different phases of fruit development and to irrigate whenever it is beneficial for the fruit quality. All these results, the very good cooperation, for which I would like to express my sincere thanks, and the many new ideas we intend to pursue in joint research and development work in the future."

https://tlllr.thueringen.de/wir/gartenbau

Freistaat Thüringen
Landesamt für Landwirtschaft und Ländlichen Raum

Lead application IoT systems for cooperative environmental monitoring: www.imms.de

More voices from academia: www.imms.de

Heinz-Wolfgang Lahmann, Business Unit Manager Measurement Technology/ Test Bench Construction and Development, GFE – Gesellschaft für Fertigungstechnik und Entwicklung Schmalkalden e.V.

Photograph: GFE.

Heinz-Wolfgang Lahmann, GFE – Gesellschaft für Fertigungstechnik und Entwicklung Schmalkalden e.V.

"We as GFE – Gesellschaft für Fertigungstechnik und Entwicklung Schmalkalden e.V. (Society for Production Technology and Development Schmalkalden) are an industry-oriented research institution that offers our customers complete tool solutions. For over 30 years, we have been developing product and technology solutions for companies together with our partners, while at the same time taking a practical and demand-oriented approach to implementation. For this purpose, we have a large partner network and are involved in numerous projects in research, development and industry every year. As part of this, we also maintain long-standing relationships with IMMS. As partners in the Mittelstand 4.0 Competence Centre Ilmenau and in the new Mittelstand Digital Centre Ilmenau, GFE and IMMS have been jointly supporting SMEs in their digital transformation for more than six years.

More on SME Digital in this report

Artificial intelligence (AI) is playing an increasingly important role in digitalisation. In our view, AI technology also has great application potential for machining processes and the associated tools. Combined with suitable sensor systems and process-related data processing systems, AI enables, for example, solutions for in-process quality assurance in precision metalworking or for wear predictions in cutting tools. We therefore turned to IMMS with its expertise in the development and application

More on the KIQ projekt in this report

of intelligent sensor systems, embedded electronics solutions and AI to investigate the boundary conditions and concrete solution approaches for the use of AI in this domain as part of various research and implementation projects. In addition to scientific publications, this also resulted in demonstrators that can provide SMEs with a practical insight into the possibilities of AI.

In our collaboration with IMMS, we particularly appreciate the expertise in the field of sensor data acquisition and processing, the high application orientation of the solutions and the constructive contacts with its employees – not least when working together on site on machines and equipment. We are in regular exchange with IMMS and are constantly developing new ideas and starting points for the use of current digital technology and, in particular, AI in tools and tooling machines. We look forward to tackling the next topics together."

www.gfe-net.de

GFE – Gesellschaft für Fertigungstechnik und Entwicklung Schmalkalden e.V.

Lead application Adaptive edge AI systems for industrial application: www.imms.de

Working hand in hand with the Technische Universität Ilmenau

Being an affiliated institute of Ilmenau University of Technology (TU), IMMS benefits from networking with the university while the TU benefits from the Institute's close relations with industry. In 2020, 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

IntelligEnt* research group: EDA Competition Award for „Trash or Treasure" – Intelligent Layout Processing

A team of eight students, PhD students and researchers from Ilmenau TU and IMMS won the EDA Competition Award of the IEEE Council on Electronic Design Automation (CEDA) on 22 July 2021 on the occasion of the international conferences on methods for the design of integrated circuits SMACD 2021 and PRIME 2021. In the joint research group IntelligEnt, IMMS and the Department of Data-Intensive Systems and Visualisation (dAI.SY) from Ilmenau TU have developed an AI-based anomaly detection method that can automatically detect unproven and potentially faulty sections in layouts. With the award-winning plugin for the free PCB design tool KiCad, signals can be categorised in KiCad and transferred to the training or evaluation process.

More on this award in this report

More on the IntelligEnt research group: www.imms.de

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

Since 2021, IMMS, Ilmenau TU and nine other Thuringian partners have been 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 semicon-

QuantumHub Thüringen at www.imms.de

ductor technology (CMOS). They are used to convert single photons into electrical signals and allow operation at room temperature without large and complex cooling systems.

thurAI*: Sensor technology for SmartCity and methods to intelligently process data in the network for AI evaluations

In the thurAI project, Ilmenau TU, Jena FSU and IMMS are working on current solutions in the three areas of Smart City, healthcare and medical technology as well as production and quality assurance. IMMS and Ilmenau TU will implement a "LivingLab" in Ilmenau for the 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.

thur AI at www.imms.de.

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

Until 2022, 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.

More on NanoFab at www.imms.de.

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

The IMMS contribution is, as "Migration Model Factory", to put its shoulder to the introduction of Industry 4.0 technology for the improvement of plant and processes. An example of what this means is retrofitting machinery and equipment with wireless and networked sensors so that data can be obtained and processed which will underpin new diagnostic, maintenance and service concepts. Combining open-

More on SME Digital at www.imms.de.

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.

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 until 2022 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.

More on HIPS at www.imms.de

Joint encouragement of young academics

IMMS not only complements teaching at Ilmenau TU with extensive practical offers. Some courses are also given by IMMS staff. 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.

Internships, BSc/MSc/HiWi subjects: www.imms.de

ENCOURAGEMENT OF YOUNG ACADEMICS

Jun Tan successfully defended his dissertation “Design Methodology and Implementation of Fully Passive RFID SoC with Temperature Sensor” at the Ilmenau TU on 18 February 2021. Photo: 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.

Internships, BSc/MSc/HiWi subjects: www.imms.de

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.

Hani Abdullah, M.Eng., scientific employee at IMMS

”After my master’s thesis ’Development of core assemblies for a universal UHF RFID transmitter and 4-channel receiver‘ with Professor Ludwig Niebel at the Ernst-Abbe-Hochschule Jena, University of Applied Sciences, I got in touch with Eric Schäfer from IMMS. I knew IMMS from my on-the-job supervisor Professor Johannes Trabert. Eric was very interested in the RFID topic of my thesis and introduced me to the institute and the projects. There were many interesting questions about RFID transponders and ultra-low-power applications that I wanted to research there. In the official job interview, I could then get to know my future colleagues and could well imagine working at IMMS: We immediately started discussing contactless data transmission, far-field communications and especially RFID, and it was like a brainstorming session for new research and development work. Since then, I have been involved in a project that is all about RFID. The goal is to build integrated sensor systems that use extremely little energy and can thus be used to develop battery-free RFID sensor transponder systems. This will enable many applications in IoT and Industry 4.0, where many small sensors are to be used and not maintained.

I have been at IMMS since the beginning of 2020 and my work focuses on the application and verification of mixed-signal ASICs, especially for RFID transponders. There, I have developed a test setup for battery-free RFID sensor transponder systems. This can be used to test and characterise our passive UHF RFID transponders together

Hani Abdullah, M.Eng., scientific employee in the Microelectronics department at IMMS in Erfurt.

Photograph: IMMS.

Internships, BSc/MSc/HiWi subjects: www.imms.de

More voices from IMMS: www.imms.de

with commercial, often power-hungry sensors. These findings have been incorporated into the new chip developments for passive UHF RFID sensor applications. It is very exciting to be able to contribute to completely new and very sophisticated solutions.

I really enjoy working here in a team where you can openly discuss and exchange your ideas. This and the flat hierarchies are a great pleasure for me and I like to think about the next working day. Not only that! The projects we have at IMMS are not only important to support companies with innovations. Rather, we work on solutions from which our society can benefit. That motivates me immensely because I want to contribute to a better society."

Jakob Hampel, M.Sc., scientific employee at IMMS

"With the goal of completing the mandatory internship in the Computer Engineering course of study, I became aware of IMMS through the open day and through Professor Sommer's lectures. At the department of Industrial Electronics and Measurement Technology I developed a software to evaluate and visualise measurement data from wafer tests and automatically generate a test report based on that data.

Internships, BSc/MSc/HiWi subjects: www.imms.de

Immediately after completing the internship, I began working on my Bachelor's thesis – again at IMMS. This involved developing an FPGA configuration for evaluating a single-photon detector. Even though I did not have much experience in the very interesting field of FPGA development, I was able to acquire the necessary expertise thanks to Professor Töpfer's supervision and the assistance of my IMMS colleagues. In the subsequent student assistant position at IMMS, I further deepened the knowledge gained during the Bachelor's thesis to then work on an advanced FPGA topic for my Master's thesis. The helpfulness of colleagues in the department of Industrial Electronics and Measurement Technology, especially for designing analogue circuits and operating the complex measurement instruments, played a key role in successfully completing the Bachelor's and Master's thesis.

More voices from IMMS: www.imms.de

In my Master's thesis, I developed a time-correlated single-photon counting system that is fully integrated on the FPGA. This not only resulted in a very good Master's degree, but has also been further developed into a complete product for X-FAB as a SPAD-EvalKit and is being used in many different measurement applications. Thanks

Jakob Hampel, M.Sc., scientific employee in the Industrial Electronics and Measurement Engineering department.

Photograph: IMMS.

to the supervision at IMMS and the opportunities to always learn new things, I was able to extend my knowledge in this very interesting field from a beginner's level to an advanced level at which it was poissible to complete a research topic during a Master's thesis.

Since then, I'm working as a scientific staff member at IMMS, developing FPGA solutions for a multitude of different measurement setups in research projects as well as industrial commissions. Due to the proximity to Technische Universität Ilmenau and other research institutes, we are always confronted with exciting new tasks and always able to learn new things. Currently I'm working on characterizing semiconductor-based single-photon detectors for application in quantum communications systems in the QuantumHub Thüringen project."

Jonathan Josue Gamez Rodriguez, M.Sc., scientific employee at IMMS

„IMMS offers an extremely creative and versatile working atmosphere. The implementation of projects with various partners from science and industry always brings new challenges that have to be met. With the help of state-of-the-art technology, a wide range of competences in the team and an open working atmosphere, I am developing on a professional level and also have a lot of fun with the tasks.

I mainly deal with the software development of embedded sensor systems. This usually involves several steps: configuration and communications with sensors through various protocols, acquisition and processing of data and transmission to other sys-

Internships, BSc/MSc/HiWi subjects: www.imms.de

More voices from IMMS: www.imms.de

Jonathan Josue Gamez Rodriguez, M.Sc., Embedded Hardware- and Software Engineer in the System Design department at IMMS in Ilmenau.

Photograph: IMMS.

tems. Such operations are increasingly relevant in our modern world, where automation and self-monitoring of processes increase their efficiency and thus our quality of life.

Since I have been working at IMMS, I have been continuously expanding my knowledge from my studies and at the same time I can try out new concepts and methods to find ever better solutions. The tasks are always new and never boring. If a subtask of a project is very complex, I can always turn to my colleagues to either discuss alternative solutions in the team or get help directly. I experience this willingness to help not only from colleagues from the same team, but also from colleagues from other departments.

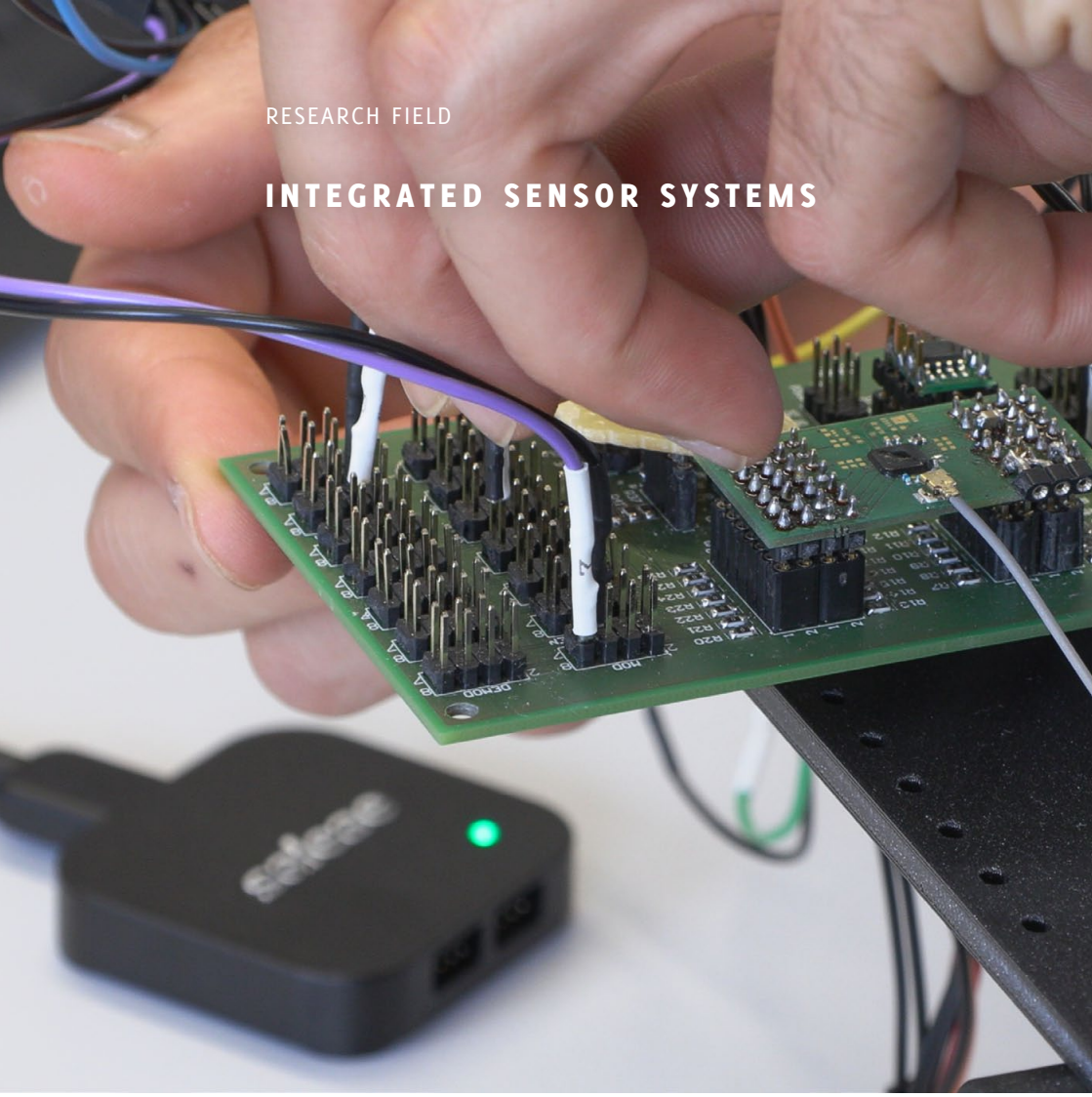
One also finds resonance among work colleagues for private initiatives. A great example in my experience is the participation in the Stadtradeln (city cycling) competition, which I suggested. Many colleagues were happy to participate, and the motivation was so good that we were awarded gold by the Ilmenau municipality this year – but above all, it was a lot of fun. I can say the environment is very friendly and I feel very comfortable.“

Internships, BSc/MSc/HiWi subjects: www.imms.de

More voices from IMMS: www.imms.de

RESEARCH FIELD

INTEGRATED SENSOR SYSTEMS



Preliminary investigations for a UHF RFID sensor transponder IC for monitoring plants in greenhouses and for a wake-up receiver IC for monitoring wind turbines, which we are developing in the StorAIge project. Photograph: IMMS.

The StorAIge project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 101007321. The JU receives support from the European Union's Horizon 2020 research and innovation programme and France, Belgium, Czech Republic, Germany, Italy, Sweden, Switzerland, Turkey. StorAIge is funded by the German Federal Ministry of Education and Research (BMBF) under the reference 16MEE0155T and by the Thuringian Ministry of Economic Affairs, Science and Digital Society (TMWWDG) under the reference 2021 ECS 0003.

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.

More on integrated sensor systems: www.imms.de

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.

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.

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Preliminary investigations for a UHF RFID sensor transponder IC for monitoring plants in greenhouses and for a wake-up receiver IC for monitoring wind turbines, which we are developing in the StorAIge project. Photograph: IMMS.

Highlights of 2021 in our research on integrated sensor systems

Start of StorAIge* – ultra-low power embedded memories in wireless front-end ICs for wireless sensors

Innovative, miniaturised and extremely power-saving wireless sensor solutions are the basic building blocks for Industry 4.0 applications

At IMMS, we are developing two wireless sensor ASICs for Industry 4.0 applications in the StorAIge project. In close cooperation with the consortium partners microsensys and endiio, we will develop a UHF RFID sensor transponder IC for monitoring plants in greenhouses and a wake-up receiver IC for monitoring wind turbines. These new and innovative ICs will use X-FAB's benchmark ULP memory to ensure that the chips require very little power to operate.

StorAIge at www.imms.de

Development of a UHF RFID sensor transponder IC with extremely low power consumption for monitoring plants in greenhouses

In highly automated and modern greenhouses, plants are continuously moving on a conveyor belt to provide same climatic conditions to all the plants that are being produced. It is also very important to continuously monitor temperature and soil moisture of the individual plants to ensure that all plants have even growing conditions. Monitoring with battery-based wireless sensors is usually very expensive for such applications. Passive UHF RFID-based sensor transponders, in contrast, are not powered by batteries but by the energy from the readers and are therefore considered an excellent alternative.

Lead application RFID sensor technology: www.imms.de

The challenge here is to measure the soil moisture sensors without batteries at a range of two metres and to read them passively while the plants are moving continuously on the conveyor belt. With our know-how from the BMBF project RoMulus, we are currently developing an extremely low-power UHF RFID sensor with intelligent energy management for such demanding applications in the StorAIge project at IMMS.

Development of a wake-up receiver IC with extremely low power consumption for monitoring wind turbines

Among all components, the gearbox in wind turbines causes the largest share of those failures that have a direct impact on operating and maintenance costs. To prevent cost-intensive bearing damage in the event of a failure, extensive data, such as vibrations and the temperature, must be recorded locally via sensors and evaluated with local intelligence for diagnosis. Event-controlled wake-up receivers are a key component for the low-energy operation of sensors in such applications.

In StorAIge we will develop an ultra-low power wake-up receiver IC for wireless sensor applications at IMMS. The challenge is to ensure that the sensor nodes can operate under strict power consumption limits in the nanowatt range, among others, and are able to remain in a “sleeping but aware” state and immediately switch operating mode upon receiving a wireless wake-up signal. Our wake-up receiver aims to ensure that in demanding applications such as wind turbines, where extreme and difficult conditions prevail, faults can be detected quickly, and maintenance-intensive consequential damage can be avoided.

Core topic ULP-sensor systems: www.imms.de

StorAIge at www.imms.de

Scientific debate (public part) in the PhD examination of Jun Tan on 18 February 2021 at Technische Universität Ilmenau: Univ.-Prof. Dr.-Ing. habil. Hannes Töpfer (Chair of the PhD Committee), Jun Tan, Univ.-Prof. Dr.-Ing. Ralf Sommer (supervisor), Univ.-Prof. Dr.-Ing. Jens Müller, Dr.-Ing. Dominik Krauße (l.t.r.). Photograph: Ralf Sommer.

Highly accurate and battery-free measurement via RFID – IMMS PhD candidate defends dissertation on precise passive RFID sensor technology

Jun Tan, scientist at IMMS, successfully defended his dissertation "Design Methodology and Implementation of Fully Passive RFID SoC with Temperature Sensor" at Technische Universität Ilmenau on 18 February 2021.

Highly accurate, small and battery-free – to date unrivalled in RFID sensor technology

"My goal was to combine precise low-power microelectronic sensor technology with miniaturised and passive RFID technology. If this succeeds, many applications will first become possible, for example in the field of life sciences," says Jun Tan. "High-precision individual sensors already exist, for example temperature sensors that can measure from -55°C to 125°C and are accurate to within ±0.15°C. But they are not readily suitable for wireless measurements via RFID or even for passive, i.e. battery-free RFID transponders." With passive and thus maintenance-free RFID sensor technology, the RFID readout unit generates a magnetic field that is sufficient to supply the RFID transponder with power, and to record and send measurement data.

Lead application RFID sensor technology: www.imms.de

This not only required concepts for extremely energy-efficient circuits so that they could work with the little current from the RFID field. It also had to be ensured that neither the power supplies nor the wireless communication interfered with the targeted high-precision measurements. "For applications with small installation space, it is also better to integrate the temperature sensor directly in the chip" Tan explains further. "There are already solutions for this, too, but they only map very narrow temperature corridors of, for example, 50 – 60 °C and are only accurate to ±0.8 °C in these."

Core topic ULP-sensor systems: www.imms.de

New measuring concept for hitherto highest accuracy and largest working range

Jun Tan's concepts have culminated in an RFID chip whose integrated temperature sensor can measure over a wide range from 0°C to 125°C with a systematic absolute accuracy (3σ) of ±0.4°C. No other component needs to be connected to this chip except for the RFID antenna, and it achieves the highest accuracy with the widest operating range compared to currently known RFID temperature sensors.

"The fact that the chip works so accurately is mainly due to the new power management and communications concept," says Jun Tan. "The sensor itself can be accurate. But I don't get much of that when I'm receiving data and taking a measurement at the same time, because the sensor is always disturbed exactly when the reader is requesting temperature data." Tan has therefore developed a solution where a single command can serially record and transmit multiple readings. His power management system provides a stabilised supply voltage to the temperature sensor. The combination of these two approaches improves accuracy by a factor of 16.

Work goes hand in hand with new RFID developments for industrial use

"Jun Tan has not only developed new concepts for this chip, he has also published his work in the most relevant journals for the RFID community and even won the best paper award at an IEEE conference in Japan," explains Univ. Prof. Dr.-Ing. Ralf Sommer, Tan's doctoral supervisor and scientific director of IMMS as well as head of the Department of Electronic Circuits and Systems at Ilmenau TU. Over the years, Tan has developed his approaches in various R&D projects at IMMS, mirrored them with requirements from industry, consistently developed them further and incorporated them into new concepts that are being pursued further for the services offered by IMMS in RFID sensor technology, Sommer continues. The main focus is on passive RFID sensor transponder chips that can be used to operate various commercial individual sensors. "Compared to Jun Tan's fully integrated RFID temperature sensor, an RFID chip solves the power supply, signal quality and communications challenges of several individually connected sensors thanks to new concepts, which was not possible before. This allows new point-of-care applications and automation solutions to be developed faster, easier and cheaper. Without Jun Tan's work, we would not yet be where we are now."

Lead application RFID sensor technology: www.imms.de

Set-up of the microfluidic cartridge for testing with SPARCL® chemiluminescence assay.

Photograph: IMMS.

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

Start of KODIAK* – image sensors for chemiluminescence assays with Thuringian industry and institutes from Erfurt-Südost and Jena

Lab-on-chips (LOC) integrate various laboratory diagnostic procedures for sample preparation and analysis on one chip and can process and evaluate patient samples automatically. The disposable cartridges are often no larger than a credit card, their device platforms small and thus optimal for diagnosis or first aid in medical practices or for point-of-care diagnostics in general. Results can thus be provided more cheaply, faster and earlier than conventional analyses in a medical laboratory. In KODIAK, electronic, optical and fluidic components and associated integration techniques are being developed to open up LOC-based point-of-care diagnostics for further use cases.

KODIAK at www.imms.de

Lead application Sensor systems for in-vitro diagnostics: www.imms.de

Highly sensitive image sensors with SPADs for chemiluminescence assays

IMMS is contributing its expertise on CMOS-integrated optical sensors to the project. We are investigating how the new single photon avalanche diodes (SPADs) of our project partner X-FAB can be used in highly sensitive image sensors for chemiluminescence LOC assays. We are developing a line sensor for reading chemiluminescence in microfluidic cartridges. In addition, hardware and software modules are also being developed to evaluate the sensor chip in an application-oriented manner.

First application – diagnosis of the frequently lethal CR syndrome

The development is essentially driven by enabling rapid and cost-effective diagnoses for cytokine release syndrome (CRS) and at the same time demonstrating the suitability of the technical project results in medical applications. CRS occurs as a

serious side effect in a variety of diseases and therapies, such as immunotherapy, graft-versus-host disease, sepsis and infectious diseases such as Covid-19, and is often lethal. Depending on the study, for example, between about 20 – 45% of patients treated with CAR T-cell therapy in oncology suffer from CRS, as do the majority of corona patients who die. CRS must therefore be recognised and treated as quickly as possible. Currently, diagnosis is symptomatic, i.e. delayed and unspecific, and via blood tests and thus invasive, which excludes e.g. online monitoring. With the new image sensors, serious disease processes are to be detected earlier, clinical capacities are to be used more effectively and the medical care of patients is to be strengthened.

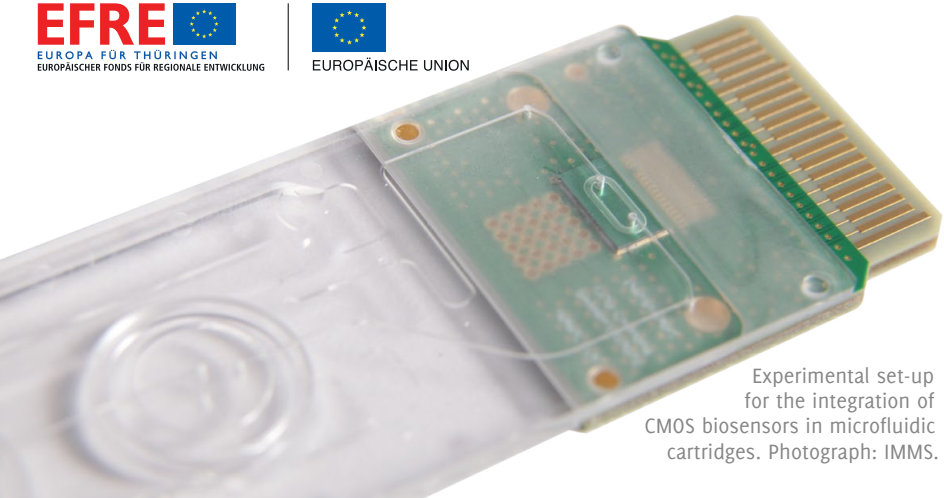
Start of SensInt* – CMOS image sensor for time-resolved fluorescence detection for direct integration into microfluidic cartridges via 3D screen printing

High demand for point-of-care tests

Lead application Sensor systems for in-vitro diagnostics: www.imms.de

The SARS-CoV-2 pandemic has not been the first time that the demand for solutions for rapid, patient-oriented diagnostics (point-of-care, POC) has grown strongly. To effectively stop the spread of infectious diseases, a dense testing regime has now been identified as a crucial tool in pandemic response. Microfluidics has already been established for years as the key technology in this field, with which very accurate results can be obtained on a molecular biological basis, e.g. by PCR. To be able to offer such systems smaller, more portable and, prospectively, cheaper, sensors for detection are increasingly being integrated into such microfluidic cartridges.

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



Experimental set-up for the integration of CMOS biosensors in microfluidic cartridges. Photograph: IMMS.

On the one hand, there are prototype solutions with adhesive techniques or solutions for very large quantities. For the intermediate range, which is important for development, clinical investigations and market launch, there is currently no satisfactory solution.

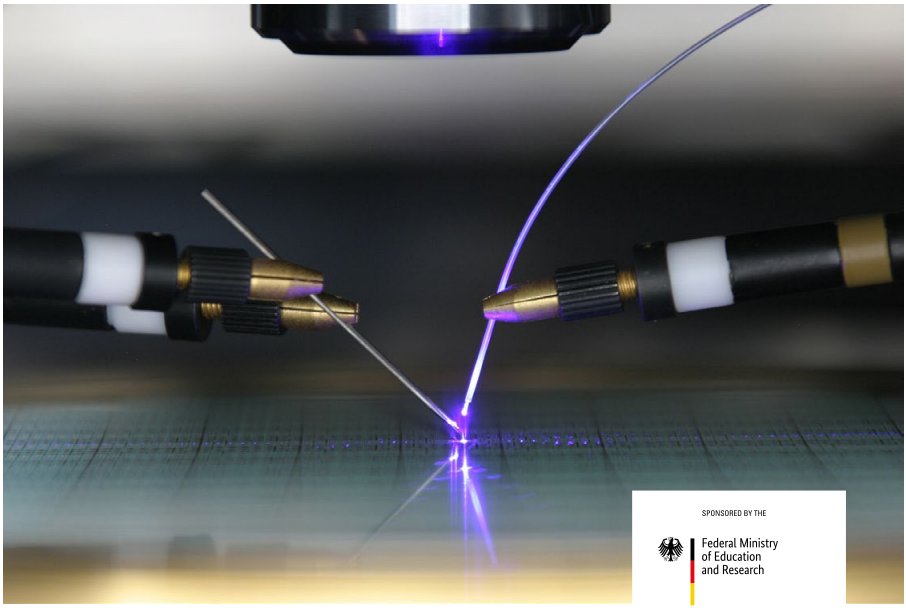
3D screen printing closes the technology gap

The project aims to exactly close this technology gap, which often becomes a "valley of death" especially for small and medium-sized diagnostic companies, by combining injection moulding, 3D screen printing and sensor technology. Using the example of a microfluidic cartridge for the molecular biological diagnosis of respiratory diseases, the entire technology chain will be demonstrated and generally applicable design rules for such integration will be developed. The challenge lies in integrating manufacturing technologies from a wide variety of fields and materials, such as thermoplastics, elastomers and silicon. This will make it possible to produce such POC tests faster and cheaper in the future.

Image sensor for integration into microfluidic cartridges

IMMS will research and prototype an optical sensor system for microfluidic fluorescence applications. This system comprises a CMOS image sensor specially developed for integration into a microfluidic cartridge, which, in addition to the optical detection elements, the photodiodes, also contains the required electronic control and readout circuits, as well as an electronics unit adapted for this image sensor, with which the image sensor can be operated.

Core topic CMOS-based biosensors: www.imms.de



Characterisation of new optoelectronic sensors in wafer composites. Photograph: IMMS.

Start of FluoResYst* – SPAD-based sensor for time-resolved readout of fluorescence-labelled DNA microarrays

Multi-drug resistance is an increasing problem in infectious diseases

According to the WHO, tuberculosis is the second deadliest infectious disease worldwide after COVID-19. To counter the multi-resistance of tuberculosis bacteria, which is becoming more and more prevalent against antibiotics, suspected cases have to be tested daily and, in case of a positive laboratory result, treated and isolated quickly. As a rule, however, the necessary laboratory infrastructure and logistics are lacking, because 95 per cent of tuberculosis cases occur in developing and emerging countries.

FluoResYst at www.imms.de

Lead application Sensor systems for in-vitro diagnostics: www.imms.de

Combination of two innovations leads to a new detection technology

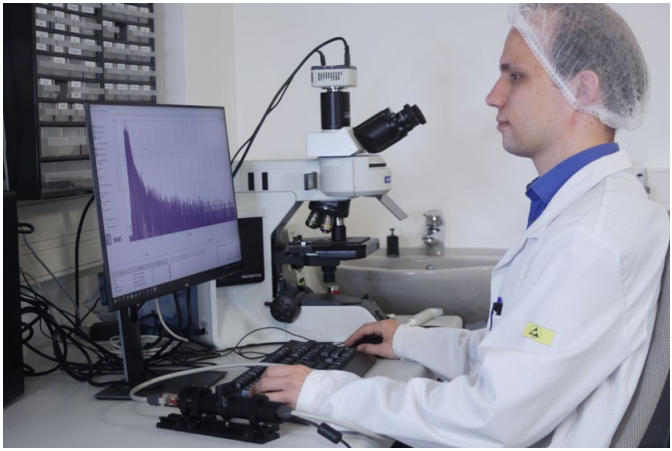
The overall goal of FluoResYst is to develop a rapid point-of-care detection system for multidrug resistance that can help to contain epidemics by accelerating on-site diagnostics outside of laboratories. The combination of photonic integration of time-resolved fluorescence measurement for short-lived fluorochromes and the biochemi-

cal fluorescence quenching antibody assay is expected to greatly simplify complex analyses that were previously difficult to access and thus make them widely available.

IMMS develops time-resolving detector chip with SPADs

In the technological part, a photonic platform is being developed for this purpose, which is to enable tuberculosis diagnostics outside a laboratory environment through a high degree of integration. The principle of the detection platform is based on time-resolved fluorescence measurement, with which complex optics and wavelength filters can be largely avoided. This is made possible by the use of a very fast excitation laser and a fast CMOS-integrated detector.

In the project, IMMS is developing this detector chip for reading out DNA microarrays. In addition to several arrays of single-photon avalanche diodes (SPADs), the chip also contains the histogram generators required for their evaluation. By the use of through-silicon vias (TSVs), the chip with its planar surface can be integrated very well into microfluidic systems. In addition to the SPADs, classical photodiodes are also distributed and evaluated in the chip, which relaxes the requirements for the homogeneity of the optical excitation and further reduces the device complexity.



Preliminary work for a SPAD test stand with measuring chamber for fluorescent dye.

Photograph: IMMS.

Core topic
CMOS-based biosensors:
www.imms.de

Project start of VE-VIDES* – Trustworthy electronics against hacker attacks

Hackers are already targeting networked vehicles, machines, industrial and telecommunications systems to gain illegal advantages, such as harming competitors, stealing intellectual property or leaking sensitive data.

At the same time, there is a growing need to make automotive systems, corporate and production networks more functional, convenient, traffic-safe and energy- and cost-efficient. These requirements alone are not only making the systems more and more complex and demanding in their development. They are also becoming increasingly networked. More complexity and more networking also offer more opportunities for attacks on these systems, which can also have a greater impact and are therefore also more lucrative for offenders.

VE-VIDES at www.imms.de

Innovative chip architectures, modelling and verification methods

In the project, IMMS and its partners are securing the design of integrated systems through innovative chip architectures and automated modelling and verification methods. This should enable the trustworthiness of the system to be continuously checked not only during the design, but also during operation, and thus a hacker attack to be blocked.

Core topic AI-based design and test automation: www.imms.de

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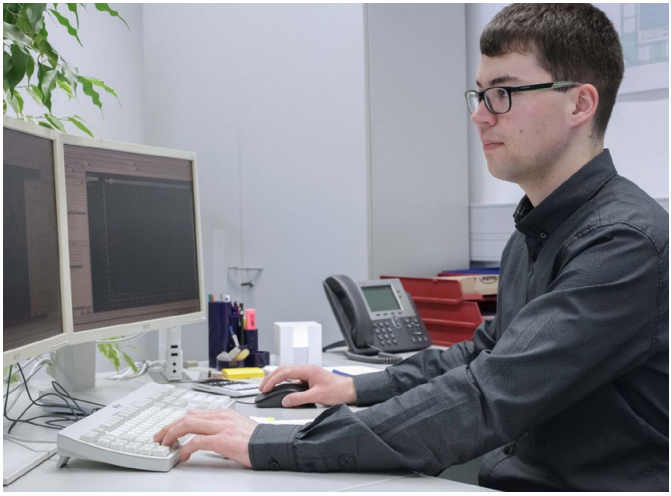

Among other things, in the VE-VIDES project, innovative chip architectures for trustworthy electronics are being developed against hacker attacks. Photograph: IMMS.

In VE-ARiS, IMMS is developing new design methods based on machine learning for copy protection of integrated circuits.

Photograph: IMMS.

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Electronic know-how protection for innovative sensor systems iC-Haus, IMMS and Wachendorff launch BMBF joint project VE-ARiS*

Product piracy has long since arrived in the world of modern highly integrated sensor systems. These systems are used primarily in key industries such as robotics, automation, drive and laser technology as well as in safety-critical applications. In addition to massive economic damage to the original developer and manufacturer, counterfeiting and active attacks on critical systems entail serious security risks. For this reason, iC-Haus GmbH, IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH) and Wachendorff Automation GmbH & Co. KG are developing novel copy protection methods for integrated circuits and circuit boards. The partners presented details of their three-year joint project "Electronic Knowhow Protection for Innovative Sensor Systems – ARiS", which started in March 2021, at the BMBF's digital conference "Trustworthy Electronics" on 14 April 2021.

VE-ARiS at www.imms.de

Counterfeits and copies as a risk to safety-critical systems and economic substance

"Even with simple copies, which are usually not intensively tested and qualified like original parts, there is a risk of malfunctions. The risks in medical technology or autonomous vehicles, for example, go far beyond those of property damage," explains Dr Heiner Flocke, Managing Director of iC-Haus GmbH and coordinator of the ARiS project. Affected are not only printed circuit boards but also the integrated circuits built into them, which were created in considerable and time-consuming development work and with the know-how of high-tech companies. Smaller manufacturers who have established their reputation with their chips in medium quantities as key products in the industrial sector are not spared either.

Core topic AI-based design and test automation: www.imms.de

Two-stage copy protection: camouflage and watermark as active defence

Therefore, new methods for camouflaging circuits and for inserting a watermark are being developed at IMMS to make it more difficult to " imitate" and thus copy integrated circuits and systems. The methods are being investigated by iC-Haus and Wachendorff to see to what extent they can be implemented and are robust enough for industrial developments, as well as being supplemented by further camouflage and defence mechanisms.

A method based on machine learning is being developed at IMMS to camouflage circuits. "We will simulate the perspective of a potential counterfeiter and thus cloud his view already in the design," explains Georg Gläser from IMMS, specialist for the integration of AI methods into design automation. This is possible, for example, by using components with the same appearance but different functions. This makes reverse engineering extremely costly and economically unattractive, Gläser continues.

The envisaged "watermarks" represent novel defence mechanisms. They are integrated on the chip level as a circuit block that acts as a digital signature. With it, the chips are only released directly before delivery or commissioning, provided that the sensors also contained in the chip deliver the expected parameters. Personalised watermarks are integrated on printed circuit boards. With an additional defence IC, the circuit board is activated by the sensor system manufacturer.

Validation on industry partners' systems – and beyond

The practical test is being carried out by iC-Haus with a chip development and Wachendorff with a new PCB design. "The new methods for copy protection are in principle suitable for all chips and PCBs. We will validate them with a new type of copy-protected position encoder IC," Flocke explains. Chip and PCB will be subjected to extensive laboratory tests, integrated into relevant field environments and tested. "With active defence at board level, we ultimately ensure the originality of all components of a system," explains Robert Wachendorff, Managing Director of Wachendorff Automation GmbH & Co. KG. Both industrial partners have their sights set on integrating the new processes into their own product ranges, summarises Flocke. "Moreover, this is interesting for the entire industry and can create a standard claim for trustworthy electronics."

Core topic AI-based design and test automation: www.imms.de

The SMACD & PRIME 2021 conferences planned for Erfurt are being held virtually from 19-22 July. Photo Krämerbrücke Erfurt: lapping @ Pixabay.

International conferences on methods for the design of integrated circuits – young scientists from electrical engineering visit Erfurt virtually

From 19 – 22 July 2021, mainly European experts take part in two international conferences on methods for the design of integrated circuits (SMACD) and on research by doctoral students in microelectronics and electronics (PRIME). The events, which were launched in 1991 and 2005, invite scientific exchange on application-oriented developments at changing, mainly European, locations. This year they are jointly organized by IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH), Technische Universität Ilmenau, RWTH Aachen and the Informationstechnische Gesellschaft (ITG) of the VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V. (Association for Electrical, Electronic & Information Technologies). For safety reasons, the conferences originally planned in Erfurt take place in virtual form.

More on the encouragement of young academics: www.imms.de

Conferences should inspire young talent beyond the topics to Germany

"Young professionals traditionally provide many topics for both conferences and regularly make up about half of the audience. The feedback from the community is an enormous incentive for them and shows them new perspectives for their work,"

explains Univ.-Prof. Dr.-Ing. Ralf Sommer, General Chair of SMACD 2021, Scientific Managing Director of IMMS and Head of the Department of Electronic Circuits and Systems at TU Ilmenau. “At the same time, we would naturally like to take the opportunity to focus on Germany as their future center of work and life,” Sommer continues. He personally looks to Erfurt as a microelectronics location, Thüringen’s university and research landscape and institutes such as IMMS, in which the specialists of tomorrow are involved in practice during their studies and enabled for a career start in industry and applied research. Here, as in Germany as a whole, it is important to strengthen and expand microelectronics competencies in order to remain internationally competitive with safe and reliable chip developments, sufficient production capacities and, above all, with well-trained specialists.

Broad range of topics and agile formats for new ideas in microelectronics

211 authors from 21 countries submitted 72 papers for the SMACD conference, and for the PRIME conference 69 topic proposals were submitted by 237 people from 19 countries, in each case mainly from Europe. About two thirds were able to convince the committees in each case, ensuring a diverse range of topics over the four days. In particular, it is about how new methods for synthesis, modelling, analysis and simulation can be used to make the design for increasingly complex microelectronics chips more efficient and safer. Main foci include machine learning, wireless communications systems, biomedical circuits and the energy supply of integrated circuits, for example through energy harvesting.

Core topic AI-based design and test automation: www.imms.de

In the keynote contributions, Jörg Doblaski, CTO of X-FAB, will talk about the challenges and opportunities of future applications in the automotive, medical and industrial sectors. Marco Seeland from Ilmenau TU will give an overview on machine learning for the design and characterization of microelectronic systems. In addition, the program includes eight tutorials on topics such as electronic design automation, quantum computing, printed electronics, and neural networks for embedded systems. They are offered by Fraunhofer IIS/EAS Dresden, Forschungszentrum Jülich, RWTH Aachen University, University of Glasgow, Cadence Design Systems Germany, Brandenburg University of Technology, OFFIS e.V. Oldenburg and Reutlingen University, among others. In addition, IMMS, Ilmenau TU, Cadence, the University of Oldenburg and OFFIS - Institute for Computer Science are organizing a BarCamp for electronic design automation. There, all participants determine the topics, agenda

and formats and thus contribute to a lively exchange in an unconventional "unconference", which has some overlaps with agile R&D formats in industry and often leads to new ideas and joint projects.

Central link between science and practice

"Scientific support and mentoring in universities, reviewer feedback in conferences such as ours, and the associated IEEE publications are, of course, an important pillar in the promotion of young researchers," says University Professor Dr.-Ing. Stefan Heinen, General Chair of PRIME 2021 and holder of the Chair of Integrated Analog Circuits and the Institute of Semiconductor Technology at RWTH Aachen University. Furthermore, it is essential to introduce young professionals to practical challenges at an early stage and to show them real-world perspectives in the electronics industry. "To this end, we offer a comprehensive theoretically well-founded and application-oriented education at RWTH Aachen University. Our students design and implement innovative circuits from the fields of RF systems and integrated power electronics." For SMACD and PRIME, he sais, sponsors Cadence, X-FAB, Europractice, Infineon and NXP don't just give money to make the conferences happen. "Here, it's mainly about content and exchange on concrete topics that run in the lectures and are directly mirrored by the industry."

More on the encouragement of young academics: www.imms.de

Erfurt – digital and analog

The semiconductor industry, microelectronics and microsystems technology, which is currently being expanded in Erfurt, is also the subject of the video message with which Erfurt's Mayor Andreas Bausewein addresses the participants at the start of the two conferences. Many thousands of people have worked in microelectronics in Erfurt since the 1970s and many still do today. "My hope is that microelectronics will continue to grow in Erfurt and that even more young people will find their future here in the city and in this professional field," says Bausewein. To this end, he also refers to the quality of life in Erfurt. On the sidelines of the digital conference, the live broadcast of the city tour provides insights into the medieval old town, which is considered the largest area monument in Germany. Bausewein is optimistic that many will find their way to Erfurt after the conference and in a completely analog way – and want to stay.

Das Team aus Studenten, Doktoranden und Forschern der TU Ilmenau und des IMMS gewann am 22. Juli 2021 Platz 1 beim EDA Competition Award. V.l.n.r.: Prof. Dr.-Ing. Patrick Mäder (JP), Henning Franke, Univ.-Prof. Dr.-Ing. Ralf Sommer, Julian Kuners, Paul Kucera, Martin Grabmann, Tom Reinhold, Dr. rer. nat. Marco Seeland, Georg Gläser. Foto: IMMS.

EDA Competition Award for "Trash or Treasure" – Intelligent Layout Processing: 1st prize of the IEEE CEDA goes to young scientists from Ilmenau TU and IMMS

A team of eight students, PhD students and researchers from Technische Universität Ilmenau and IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH) won the EDA Competition Award on 22 July 2021. The competition was supported by the IEEE Council on Electronic Design Automation (CEDA) for young scientists and sponsored with 1000$. It called for participants to demonstrate solutions that help improve design automation for integrated circuits and systems during the international conferences on methods for integrated circuit design SMACD 2021 and PRIME 2021.

Core topic AI-based design and test automation: www.imms.de

Software plugin enables AI-based anomaly detection method from the IntelligEnt* research group for the free PCB design tool KiCAD

Julian Kuners, an engineering informatics student at Ilmenau TU and student assistant at IMMS, presented the entry "Trash or Treasure? Machine-learning based PCB layout anomaly detection with AnoPCB" to the jury of representatives from Cadence Design Systems GmbH Germany, Dialog Semiconductor Germany, Infineon Technologies Germany, Gebze Technical University Turkey and Reutlingen University.

This software project was supervised at Ilmenau TU by Dr. Marco Seeland and Prof. Dr.-Ing. Patrick Mäder from the Department of Data-Intensive Systems and Visualisation and at IMMS. The work is based on solutions developed in Thüringen's

IntelligEnt research group for the layout of microelectronic chips. “When layouting analog/mixed-signal circuits, you design the blueprint for the chip manufacturer. However, formally correct layouts can contain inconsistencies, such as substrate coupling and mismatch,” explains Georg Gläser from IMMS, specialist for the integration of AI methods into design automation and head of the research group. Design experience of engineers plays a major role especially in the geometric design of circuits, and these last steps on the way to manufacturing require knowledge about which wires carry particularly sensitive or highly interfering signals and how these must be handled, Gläser continues. “We have therefore developed an AI-based anomaly detection method in the research group that can detect non-proven and potentially faulty spots in layouts.” The solutions for a flexible data representation are important here, because they can be used to process layout data for both chips and printed circuit boards - and the latter is what the award-winning contribution is about. “Julian Kuners, Henning Franke and Paul Kucera then further developed the software project as student employees at IMMS. They put the finishing touches on our learning anomaly detection method as a plug-in for the free PCB design tool KiCad. This allows our approaches to be applied much more broadly,” is Gläser’s assessment.

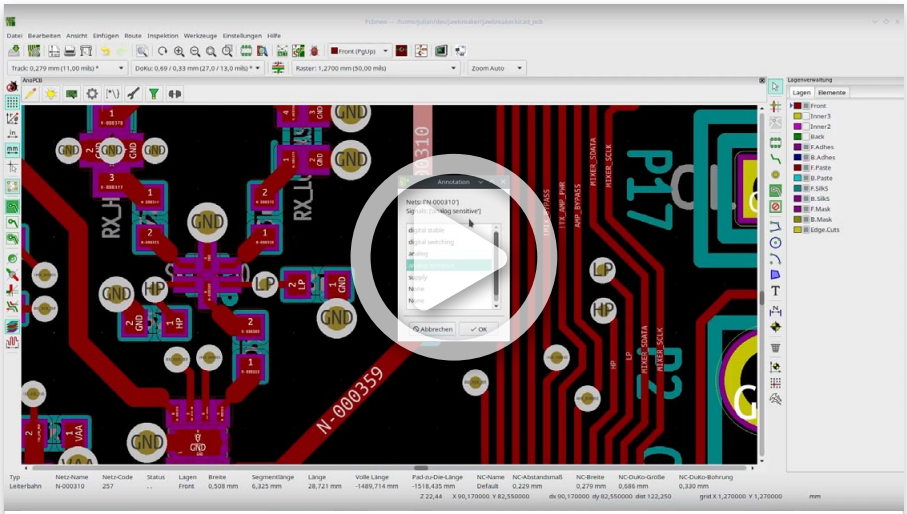
More on the IntelligEnt research group: www.imms.de

Plugin automatically detects unchecked and potentially faulty parts in layouts

With the plugin, KiCad signals can be divided into categories and passed on to the training or evaluation process. The system was designed in such a way that the design data is prepared at the user’s site for the process and then transmitted to a central server for processing. Thus, on the one hand, a graphics processor, if necessary, is only needed in the server and, on the other hand, the designs of several users can be combined.

Core topic AI-based design and test automation: www.imms.de

The jury evaluated the candidates’ solutions on the basis of complexity, degree of automation, designer interface, applicability, degree of integration with available design tools and robustness, among others: “The presented tool convinced the jury by the complexity of the posed problem, which in our view was solved well. The tool is user-friendly and we see it not only as an academic solution, but also as a solution that can be used in practical applications by PCB designers. The tool has considerable potential and we are interested to see how it progresses,” says jury member Anton Klotz of Cadence Design Systems GmbH.



AnoPCB – plugin for the free PCB design tool KiCad for artificially IntelligEnt layout processing. Video-Tutorial von Julian Kuners, IMMS / TU Ilmenau.

https://youtu.be/AXTA3GQwlvM

Tutorial at YouTube on the AnoPCB plugin

“For the first training, we used open-source designs such as Crazyflie and HackRF and then built in fault spots there. With our plugin for anomaly detection, we were able to locate these spots quickly and correctly,” explains Julian Kuners. “Of course, this spurs us on - and the prize anyway. We would like to use the opportunity and call on developers to work with the plugin. The more training data there is, the more we can expand and improve it.”

PlugIn download at GitHub

For this purpose, the plugin was made available on GitHub and a video tutorial was published.

RESEARCH FIELD

SMART DISTRIBUTED MEASUREMENT AND TEST SYSTEMS

IGF Industrielle Gemeinschaftsforschung

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

In the ViroGraph project, IMMS is developing a novel technology platform with graphene-based field effect transistor for the detection of SARS-CoV-2 together with Friedrich Schiller University Jena and fzmb GmbH Research Centre for Medical Technology. The picture shows preliminary investigations at IMMS with the sensor of FSU Jena with 15 graphene FETs for miniaturised measurement technology. Photo: IMMS.

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

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

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

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

Smart distributed measurement and test systems

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 2021 in our research on smart distributed measurement and test systems

Start of ViroGraph* – novel technology platform with graphene-based field-effect transistor for the detection of SARS-CoV-2

ViroGraph at www.imms.de

Testing, testing, testing – if there is one thing the Corona pandemic has taught us, it is the importance of diagnostic tools that can quickly and reliably detect pathogens or antibodies, for example. The diagnostic toolbox must be constantly expanded with new innovative methods to be able to meet both SARS-CoV-2 and future challenges of this kind. Chemists of Friedrich Schiller University Jena, IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH) and fzmb GmbH, Forschungszentrum für Medizintechnik und Biotechnologie are therefore jointly developing a new technology platform for rapid tests. On 5 March 2021, the project "ViroGraph – Multiplex Detection System for the Identification of Viruses based on Graphene Field Effect Transistors", which is funded by the German Federal Ministry of Economics and Technology and is scheduled to run for two and a half years, started with a virtual kick-off meeting that was also attended by the members of the accompanying committee from six companies and institutions.

The aim of the new electronic platform is to open up the graphene sensors already researched at Jena University for new so-called point-of-care devices. In the future, such small and mobile devices should be as easy to use as Covid 19 rapid tests on site and detect viruses, viral proteins, or antibodies highly sensitively – comparable to PCR tests. With the new project, the partners want to lay the foundation for many more precise, sensitive and specific applications in the field of on-site diagnostics beyond SARS-CoV-2.

Preliminary investigations at IMMS on the sensor of FSU Jena with 15 graphene FETs for the miniaturised measurement for SARS-CoV-2 detection. Photo: IMMS.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Sensor made from graphene

ViroGraph at www.imms.de

In principle, certain proteins are applied to the test strips of the currently used rapid tests as capture molecules, which – if present in the tested sample – react with virus components or with antibodies. This produces a coloured stripe that indicates the result. In the new platform of the ViroGraph project, a novel electronic sensor made of graphene will take over the task of the test strip – covered by a carbon membrane only one nanometre thick, which fixes the capture molecules on the sensor surface. If the analytes from a sample – such as antibodies or virus components – accumulate on the sensor surface, the electrical conductivity of the sensor changes. This parameter can be read electronically and provides the test result.

"Field-effect transistors are already used, for example, to measure pH values, but they have not been sensitive and specific enough for applications in the field of immunological diagnostics," explains Prof. Dr. Andrey Turchanin from Jena University. "However, by combining heterostructures made of graphene, which provides an appropriate conductivity, and the molecular carbon nanomembrane, which biochemically functionalises the sensor surface, this weakness could be remedied. This is because the 2D material graphene, which consists of only one atomic layer, is characterised by a special electrical conductivity - sensitive changes in conductivity during the coupling of analytes, i.e. the molecules we are looking for, can be measured quickly and easily."

Small devices and many parameters per rapid test

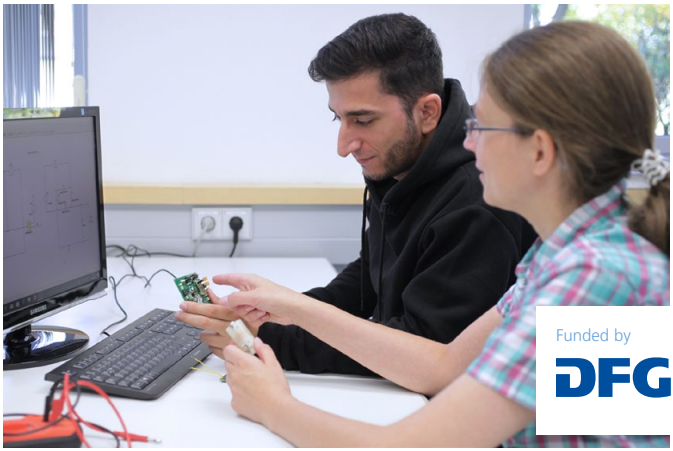
To be able to measure these smallest electrical currents in the range of a few nanoamperes at all, the project coordinators of IMMS are developing suitable miniaturised measuring technology. “This is important to integrate the performance required for our application of very large measuring devices that can normally determine such parameters into a handy point-of-care device,” says Michael Meister from IMMS. “A particular challenge here is also to measure several graphene sensors simultaneously to enable multi-parameter analytics.”

This is where the particular strength of the electronic method should lie: “We want to lay the foundation for a multiplex detection system with which we can detect several analytes simultaneously,” explains Dominik Gary from fzmb GmbH, whose employees are developing immunological and molecular biological detection systems for the new sensor. “Thus, the ViroGraph system would possibly even be suitable for gene typing and could therefore detect various mutations of viruses in a rapid procedure.”

View from industry

“For us as experts in immunoassays and ELISA, certainty of results and simple and rapid test procedures are central,” explained Dr. Peter Rauch, member of the ViroGraph project advisory committee and managing director of CANDOR Bioscience GmbH. The SARS-CoV-2 virus pandemic clearly shows the need for point-of-care systems with high analytical performance that can be used on patients on-site at reasonable prices. “The approaches pursued in the project can meet the challenges electronically. We will therefore follow the work with great interest and provide advice and support.”

Core topic Modular and mobile test systems: www.imms.de



In the ECo-Harvester project, a computer-aided design methodology is being developed for the co-design of mechanics and electronics for electrodynamic vibration harvesters.

Photograph: IMMS.

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Project launch of ECo-Harvester* – ambient energy for decentralised sensor applications

Hahn-Schickard-Gesellschaft für angewandte Forschung e.V. and IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH) started work on their three-year DFG research project "ECo-Harvester - Design methodology for the co-design of mechanical structure and interface circuitry of electrodynamic energy harvesters" in a virtual kick-off meeting on 15 February 2021.

ECo-Harvester at www.imms.de

Energy harvesters convert ambient energy into electrical energy in order to operate, for example, energy-autonomous wireless sensor nodes for monitoring tasks in industrial environments and to minimise the necessary maintenance and installation costs. Energy harvesters thus have a high potential to become a key technology for the decentralised distribution of sensor applications.

In the ECo-Harvester research project, a computer-aided design methodology for the co-design of mechanics and electronics for electrodynamic vibration harvesters is to be developed to derive the optimal harvesting system depending on given requirements.

"We don't want to simply assemble two components, but aim for an overall system design. The optimum of the overall system is not always the optimum of the subsystems," explained Prof. Dr. Ralf Sommer, scientific director of IMMS. This overall system view is necessary so that the efficiency of the system can be increased, i.e.

it delivers more power or can be built smaller with the same power, Sommer continued. Such an approach expands the state of the art, as currently the components are often developed separately from each other.

IMMS will focus on mechanical modelling including magnetic fields and mechanical damping of energy harvesters, which are used to extract energy from vibrations. Hahn-Schickard will focus on the front-end circuits with high efficiency or low losses in order to provide the energy from the harvester mechanics in a suitable form for sensor systems.

"However, since both partners are looking beyond their main areas of focus, especially at the interaction of harvester design and interface circuitry, we can exploit synergy effects," said Dr.-Ing. Thorsten Hehn, group leader for electronic systems at Hahn-Schickard. By appropriate modelling, an optimal overall concept for given framework conditions, such as signal shape, frequency and amplitude of the excitation, size of the harvester, etc., can be generated from the topologies for the harvester and the interface circuit, including parameter determination. This not only enables a cost-effective design, but also extended application scenarios through improved system properties.

ECo-Harvester at www.imms.de

"The challenges lie in the fact that there are a large number of basic topological structures on the part of the mechanics and, for example, many voltage ranges on the electronics side," Hehn summarised. "The exciting question is what is best for the overall system. We look forward to the answers we will provide together."

Demonstrator for electromagnetic energy harvesters, for which IMMS had already developed a design methodology for the mechanics in a previous project and verified it with demonstrators. In the ECo-Harvester project, mechanics and electronics will be designed together.

Photograph: IMMS.

For such a mobile multi-sensor test device, IMMS is developing the real-time capable platform and algorithms. Photograph: IMMS.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Start of the Trib.US* project – real-time capable platform and algorithms for mobile multi-sensor inspection device for conveyor belt maintenance

No branch of industry can be imagined without rollers in conveyor belts. If a belt comes to a complete standstill because of a defective conveyor roller, an entire plant can shut down. It is important to detect wear on such rollers in time to prevent downtime costs. However, the problem is that a single belt consists of a large number of rollers and these are installed in such a way that they cannot be checked easily or only at great expense. In Trib.US, IMMS and Sonotec GmbH are therefore developing an integrated mobile solution that supports inspectors in making maintenance decisions on transport rollers.The goal is a portable device with which the maintenance technician can precisely locate defects in order to reduce or prevent downtimes in production.

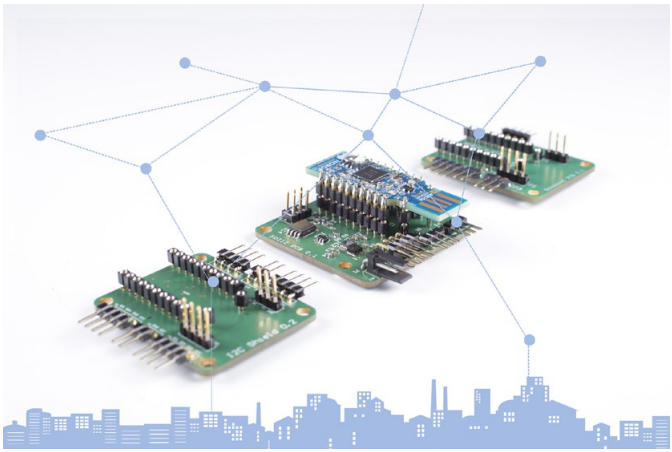
The device will use ultrasonic and speed sensors to detect deviations in the signals that distinguish defective transport rollers from those running normally. The development will make it possible to use correlation and sensor data fusion to draw conclusions on the location of the defect and display this information directly to the inspector in real time on his portable device. This makes it possible to check during operation, to immediately identify a defective transport roller and, in the event of bearing damage, to remove it in a targeted manner.

For this purpose, IMMS is developing the real-time capable platform as well as the algorithms for signal evaluation and correlation, while its partner Sonotec GmbH is developing the ultrasonic sensor technology and implementing the user interface as well as the associated management software for the maintenance staff.

More on Trib.US at www.imms.de

Lead application Adaptive edge AI systems for industrial application: www.imms.de

Core topic Real-time data processing and communications www.imms.de



Measuring modules for connecting different sensors to an environmental monitoring platform developed at IMMS, which is the starting point for the work on SmartCity sensor technology.

Photograph: IMMS.

Freistaat Thüringen
Hier hat Zukunft Tradition.

Start of thurAI* – sensor technology for SmartCity and methods to intelligently process data in the network for AI evaluations

In the thurAI project, Ilmenau TU, Jena FSU and IMMS are working on current solutions in the three areas of Smart City, healthcare and medical technology as well as production and quality assurance. IMMS and Ilmenau TU will implement a "LivingLab" in Ilmenau for the 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.

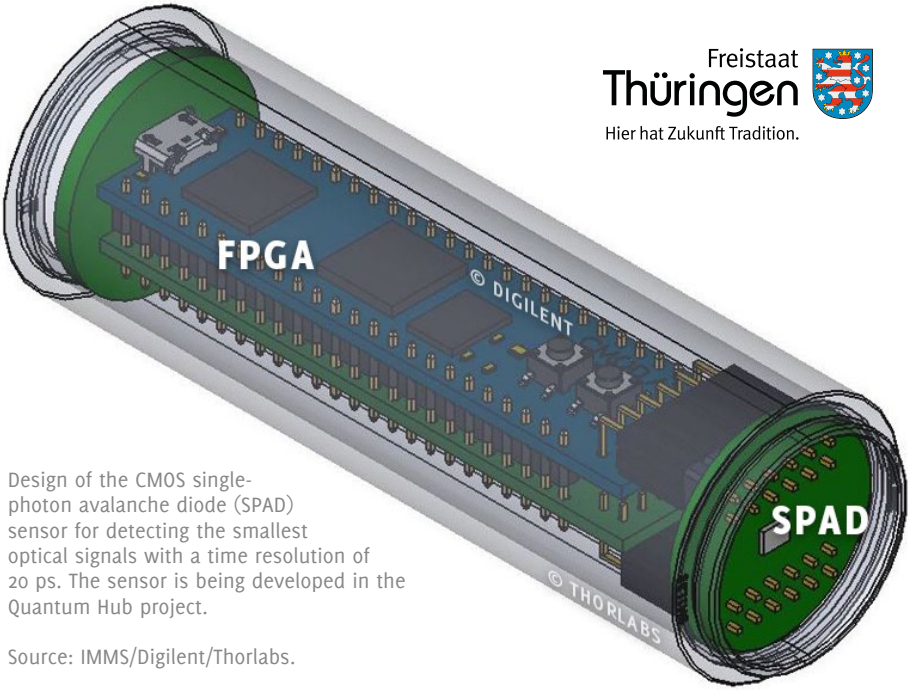
thur AI at www.imms.de.

On the one hand, IMMS will select and test sensor technology for recording various parameters. To this end, it will further supplement and expand existing measurement platforms. Topics here are energy self-sufficiency, size optimisation as well as the creation of intelligent IoT systems with e.g. analysis functions integrated at the gateway and concepts for cooperative measurement tasks in which several sensor information can be combined.

Lead application IoT systems for cooperative environmental monitoring: www.imms.de

The second focus of work is on the provision of so-called "smart data" through suitable pre-processing mechanisms at the sensor node itself or in the downstream network. The goal is to ensure that clean data is stored in the data platform, thus facilitating the application of AI algorithms.

Core topic Embedded AI: www.imms.de



Design of the CMOS single-photon avalanche diode (SPAD) sensor for detecting the smallest optical signals with a time resolution of 20 ps. The sensor is being developed in the Quantum Hub project.

Source: IMMS/Digilent/Thorlabs.

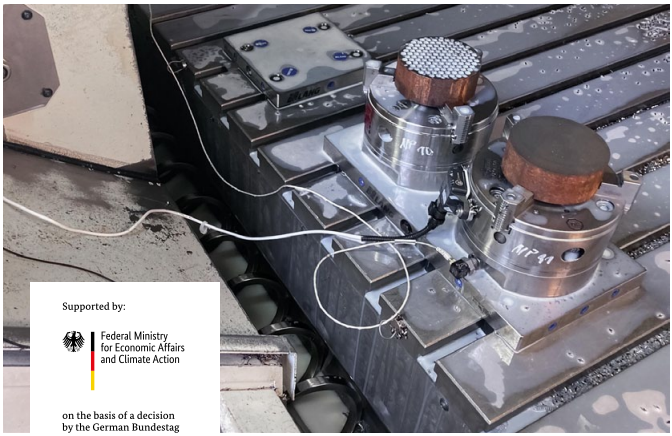
Quantum Hub Thüringen* launched – for quantum technology from Thüringen, Germany, IMMS is researching CMOS-based single-photon detectors

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 components, disruptive applications are made possible, for example in the field of data processing (quantum computers), communications (tap-proof communications) and metrology (quantum imaging, quantum sensor technology).

QuantumHub Thüringen at www.imms.de

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. Statistical evaluation is required to interpret the sensor signals, which is performed by a programmable logic device (FPGA). In addition, the integration of such an optical sensor element in conjunction with the necessary evaluation electronics in a microchip is also being targeted.

Core topic Modular and mobile test systems: www.imms.de



In the KIQ project, IMMS investigated solutions for embedded AI and, on this basis, implemented an AI-based retrofittable and cost-effective solution for quality assurance of cutting tools.

Photograph: IMMS.

Mittelstand-Digital

KIQ* project – IMMS has developed an AI-based, retrofittable and cost-effective solution for quality assurance of machining tools

Recognising and eliminating actual wear instead of prematurely changing tools

To ensure consistent quality in machining and to avoid unplanned machine downtimes as well as rejects due to worn tools, these are replaced regularly. Depending on the boundary conditions, however, wear can vary by up to 50%. Therefore, the tools are usually changed far before the end of their service life, which leads to additional costs.

KIQ at www.imms.de

Although the wear of the tools can be determined at special test stations with optical and tactile measuring methods. But since this is too time-consuming in practice, the tools are usually replaced at fixed intervals. With a new approach, the wear can be determined using various measured variables during machining. Together with its partner GFE, IMMS has implemented an AI-based, retrofittable and cost-effective solution for this purpose.

Lead application Adaptive edge AI systems for industrial application: www.imms.de

In principle, the measurement data of the sensors already integrated in the spindle, such as current or vibration sensors, can be accessed for this purpose on newer machines. However, they cannot be used to their full extent and in real time. This is currently only possible with retrofittable solutions.

AI-based retrofittable and cost-effective solution for quality assurance of drills in machining

In the project, IMMS retrofitted a precision machining centre for the project partner with vibration sensors and a compact processing unit close to the machine with integrated AI. With this, the vibrations occurring during drilling in different frequency ranges were recorded simultaneously at several points in the machining area and used as training data for a software based on machine learning. This is capable of both estimating the current state of wear and predicting the remaining useful lifetime (RUL) of the tool.

Data is collected using 3-axis accelerometers on the spindle housing and the workpiece fixture. To reduce the amount of data and derive specific features, the signals are first preprocessed with various operations. The AI model was trained with the data from several measurement series based on an artificial neural network. The signal preprocessing and the trained AI model can be executed in real time in a compact box directly on the machine. The result can be provided directly at the machine both as a predicted remaining tool life and as a classified wear condition of the tool.

The work on KIQ was a sub-project in the SME 4.0 Competence Centre Ilmenau.

Lead application Adaptive edge AI systems for industrial application: www.imms.de

More on SME Digital at www.imms.de.

With deployed wireless sensor nodes like this one at and inside the Newton Building, IMMS is collecting microclimatic data for energy consumption optimisation distributed over a building complex at the Ilmenau TU campus. The cylindrical housing protects the sensors from heat build-up due to direct exposure to the sun. Photograph: IMMS.

InSignA* project and high-perfomance centre – microclimate data to optimise energy consumption

Pilot project real-time capable energy simulation platform

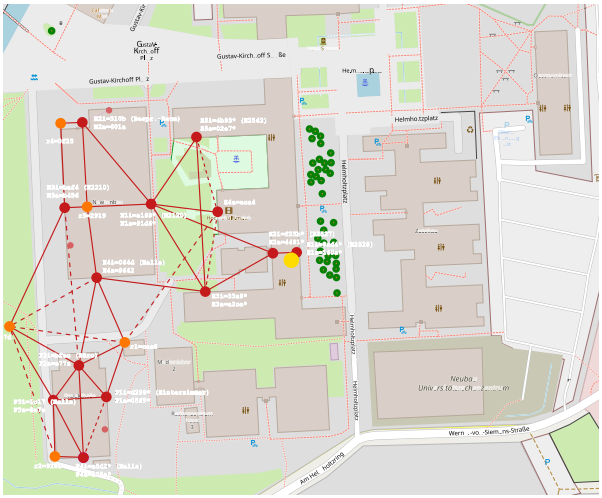
The objective was the design, conception and implementation of a cross-institutional, real-time-capable simulation platform for cross-sectoral energy systems. These link the areas of electricity, heat, gas, transport, and industry via so-called sector coupling.

A building complex on the campus of Technische Universität Ilmenau served as a model for this. Both energy meter data and microclimatic sensor data were to be collected for this complex. The combination of both makes it possible to associate energy consumption with weather-related data, to identify correlations, and to derive energy-saving measures from them.

Lead application IoT systems for cooperative environmental monitoring: www.imms.de

Our contribution: Wireless microclimate measurements

In the pilot project, IMMS together with the Department of Theoretical Electrical Engineering (TET) of Ilmenau TU deployed microclimate sensors, collected measurement data, and evaluated them. For the “microclimate”, temperature and humidity are recorded at various measuring points within the building complex.



Network topology of the wireless sensor deployment at buildings Helmholtzbau, Newtonbau, Projekthalle. Illustration: IMMS.

For this purpose, we adapted an existing technology for wireless sensor nodes (MiraOS) to the needs of the project, assembled appropriate hardware, and configured software to collect microclimate data inside and outside the buildings Helmholtzbau, Newtonbau, and Projekthalle on the campus of Ilmenau TU.

The battery-powered and thus self-sufficient wireless sensor nodes organise their communications autonomously and send their measurement data – depending on the local wireless conditions, across several of the nodes – to a central gateway. This gateway collects the measurement data and stores it in a database at IMMS. From there, the data can be visualised or exported for analysis. Ultimately, they flow into the simulation platform of the pilot project.

Air temperature and humidity inside and outside (in the same area of the building envelope) are measured on the four sides of the buildings roughly corresponding to the points of the compass, and surface temperatures of the facade or wall surfaces inside are also measured at some of the measuring points.

Lead application IoT systems for cooperative environmental monitoring: www.imms.de

Results of the pilot project flow into the InSignA high-performance centre

At the end of the project period, microclimatic measurement data for the model building complex were available for a period of approximately six months. To extend the data base to a full year, the sensor network will continue to operate beyond the end of the project.

Analyses by the TET department have already demonstrated correlations with energy consumption as well as weather data. To derive concrete measures for energy

Microclimatic value curves over a period of two weeks in December 2021.

Shown are curves for ambient temperature and relative air humidity of sensors on the outside („…a“) and inside („…i“) of Helmholtzbau („H…“), see previous image.

Diagram: IMMS (dashboard solution Grafana)

savings, finely resolved measurement data on energy consumption in the buildings is still required. For this purpose, the Department of Buildings and Technology (DGT) of Ilmenau TU is carrying out expansion and development measures.

The partners aim to continue this preliminary work in further projects within the high-performance centre and, in addition to generating proposals for energy-saving measures, also to assess their effect by means of sensors.

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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.

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 contributes to InSignA on behalf of the latter.

Activities in the SME 4.0 Competence Centre Ilmenau and in the SME Digital Centre Ilmenau*

Ilmenau work of the Competence Centre as a basis for continuation in SME Digital

In October 2016, the "Mittelstand 4.0-Kompetenzzentrum Ilmenau" (SME 4.0 Competence Centre Ilmenau) started its work. Along with four other partners from Thüringen, IMMS was involved from the very beginning in making digitalisation understandable and vivid for small and medium-sized enterprises. At the end of September 2021, five years after the start, the team of the competence centre could look back on 250 digitisation projects, 600 lectures, 170 regulars' tables and 210 specialist workshops for SMEs, as well as 2,000 information talks on digitisation. After the expiry of the SME 4.0 funding, the German Federal Ministry for Economic Affairs and Climate Action (BMWK) decided to further develop the proven concept and to set new priorities with the funding announcement for a nationwide "SME Digital Network". Four Thuringian partners have therefore been supporting small and medium-sized enterprises as part of the "Mittelstand-Digital Zentrum Ilmenau" (SME Digital Centre Ilmenau) since October 2021 – including IMMS.

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The SME Digital Centre with its four model factories now also places a clear focus on sustainability, platform economy and AI. As a model factory for smart sensor systems, IMMS is primarily dedicated to the topics of retrofitting, predictive maintenance, smart sensor systems and diagnostic solutions. For example, retrofit solutions can be provided for machines with which the machine status can be automatically recorded and visualised. Another core competence is the practical implementation of smart sensor systems, in which machine tools, for example, are being monitored by artificial intelligence. In addition, demonstrators illustrate digital diagnostic solutions that can, 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 at all the centre's partners.

In addition to online events and information material, further demonstrators were also created in 2021 in the Smart Sensor Systems Model Factory at IMMS, about which companies were able to obtain information via websites, downloadable brochures, explanatory videos and live demonstrations during online lectures. In addition, further digitalisation projects could be implemented in cooperation with companies. Possible applications of artificial intelligence (AI) in manufacturing SMEs were used in the above-described **KIQ** project “Predicting tool wear in cutting machines with retrofittable sensor technology and artificial intelligence”.

With the “**Condition monitoring of a DATRON milling machine**” demonstrator, it is shown how condition parameters of a machine can be automatically recorded, transmitted and evaluated with OEM interfaces and a compact data processing and communication unit. Many modern CNC milling machines already support the remote enquiry of data and operating states, but a more extensive logging or archiving of

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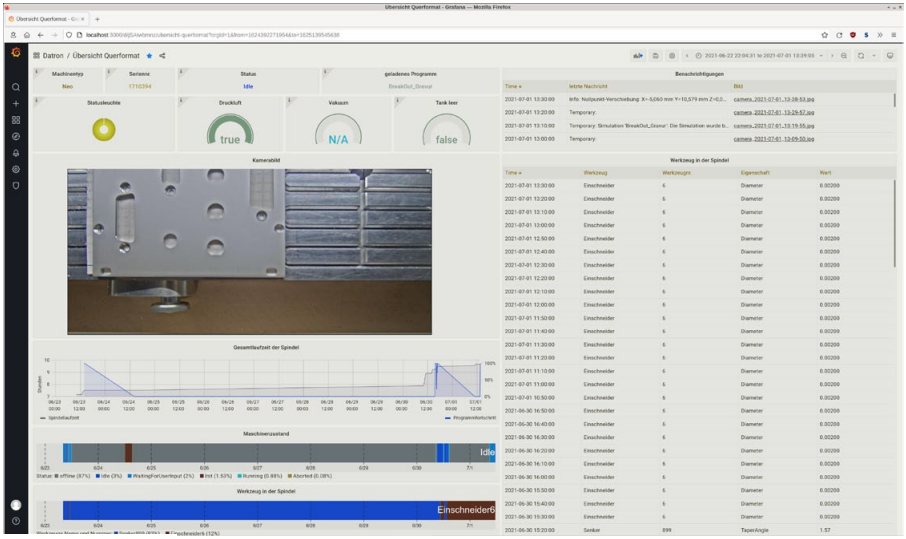
Condition monitoring of a DATRON milling machine. Via a PC, access to a dashboard is possible, which displays current machine and production parameters. Source: IMMS.



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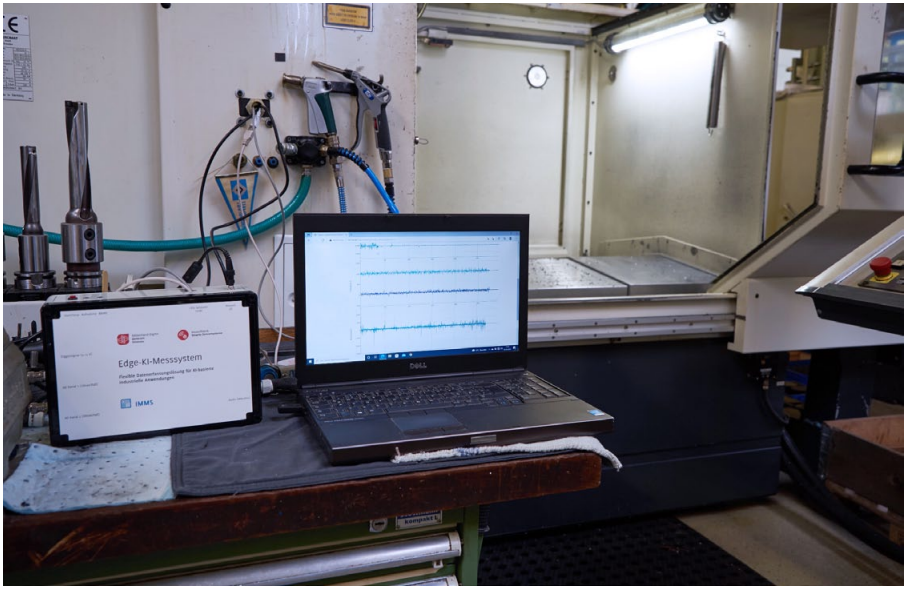
Mittelstand-Digital Zentrum Ilmenau

these data has not been possible so far. With the implemented solution, the machine data can be read out via REST API using a mini PC and written to an InfluxDB time series database. A dashboard created with the Grafana visualisation tool can display the current status and past states of the machine. This dashboard is accessible from the entire local network.

The transition from analogue to digital maintenance plans for machinery and industrial plant is illustrated with the "**Smart Maintenance**" demonstrator. With the help of maintenance cards, companies describe the maintenance cycles for machines and document their execution. The creation of an optimal maintenance plan can be very time-consuming. With digital maintenance software, such as anexio®, there are many options that can be automated. Maintenance staff and production managers are supported by web apps (maintenance and planning client). As a result, the maintenance-related production downtimes of machines can be minimised and the additional documentation effort reduced.

A "**Flexible Data Acquisition Solution for AI-based Industrial Applications**" was designed and implemented for the collection and pre-processing of sensor and process

Data acquisition solution for industrial AI applications. The robust device solution (pictured left) is used directly on a machine tool. A laptop, for example, can also be used for setting the parameters for the measurements and displaying the data. Photograph: IMMS.



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data on plant and machinery in real manufacturing environments. The device can record sensor data via various measurement channels and data interfaces and store it internally in a structured manner, so that the subsequent processing and analysis of the data is significantly simplified. Even large amounts of data that accumulate during longer measurement campaigns can be processed. The solution is robustly implemented and has a web-based user interface so that it can be accessed wirelessly with a smartphone, for example. For AI applications on condition assessment of cutting tools, extensive data sets could already be created with this data collection solution.

Networking with digitisation players expanded

Another important component of the work at the SME Digital Centre Ilmenau is the networking of the actors involved in the digital transformation of companies. In the nationwide SME Digital Network, there was a regular exchange – among other things in topic-specific working groups or at regional conferences of the participating centres – on the needs of the companies, the expansion and the target group-oriented design of the support services. IMMS was also in regular exchange 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), the Thuringian Centre for Learning Systems and Robotics (TZLR) and the Thuringian Competence Centre Economy 4.0.

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Together with the SME Digital Centre Ilmenau, we launched an initiative to establish the "AI Hub Sachsen-Thüringen" in October 2021 as a new offer for SMEs to support the transfer of AI technology and the results of AI research into practically usable applications. In addition to the SME Digital Centre Chemnitz and other partners with AI qualification offers, the national AI competence centre "ScaDS.AI – Centre for scalable data analytics and artificial intelligence" in Dresden/Leipzig is also involved as a player in top AI research.

KI HUB SACHSEN THÜRINGEN

Machine learning on resource-constrained microcontrollers for edge AI and IoT applications

Figure 1: At IMMS, algorithms for embedded systems were designed, optimised and implemented in a demonstrator for AI-based fan monitoring using the machine learning approach TinyML: Motor bearings or fan blades can be directly monitored with the compact retrofittable solution. Defective parts are indicated directly via a red LED. Photograph: IMMS.

Motivation and Overview

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For many industrial applications, distributed sensor technology is required at various points and often over a long period of time directly in the process, e.g. to collect data for predictive maintenance or wear or to detect fault conditions as well as anomalies in the systems. IMMS is researching on adaptive edge AI systems to integrate AI directly into the sensor and thus make decisions in real time without a detour via the cloud. Automated adaption to new environmental conditions opens up versatile edge computing and IoT applications. To achieve this, IMMS is working on one hand towards making embedded ultra-low-power systems (ULP) more and more energy-efficient. On the other hand, IMMS is researching on developing and optimising machine-learning algorithms and software for such ULP systems.

The reason for this is that these miniature devices operate with a power consumption of only a few milliwatts and only a few kilobytes of internal memory and, due to their limited resources, cannot be used for conventional machine learning models designed for high-performance computers. To obtain the results needed for

the application with as few resources as possible, IMMS has built its solutions on Tiny ML (tiny machine learning). This branch of machine learning includes hardware, algorithms and software. With it, IMMS was able to run AI algorithms directly on the sensor and thus evaluate and analyse the data directly on battery-powered ULP systems.

The example shown here can be used to monitor the condition and maintenance requirements of fans. This can also save energy, as no data transmission to an energy-intensive server is required. In addition, the security of the data is guaranteed as it is processed directly at the sensor and no raw data is transmitted.

The aim is to use these solutions as a basis for developing adaptive edge AI systems for further industrial applications. As an example, classical ML algorithms and deep neural networks are being designed, developed and trained at IMMS, which, beyond pure data collection and analysis, also enable AI-based predictions for predictive maintenance applications, such as prognosis of remaining useful lifetimefor drill bits.

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Classical Machine Learning versus Deep Learning

When designing AI-algorithms for predictive maintenance or condition analysis of machines, two basic approaches can be used. The classic machine learning with feature engineering and a deep learning approach.

Classical machine learning involves algorithms that recognise patterns from processed and structured data in a goal-oriented and automated manner. Without a defined objective and processed data, no analyses and predictions are possible. Machine learning is therefore generally used for small, structured data sets.

For the applications mentioned, relevant information, characteristics or features are calculated from the sensor signals by means of signal processing. For this purpose, statistical methods can be used for analysis in the time domain, such as mean value, kurtosis or crest factor, but also analyses in the frequency domain, such as Fourier or wavelet transforms.

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In **deep learning**, on the other hand, a large amount of unstructured data is processed in many iterations, analogous to human learning. Artificial neural networks

extract the features and structures required for analysis from the data themselves. In contrast to machine learning, data processing and feature extraction are carried out autonomously, if enough data and computing power are available.

For the aforementioned applications with deep learning, the sensor data are fed directly into a neural network, an AI model. For the training of such a model, a lot of data is needed, distributed as equally as possible for different machine states.

Machine learning, on the other hand, is more complex than the deep learning approach, but can be partially explained to the developer by the manual selection of features. The machine learning approach is more suitable when expert knowledge can be used or when only few data is available, as is often the case in predictive maintenance.

Optimisation in classic machine learning

High-dimensional AI models are powerful but require memory, computing power and energy

AI models are often designed to achieve maximum classification or prediction accuracy. Optimisation is one of the most important aspects of AI-based intelligent algorithms in order to implement them on resource-constrained, energy-efficient embedded systems. System requirements such as energy consumption and hardware costs depend on the model used. For predictive maintenance (PdM) and machine health estimation, not only raw sensor data but also spectral information statistics are very informative, creating a very large design space. Each additional sensor and feature extractor improves the performance of the AI model, but also increases the system complexity. Such a large feature space increases the system requirements in terms of memory, computing power and energy. This makes PdM on resource-constrained devices such as microcontrollers a major challenge.

Feature Ranking streamlines AI models by sorting out redundant features

The following investigations were carried out on the publicly available datasets Prognostia[1] and XJTU[2] in order to achieve comparability of results for existing models. These data sets contain sensor data on the wear process of ball bearings.

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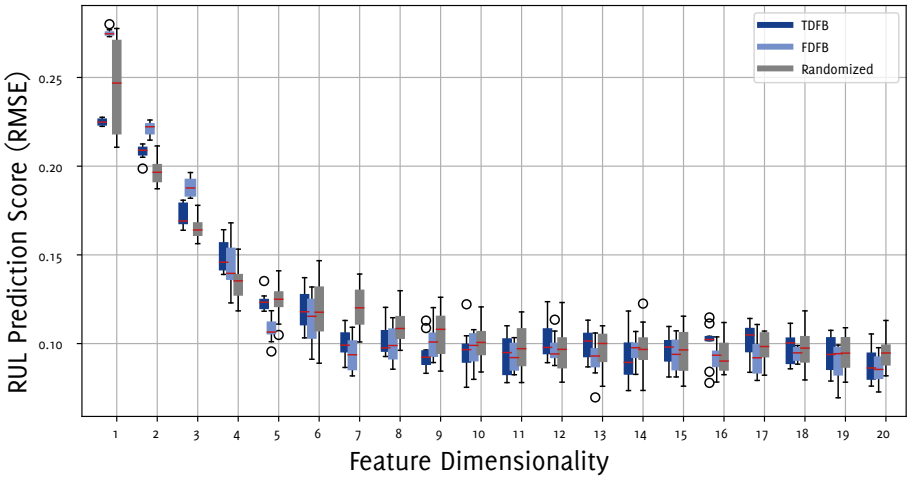

Figure 2: Attributes sorted by means of feature ranking. Graphic: IMMS.

In many applications, each additional sensor information or feature extractor can potentially improve the overall performance of the AI model. However, more features and thus higher dimensionality do not always guarantee higher prediction accuracy. Highly correlated features and overfitting can lead to a suboptimal solution.

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One way to solve the high dimensionality problem is to use feature ranking (FR) algorithms to analyse the effects of each variable (feature or input) that are fed into the AI model. FR methods provide a detailed, interpretable metric of feature importance which can be used to build an optimised system for the particular application. There are a few different approaches that have been studied and evaluated at IMMS: wrapper methods, which are computationally intensive but very accurate; filter methods, which are very fast to compute, but can deviate from the optimal results; embedded methods, which require one-time training and are more accurate compared to filter methods.

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The aim of the work was to find the optimal FR method for analysing the information content of features or input vectors, in order to reduce the overall system resources (computational effort, memory, energy requirements). To do this, the non-informative, redundant input signals and their features are removed from the AI model. An example is shown in figure 2. The x-axis represents the dimension of the features coming from two different vibration sensors (horizontal and vertical axes), which have been split into their spectral components. The y-axis is the error of the trained AI model in state estimation. Each box plot illustrates the error statistics for

the given dimension of features. It can be observed that the estimation error does not improve significantly further after 7 features. This means that the remaining 13 out of 20 features are not meaningful, which may be due to noise and redundant information.

For the example considered, a publicly available dataset, most of the informative features come from one sensor. This means that hardware and computational costs can be reduced by completely removing the other sensor and its corresponding features from the system. This reduced feature dimensionality can serve as a new basis for the development of optimised embedded systems.

Optimisation for Deep Learning for resource-constrained systems

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Neural networks can be reduced or made smaller by pruning. This involves removing connections and entire neurons in the network. The aim of pruning is to reduce the size of the network in such a way that the accuracy of the pruned model is only minimally reduced.

The approaches can be roughly divided into structured and unstructured pruning. Both have their advantages and disadvantages. Neural networks can also be represented as matrices. Unstructured pruning has only a minor effect on the accuracy of the pruned model, but can force operations on sparse matrices that are difficult to accelerate. This can lead to longer processing times and thus higher energy consumption of the system.

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IMMS has been working on structured pruning by investigating and optimising AlexNet andResNet AI models based on a publicly available data set (XJTU[2]) and the results of other research projects.[3] Structured pruning does not lead to sparse matrices and is better suited for implementation on microcontrollers. In the models, structured pruning removed the complete filters of the convolutional layers of the model.. This can change the shape of the inputs and outputs of the layers but allows operations on dense matrices. Structured pruning can have a significant impact on the achieved accuracy if done aggressively. Therefore, a threshold value of 3% for the maximum difference in accuracy between the original AlexNet and ResNet models and the pruned models for the accuracy was set before pruning. Pruning is stopped when the accuracy difference falls below3%.

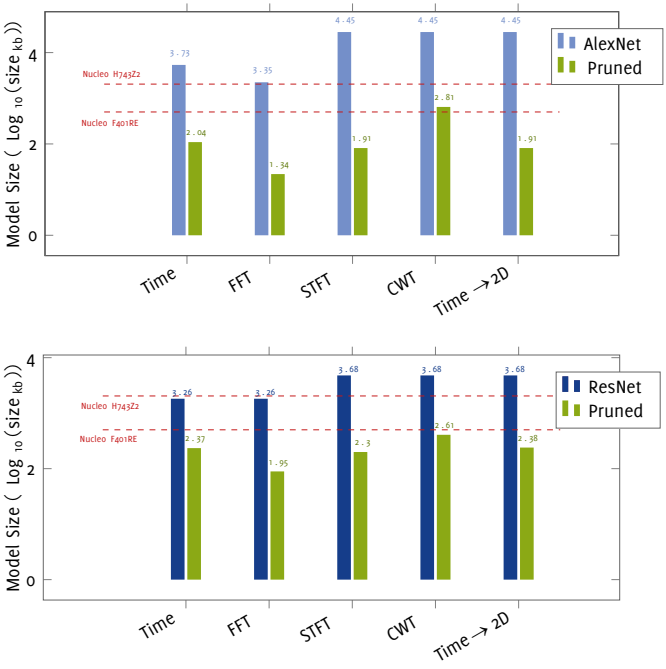

Figure 3:

Comparison of the memory requirements of the original AlexNet and ResNet models with the pruned models, and illustration of the available memory of two microcontroller types (STM32F401 and STm32H743).

Diagrams: IMMS.

Figure 3 shows the results of the memory requirements of the original models and the pruned models. For better classification, the available memory of two microcontroller types (STM32F401 and STM32H743) are also shown. The original models require more memory than is available in the microcontroller. In contrast, the adapted models can be implemented on one microcontroller. The table compares the achieved accuracies of the models.

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	AlexNet		ResNet	
Features	**Original**	**Pruned**	**Original**	**Pruned**
Time signal	96,10%	93,23%	99,73%	97,02%
FFT Fast Fourier transform	98,4%	96,87%	99,21%	97,84%
CWT Continuous wavelet transform	90,02%	87,43%	92,91%	90,23%
2D time signal	97,70%	95,35%	95,57%	93,23%
STFT Short-time Fourier transform	98,37%	97,65%	99,6%	96,35%

Demonstrator

IMMS has created a demonstrator for AI-based fan monitoring in order to test the methods presented for the optimised use of algorithms for embedded ULP systems and to illustrate them in the application field of predictive maintenance, see figure 1. Motor bearings or fan blades can be monitored directly with the compact retrofit solution. The fans can be switched on and off individually on the demonstrator. The sensor system is placed in the centre of one of the fans and is attached by a magnet. Defective parts are indicated directly via an LED in red, intact ones in green.

First of all, a data set was recorded using ten commercially available PC fans with vibration sensors. The ball bearings of three fans were worn out. Using the two approaches presented, i.e. classical ML and a neural network, two AI models were trained with the fan dataset which can estimate the state (intact and defective) of the fans.

A battery-powered system consisting of a vibration sensor, microcontroller (STM32L4) and LEDs for status display were developed, manufactured and put into practice. The two AI models were optimised using the methods presented and implemented on the microcontroller.

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Applications

In its work on adaptive edge AI systems, IMMS focuses on determining and forecasting machine and tool conditions for predictive maintenance applications with the help of AI. In addition to the example application for AI-based fan monitoring described above, IMMS has retrofitted vibration sensors to a metal-cutting machine in a further application and recorded the vibrations occurring during drilling at several points in the machining area. The aim of the investigation was to estimate the remaining service life of the drills in order to thus make optimum use of the tools and to avoid rejects due to damaged tools. To reduce the amount of data and derive specific features, the data is first pre-processed with various signal processing operations. With the data from several measurement series, the AI model was trained on the basis of an artificial neural network. The result can be displayed via a compact box retrofitted directly to the machine, both as a predicted remaining tool life as well as a classified wear condition of the tool in real time.

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Summary and outlook

IMMS has successfully implemented the methods for optimising AI models for ULP systems in a demonstrator and published as well as presented them at technical conferences. In the future, the focus will be on the automatic analysis and selection of the important features, where currently more complex manual interventions are still necessary. In addition, IMMS will investigate how the pruning of neural networks can be applied to other AI models, e.g. autoencoders. The demonstrator will soon be extended with a radio interface for integration into existing systems. The aim of further developments is to make AI solutions more applicable for SMEs by automating the time-consuming processes involved in AI development as far as possible. This should significantly accelerate the derivation of further applications.

Contact person: Dipl.-Ing. Sebastian Uziel, sebastian.uziel@imms.de

Literature:

[1] P. Nectoux, R. Gouriveau, K. Medjaher, E. Ramasso, B. Chebel-Morello, N. Zerhouni, and C. Varnier, **Pronostia: An experimental platform for bearings accelerated degradation tests.** *in IEEE International Conference on Prognostics and Health Management, PHM'12. IEEE Catalog Number: CPF12PHM-CDR, 2012, pp. 1 – 8.*

[2] Biao Wang, Yaguo Lei, Naipeng Li, Ningbo Li, **A Hybrid Prognostics Approach for Estimating Remaining Useful Life of Rolling Element Bearings.** *IEEE Transactions on Reliability 2020, 69, 401 – 412.*

[3] Zhibin Zhao, Tianfu Li, Jingyao Wu, Chuang Sun, Shibin Wang, Ruqiang Yan, Xuefeng Chen: **Deep learning algorithms for rotating machinery intelligent diagnosis: An open source benchmark study.** *ISA Transactions 2020, 107, 224 – 255.*

The research on methods for the optimised use of algorithms in adaptive edge AI systems was developed in the internal AI research group which is funded by the Land of Thüringen. The work on the example applications or the demonstrator was funded in the "SME Digital Centre Ilmenau" by the German Federal Ministry of Economics and Climate Protection (BMWK) under the reference 01MF21008C.

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Intelligent sensor technology for digitalisation in agriculture

IMMS is working on self-sufficient modular sensor systems for cost-effective options for data collection in agriculture. To this end, we have developed the prototype shown here for a modular IoT platform that can be used to record abiotic parameters in orchards and evaluate site factors, among other things. Photograph: IMMS.

Motivation and overview

Irrigation plays an increasingly important role in ensuring high yield quality for many fruit growers. In times of climate change and increased drought, however, it is important to use the resource water as sparingly as possible. Evaluating how to ensure this is part of the studies of our partners from the Lehr- und Versuchszentrum Gartenbau (LVG, a teaching and research centre for horticulture) in Erfurt. To help them, IMMS has developed and tested technology in the EXPRESS project. Long-term results of irrigation trials at LVG show that all irrigated varieties have higher fruit size and quality than the non-irrigated control. These characteristics are important to survive in the marketplace, because only the best quality can command prices that economically justify the expense. Irrigation is therefore becoming increasingly important if fruit production in central Germany is to remain competitive. At the same time, however, drought and persistent dryness are making it increasingly important to use the water applied as sparingly as possible.

More on EXPRESS at www.imms.de

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For these optimisations, data must be collected by different sensors and combined afterwards. However, since systems available on the market are often only

tailored to one problem, it is difficult to integrate different sensors into one system and thus realise flexible solutions for fruit growing.

IMMS has therefore developed a modular platform with which adapted solutions can be realised with regard to the sensors used but also the radio technologies employed.

LVG has used this platform for research and, among other things, has been able to use soil moisture sensors to achieve savings over fixed irrigation intervals or irrigation according to the current standard model, and to further optimise irrigation using data on fruit development.

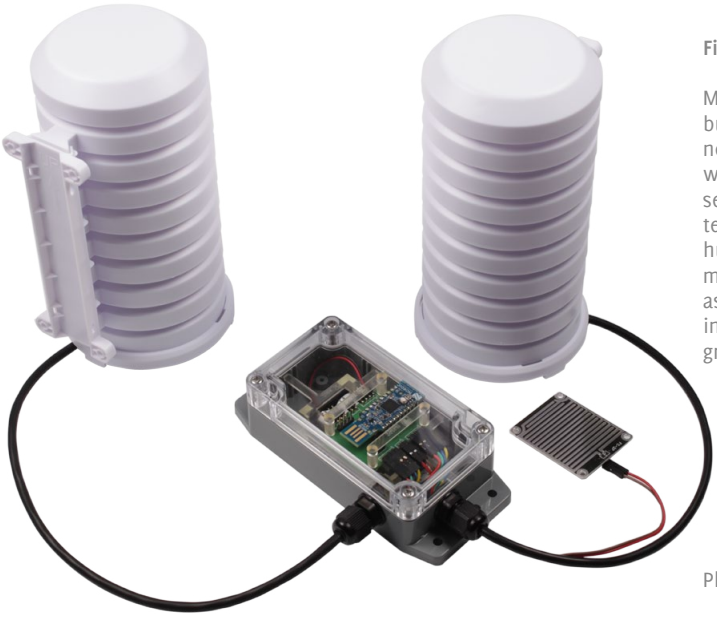

Figure 1:

Microclimate node built from components of the platform with 2 combined sensors for air temperature and humidity and a leaf moisture sensor, as currently used in fruit and wine growing.

Photograph: IMMS.

Development and construction of the modular IoT platform

The platform developed is characterised by the fact that different radio modules (currently IEEE 802.15.4, LoRa and NB-IoT) can be combined with different baseboards for connecting specific sensors. Which baseboard is used depends on the interface to the sensor. There are variants for I²C, for example, but also for specific protocols such as SDI-12. In addition to a classic energy supply via battery, options for self-sufficient supply via solar panel are also used.

Various challenges had to be met on the way to this platform. For example, a solution had to be found for the integration of more complex protocols such as SDI-12. This was solved via a protocol-specific co-processor, which is itself addressed via

Core topic
Analysis of distributed IoT systems:
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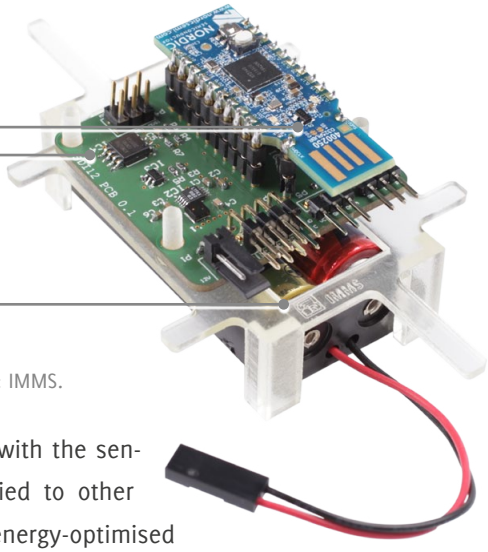
Figure 2:

Components of the modular IoT platform:

Radio module
Measurement module
. Base
. I²C mux
. Coprocessor
.. SDI-12
.. 1-Wire
Energy supply
. Battery
. Mains
. Harvester



Photograph: IMMS.

I²C and takes over communications with the sensor. This concept can also be applied to other protocols. Another challenge is the energy-optimised operation of the sensor nodes. Here, IMMS is working on the model-based evaluation of the energy consumption and the resulting lifetime of the nodes under certain scenarios. This will gain particular importance when sensors become more intelligent and do not follow a fixed scheme for the operating cycle.

The prototyping system implemented in this way makes it possible to quickly build initial solutions if the sensors support the corresponding protocol. Furthermore, flexible solutions with several sensors are possible, which can be tailored to a specific problem. In the EXPRESS project, it is now possible to record air temperature and humidity, soil temperature and humidity, air pressure, photosynthetically active radiation, global radiation, leaf moisture, and wind speed and direction.

In addition to the actual wireless sensor nodes, due to its optimised energy management, the IMMS solution also supports the connection of more energy-demanding sensors to the gateway that cannot normally be operated attached to a battery-powered wireless sensor node. The platform also provides data quality assurance measures and a comprehensive system for monitoring and diagnosing the devices in the field. In this area, it was also a challenge to be able to evaluate the device status in the field and the data quality at any time without having to be on site. To make this possible, status information was integrated into the messages and a server-side quality assurance mechanism with notification functionalities was created.

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Figure 3:

Placement of soil moisture sensors and installation of sensor nodes for LVG studies.

Photograph: IMMS.

Configuration of the modular IoT platform for experiments at LVG

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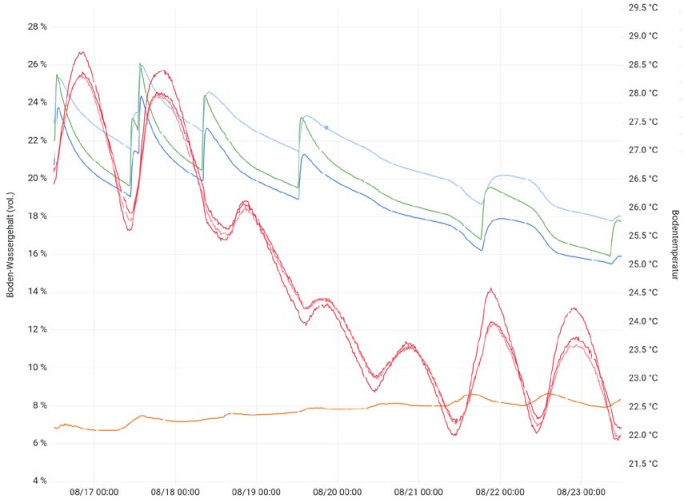
At LVG, sensor systems built using the platform were installed for a sweet cherry irrigation trial. An ad-hoc network based on the IEEE 802.15.4 radio standard was used, providing a mesh-capable multihop network. This is ideal for experimental applications with a comparatively large number of measuring points in a small area. The system records air temperature and humidity, soil temperature and humidity, leaf moisture as well as air pressure and photosynthetically active radiation at 9 measuring points. Of which the soil values and the microclimate in the plot are most relevant for irrigation. The irrigation trial at LVG includes four different means of irrigation and two types of mulch cover. The data from the sensors are collected locally at a gateway, temporarily stored as a backup and transferred to both a server at IMMS and a server at LVG, where they are stored in an InfluxDB or MariaDB, respectively, and visualised via Grafana.



	Min	Max	Last *
θ BF2	15.9 %	26.1 %	17.7 %
θ BF3	15.5 %	24.4 %	15.9 %
θ BF4	17.8 %	26.0 %	18.0 %
θ BF6	6.69 %	8.68 %	8.35 %
T BF2 (right y-axis)	21.9 °C	28.7 °C	22.0 °C
T BF3 (right y-axis)	22.1 °C	28.4 °C	22.1 °C
T BF4 (right y-axis)	22.0 °C	28.3 °C	22.0 °C
T BF6 (right y-axis)	14.8 °C	44.0 °C	36.4 °C

Figure 4:

Grafana visualisation showing the response of three soil moisture sensors to irrigation applications, enabling evaluations at LVG.

Source: IMMS.

Figure 5:
Selection of soil moisture sensors studied for irrigation control. Photograph: IMMS.

In addition to providing the technology for the trials and supporting them at LVG, IMMS has also tested the suitability of different soil sensors for this application, in order to be able to give fruit growers advice on the investments required. For this purpose, sensors in a price range of 50 to 600 EUR have been tested and compared.

Experiments using the modular IoT platform in various applications

Studies at LVG on economical irrigation and fruit growth in fruit growing

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LVG conducts annual trials in which different types of irrigation systems, such as drippers or sprinklers, and mulch covers as evaporation barriers are tested. The additional use of sensors and thus digitalisation showed its first strengths here. For example, soil moisture sensors can detect the amount of water available to the plant in the soil and help assess when and how much to irrigate. The results at LVG show that this information alone is sufficient to achieve savings compared to fixed irrigation intervals or irrigation according to the current standard model.

Further savings are possible if, in addition to the abiotic factors of soil moisture and precipitation, information about the plant itself can be considered. For example, on the initiative of LVG, IMMS has developed a sensor for measuring fruit growth and integrated it into the existing system. This sensor makes it possible to detect different phases of fruit development. This makes it possible to adjust watering so that irrigation is only applied when it benefits fruit quality.

Experiments on irrigation, bud growth, and frost warning

In addition, the trials on soil sensor technology are being conducted with other application partners, including Obstgarten Orphalgrund e.G. (Fahner Obst) in Thüringen

Figure 6:

Sensor developed at IMMS for measuring fruit growth. It can be used to identify different phases of fruit development. As a result, irrigation is only applied when it benefits fruit quality.

Photograph: IMMS.

and Biofrucht Senst in Sachsen-Anhalt, so that these results can also be put into practice. Another aspect here is that results do not only come from one location in order to cover different surrounding conditions.

With the platform developed at IMMS, it is also possible to collect data for other issues in fruit growing and viticulture. For example, a slightly modified version of the sensor for fruit growth in winter has been used at the Julius-Kühn-Institut (JKI) für Züchtungsforschung an Obst (Institute for Breeding Research on Fruit Crops) in Dresden-Pillnitz to monitor bud growth on different apple varieties. The JKI's research question here is aimed at mechanisms for plant awakening in the spring in order to minimise the associated risk of frost damage in the long term. The sensors support the researchers in this by enabling detailed monitoring of development in the spring.

The detection and advance warning of frost events based on weather forecasts and sensors installed in the field is another key topic at IMMS. Initial tests of a threshold-based warning on cell phones have already been successfully carried out. This should enable fruit growers and vintners to take countermeasures depending on the situation. The sensor systems developed are also an important basis for this issue.

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Figure 7:

Sensor for measuring bud growth. It helps to study the development of the plant and, in perspective, to breed late-frost-tolerant varieties.

Photograph: IMMS.

Outlook

With its work in EXPRESS, IMMS has helped identify suitable and affordable systems for farmers, record their capabilities, and generate benefits. In addition, with the development of the modular IoT platform for different sensors and thus different applications, IMMS has created a flexible and cost-effective system that can record all required variables with sufficient accuracy and at the same time provide usable assessments with a high practical value using as few measurement points as possible. On this basis, IMMS and LVG are striving for further cooperation in follow-up projects.

Future developments include data fusion of the measured values with weather forecasts, which are incorporated into the determination of irrigation timing. This can help to wait until precipitation is forecast and then compensate for any remaining deficit. This is another way to save additional water without compromising fruit quality and thus the success of the farmer.

It has also been shown that one of the frequently used models for irrigation can no longer accurately represent the seasonal course in times of climate change. This is due to changed conditions leading to basic assumptions of the model being only very rarely fulfilled. Here, too, the sensor technology used can provide support in the future in order to, on the one hand, determine the exact initial situation in spring and, on the other hand, to determine the necessary adjustment of the calculation factors.

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With support from

Federal Ministry of Food and Agriculture

by decision of the German Bundestag

Project manager

Federal Office for Agriculture and Food

More on EXPRESS at www.imms.de

Core topic Analysis of distributed IoT systems: www.imms.de

Lead application IoT systems for cooperative environmental monitoring: www.imms.de

RESEARCH FIELD

MAGNETIC 6D DIRECT DRIVES WITH NANOMETRE PRECISION

The solution “Picometer-Scale Positioning of a Linear Drive System via Feedforward-Feedback Control” was recognised with the Best Paper Award at ICM 2021 (IEEE International Conference on Mechatronics). More than 100 topics were presented at the conference.

The illustrated experimental setup at IMMS validates a sophisticated controller design for a linear drive system and was developed with partners from Ilmenau TU and SIOS Meßtechnik GmbH for research in the field of highly dynamic nano- and picometre positioning.

The effectiveness of the presented control strategy was verified by real-time experiments in which the developed control scheme enables positioning in the picometre range.

Photograph: IMMS.

Funded by

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

The Research Training Group 2182 on Tip- and laser-based 3D-Nanofabrication in extended macroscopic working areas (NanoFab) is funded by the German Research Foundation (DFG) under the funding code DFG GRK 2182.

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.

Magnetic 6D direct drives with nm precision: www.imms.de.

Highlights of 2021 in our research on Magnetic 6D direct drives with nanometre precision

Best Paper Award at IEEE ICM 2021 for a picometre-scale positioning solution

At the IEEE International Conference on Mechatronics (ICM) on 8 March 2021, the contribution “Picometer-Scale Positioning of a Linear Drive System via Feedforward-Feedback Control” the best paper award was conferred to Alex S. Huaman, Michael Katzschmann, Steffen Hesse, and Christoph Schäffel from IMMS, Christoph Weise, Eberhard Manske, and Johann Reger from Technische Universität Ilmenau, and Denis Dontsov from SIOS Meßtechnik GmbH, Ilmenau. Their awarded experimental setup validates an impressive and sophisticated controller design for a linear drive system. It is located at IMMS and was developed for the research in highly dynamic positioning in the nanometre and picometre range.

More on NanoFab at www.imms.de.

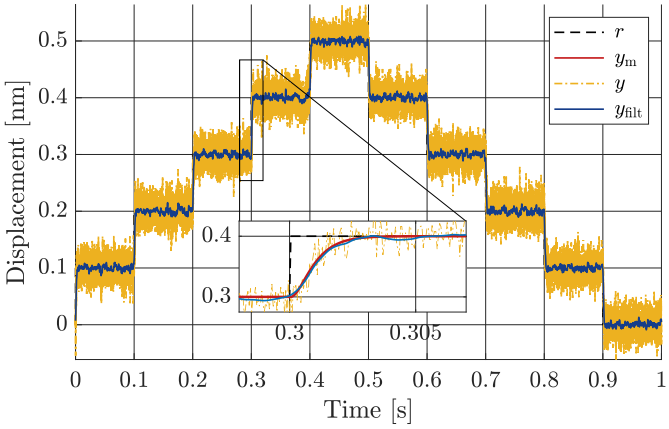

Figure 1.

Time series for set-point regulation in the picometre range.

Diagram: IMMS.

Nowadays many high-tech applications not only in semiconductor fabrication require ultraprecise position systems with sensitivities even down to the picometer range. Towards this end IMMS together with Ilmenau TU are conducting fundamental research on the physical and technological limitations of such positioning solutions. In this context IMMS developed and implemented a novel linear precision drive for picometre positioning research in travel ranges of ±15 nm. Utilising a high-precision differential laser interferometer and plane mirrors, it is possible to determine the linear displacement. For tracing picometres, a model-based control architecture comprising a feedforward stage for model-following and a feedback stage for stabilisation and disturbance rejection was adopted. The effectiveness of the presented control strategy was verified via real-time experiments, where the closed-loop system allows positioning at the picometre level, see Fig. 1. Further comparisons with other well-known control algorithms in the literature revealed fast convergence and outstanding disturbance rejection using the proposed control method.

Lead application nm measurement and structuring of objects
www.imms.de

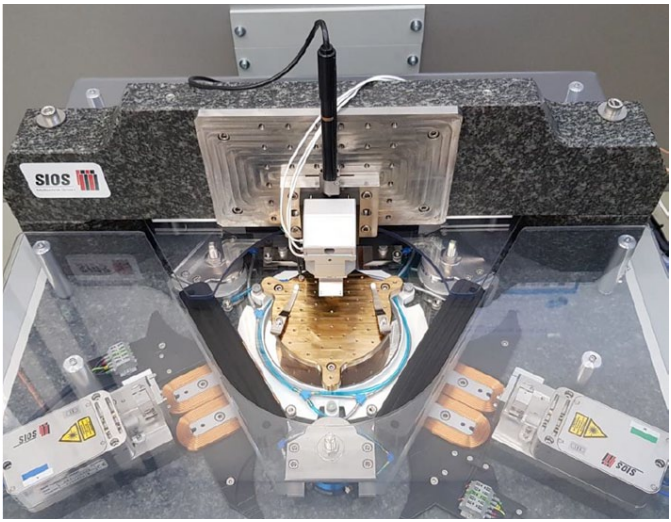

Figure 1:
Nano Fabrication Machine NFM-100.
Source: [1]

NFM-100 – Planar nanopositioning system enables atomic force microscopy in new quality

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www.imms.de

The inspection of optical precision components, wafers and masks, surface scans on an atomic level with atomic force microscopy (AFM), tip-based nanofabrication with active microcantilevers – these and many other high-tech industry technologies, even beyond semiconductor processing, rely on high-precision positioning systems to enable nanometre-level measurement, but also nanofabrication, i.e. manipulation on this scale. It is becoming increasingly necessary to be able to use such technology not only in the range of a few micrometres, but also for large measurement objects or at wafer level, in the range of a hundred millimetres or more.

For fundamental research on nanometrology and nanofabrication at Ilmenau TU, the nanofabrication machine NFM-100 was realised as a system which enables the scanning of surfaces (AFM) as well as the processing by field emission scanning probe lithography for the first time in an xy-travel range of Ø100 mm, see Figure 1.

IMMS know-how for precision positioning

For the development and realisation of the NFM-100 system under the leadership of SIOS GmbH, IMMS was able to contribute its know-how in the field of air-guided precision drives, in particular the realisation of nanopositioning systems for large travel ranges, which results not least from many years of joint research with Technische Universität Ilmenau on nanopositioning and nanomeasuring machines. The

NFM-100's positioning system consists of an integrated 3D direct drive developed by IMMS, in which the drive forces act without contact on an aerostatically planar guided quartz glass slider. The displacement and yaw of the slider are measured by ultra-stable differential interferometers from SIOS GmbH, also contact-free and with picometre resolution. With this low-noise and highly accurate feedback, a closed-loop control for x, y and φ_z is realised via the real-time control. In addition to the development and implementation of the integrated direct drive and its integration into the overall system, IMMS also contributed to the programming of the real-time control and in particular the development, implementation and fine-tuning of the control algorithms. An AFM measuring head from nano analytik GmbH is used as probing system.

Long-range AFM scans and 100-picometre steps possible

As a result, the NFM-100 system is a completely new type of device that opens up new fields of application for AFM technology thanks to its large working range. The positioning system achieves sub-nanometre position stability and enables positioning steps of, for example, 100 picometres, see Figure 2.

With these outstanding properties, the NFM-100 is being used very successfully for scientific work at TU Ilmenau in the field of nanofabrication. In 2021, for example, it was possible to achieve continuous AFM scans over 50 mm without the usual stitching, i.e. without the combination of overlapping partial images, see Figure 3.

Services for the development of mechatronic systems: www.imms.de

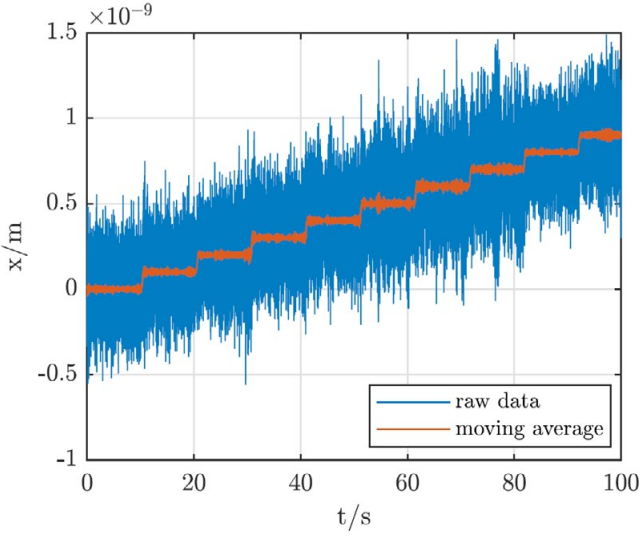

Figure 2:

Positioning of the NFM-100 system with 100 pm increments at a speed of 500 pm/s.

Source: [2]

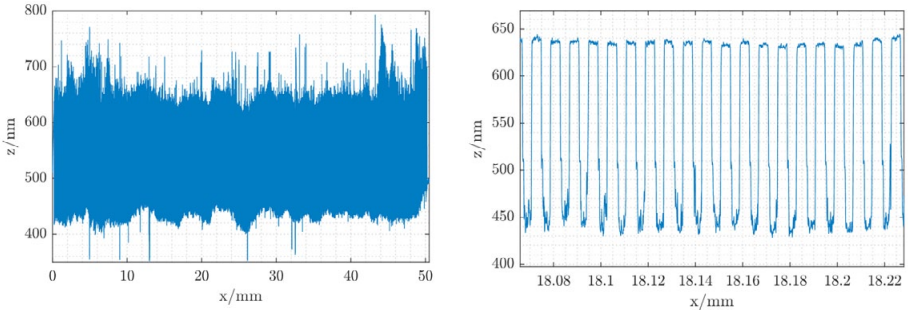

Figure 3: AFM line scan on a test grid with 8 µm pitch and approx. 200 nm structure depth. Total scan over 50 mm (left); zoom on a 170 µm section (right). Source [3].

Perspective also with vertical adjustment

The positioning system on which the NFM-100 is based can also be equipped with other sensors as a probing or manipulation system, which makes it possible to address further measuring or processing technologies at the nanometre level. In the above configuration, the positioning system is already available as a modular platform via SIOS GmbH.

However, the underlying scalable machine approach enables the implementation of a z adjustment of up to 10 mm in addition to larger xy travel ranges. For this purpose, suitable lifting modules were developed at IMMS as vertical nanopositioners with integrated weight compensation [4], [5].

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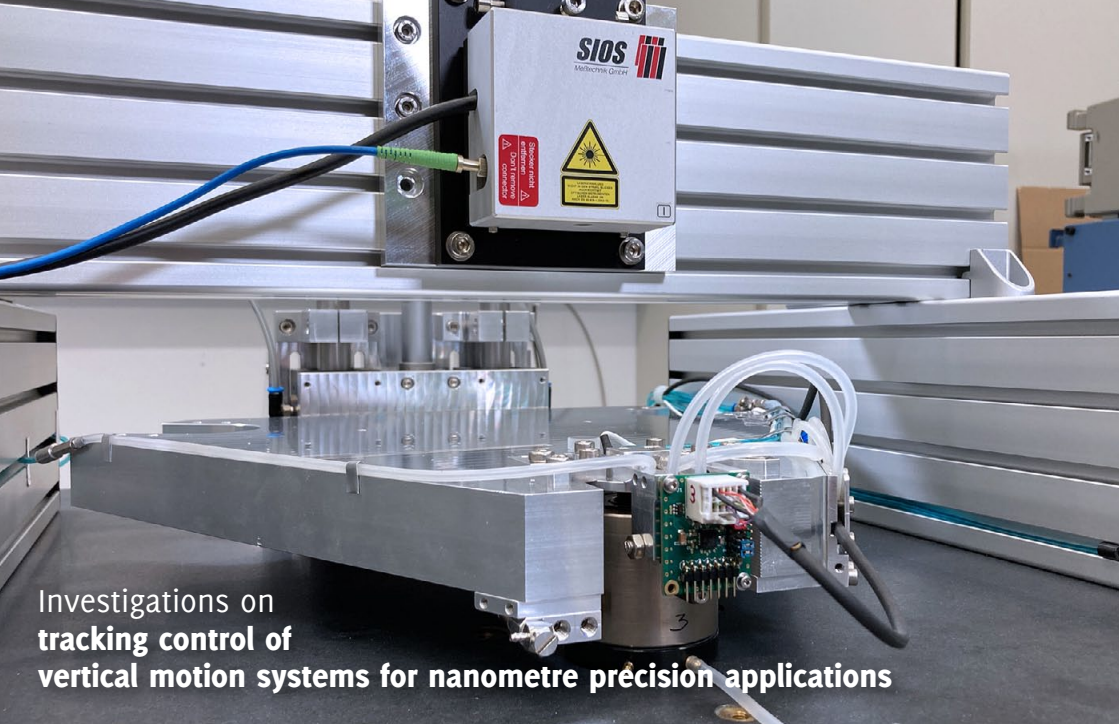
[5] Gorges S.: **A lifting and actuating unit for a planar nanoprecision drive system,** *Dissertation TU Ilmenau, 2020*



Investigations on **tracking control of vertical motion systems for nanometre precision applications**

Figure 1: IMMS developed a model-based control strategy to integrate lifting and actuating units into its existing planar nanoprecision drives. This should enable high-precision manufacturing with complete 6D systems in the future. With this test setup with one degree of freedom for one lifting and actuating unit the model-based control strategy was validated to be used in full 6D systems. Photograph: IMMS.

Motivation and overview

The rapid progress in the miniaturisation of micro- and nanosystems demands high-precision positioning systems integrating vertical actuation. In semiconductor industry and other branches where high-precision drive systems for industrial machinery are needed, requirements increasingly evolve towards ever more precise systems with sub-nanometre precision. At the same time ever larger vertical movements are to be carried out to enable more functionality and higher accuracy due to the ability to compensate for flatness deviations and to consistently touch the probe with minimum Abbe error, i.e. with minimal angular errors and offsets.

More on NanoFab at www.imms.de.

Lead application nm measurement and structuring of objects www.imms.de

For those vertical movements of a drive system, IMMS and partners are conducting research and development to equip an existing nanometre planar positioning system (NPPS100), which has a planar travel range of ⌀100 mm, with purpose-designed lifting and actuating units (LAUs). The result will be a 6D system that allows not only

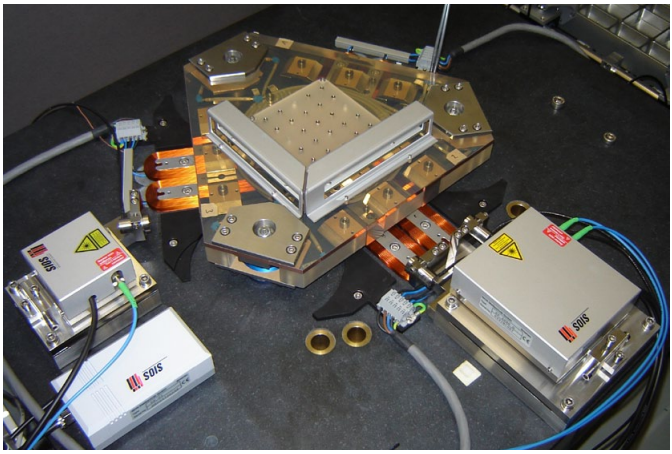


Figure 2:

Nanometre planar positioning system NPPS100.

Photograph: IMMS.

positioning in the horizontal xy-plane but also displacement in the z-direction, e.g. over 10 mm, with sub-nanometre resolution.

In the course of these investigations an initial step was the design and optimisation of a custom tailored closed-loop control for each individual LAU. This critical step in research on vertical positioning and trajectory tracking tasks is described in this article. Systematic experimental studies validate the projected performance of each lifting module and confirm the effectiveness of the proposed control system thus enabling the next steps towards the full 6D system implementation.

Concept of the 6D drive system

A full 6D system evolves from the combination of the planar drive NPPS100 (featuring motion in x, y, and φ_z) with three identical LAUs for vertical actuation in z-direction with associated tilting angles φ_x and φ_y. By using four laser interferometers (LIFs), an autocollimator, and plane mirrors mounted in the slider, it is possible to determine the position and orientation in the Euclidean space. Within this framework, vertical actuation allows the measurement and manipulation of real 3D objects rendering a minimum Abbe-error. Figure 3 shows the exploded view of the underlying planar system integrating three lifting modules.

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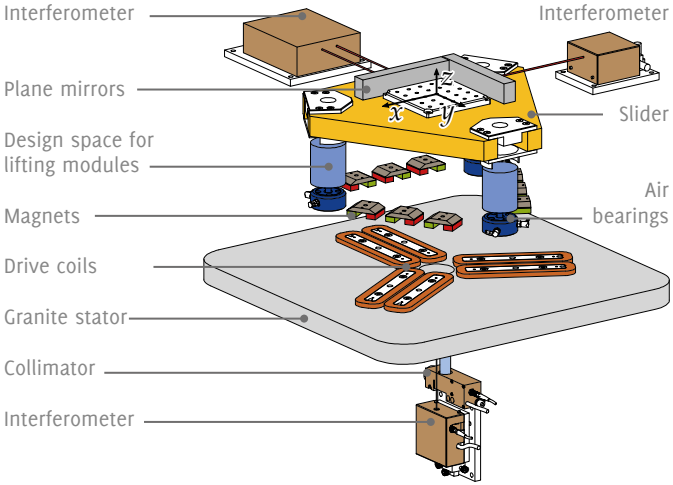

Figure 3:

Exploded view of the NPPS100-6D.

Diagram: IMMS.

Design of the lifting module revisited

The purpose of the earlier developed single LAUs is to lift a total mass of 4 kg with precise nanometre positioning. The target of the lifting module is to mimic the performance of the planar drive NPPS100 (see Figure 2) in terms of precision and dynamics, i.e. RMS position errors below 1 nm and maximum accelerations of 250 mm/s². The key task of the 3D vertical actuation (z, φ_x, φ_y) consists in moving the slider and further components, i.e. a total of 12 kg, over a vertical stroke of 10 mm. Due to the symmetric design of the triangular slider, three identical LAUs are mounted on each corner, therefore transitioning to a full 6D system (x, y, z, φ_x, φ_y, φ_z), see Figure 3.

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The design of one compact lifting module integrates a pneumatic actuator for weight-force compensation (WFC), an electromagnetic drive for precision motion, and an aerostatic vertical guiding for frictionless and stick-slip-free motion fitted into an assembly space of just 50 mm diameter by 60 mm height. An optical linear encoder is additionally integrated to initialise the LIFs. In relation to vertical actuation, the biggest shortcoming is heat emission, i.e. thermal expansion, and further associated perturbations into the measurement space.

This is solved by utilising a thermally passive WFC to counteract the static weight force. In consequence, the electromagnetic actuator only creates the precision motion force fulfilling the heat emission constraint. Real-time experimentation found that a pneumatic piston as a WFC and a Lorentz-force drive as a precision actuator

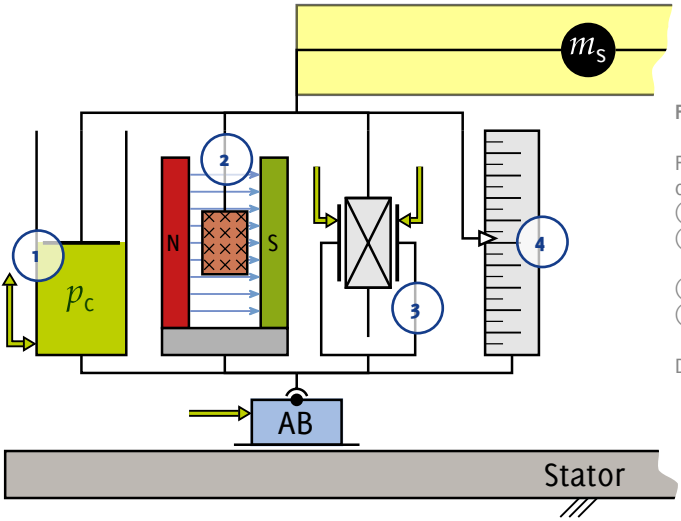

Figure 4:

Functional components of a single LAU:
(1) pneumatic WFC,
(2) precision Lorentz-force actuator,
(3) vertical guiding,
(4) integrated encoder.

Diagram: IMMS.

complement each other very well. In addition, the integrated encoder can be utilised as a fallback system in case of a laser beam break. Figure 4 depicts the functional components of a single LAU.

Single degree of freedom test-bench

As an intermediate step toward a full 6D system, one single LAU is installed individually on a test stand configuring a vertical motion system with one degree of freedom (DOF) that integrates two actuators. Figure 5 shows an overview of the test setup. The motion system is placed on a passive vibration-isolating granite stator. A single LAU is mounted at one corner of a triangular dummy slider while the other corners are hinged on a passive secondary support. By means of a high-precision LIF, the vertical displacement is measured with a resolution of 20 pm. In addition, a mirror is fixed on the centre of the slider. For precise measurement, the reflected beam must be coincident with the outgoing beam. To this end, the mirror must be adjusted precisely perpendicular to the beam of the LIF with an angular tolerance of 145 µrad approx. Note that this physical constraint limits the maximum vertical displacement up to 80 µm. For data acquisition and rapid control prototyping, we utilise a dSpace real-time system in combination with Matlab and Simulink.

Figure 5:

Lifting module that has been integrated into the 1-DOF test setup.

Photograph: IMMS.

Model-based control strategy

Typical controls used for industrial applications not suitable

The design of an appropriate control system is the key element in research on positioning and trajectory tracking tasks. Consequently, the selection of the control strategy, as well as its fine-tuning, is essential to achieve the desired performance and robustness. In industrial applications, the widely-known proportional-integral-derivative (PID) controller stands out for its remarkable performance and because it can be easily tuned using heuristic methods. However, due to the complex dynamics of the LAU, standard PID-type approaches neither meet the desired accuracy (z-position error below 1 nm) nor successfully minimise heat emission (via low current in the electromagnetic actuator), and also lack robustness against parametric uncertainties and external disturbances. Model-based control strategies provide a constructive procedure, resulting in an iterative approach for controller design whenever the dynamic model of the process is updated. This results in a more efficient implementation.

Integration of parallel vertical forces into a single pure control force

The starting point for the design of the control system is the derivation of a detailed model. It should describe the overactuated nature of the system, i.e. a system which has more actuators than degrees of freedom (DOF). In our case, the model comprised the complex overactuated dynamics of the LAU plus further components of the 1-DOF test bench (i.e. slider, air guidings, and secondary suport). To this end, the forces generated by the pneumatic WFC and the electromagnetic drive are

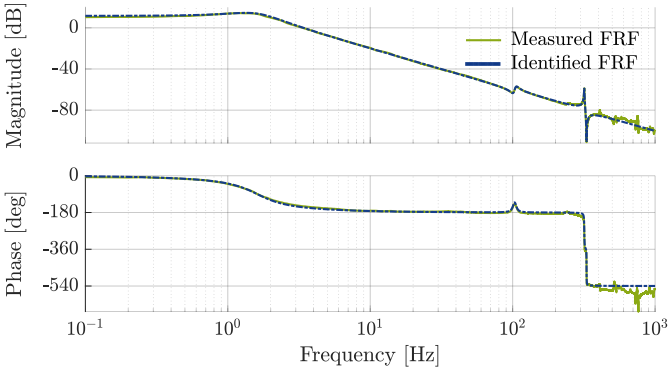

Figure 6:

Frequency response function. Input: force F* [N], output: displacement q_z [mm]

Source: IMMS.

integrated into a single pure control force by means of the application of a control allocation method (see Figure 7). By utilising control allocation, the model is reduced into a single-input and single-output system. Given the dominantly linear dynamics of the 1-DOF motion system, the frequency response is measured to get a closer look into the plant dynamics, see Figure 5. Through the application of frequency-domain system identification tools, a very reliable model is identified which captures most of the relevant dynamics (i.e., further resonance modes) of the 1-DOF vertical motion system.

The control system is designed on the basis of the identified dynamic model. Fig. 6 depicts the functional closed-loop system. The control architecture comprises a feedforward stage for trajectory tracking and a feedback stage for stabilisation and complex disturbance rejection. The core of the feedback control is an optimal linear-quadratic (LQ) baseline controller plus an adaptive augmentation. The LQ-type controller meets the expected performance via high bandwidth and provides robust-

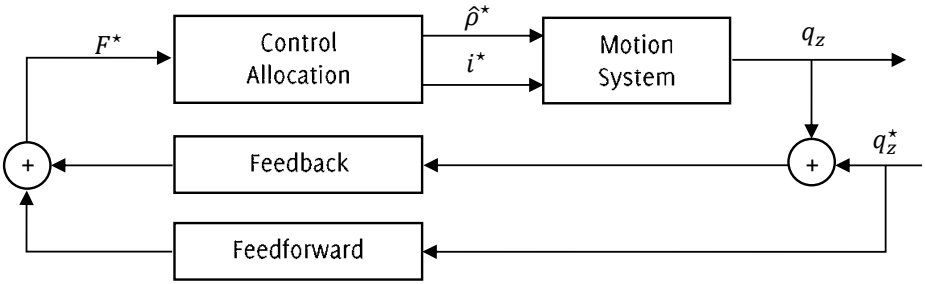

Figure 7: Block diagram of the closed-loop system. Diagram: IMMS.

ness properties. The adaptive component plays a central role to recover the target performance even in presence of external disturbances and parametric uncertainties. In this context, for real-time implementation full-state information is reconstructed by an integrated (extended) state estimator.

Results towards a full 3D vertical actuation

Investigations on tracking control are closed by evaluating the effectiveness of the proposed control system through real-time data, which is appealing for potential industrial applications. Figure 8 shows the final measurement results from the 1-DOF testing setup. At the beginning of the experiments, the lifting module was set down and rested on the massive granite stator. In the upper left graph, the noise in the position signal (in blue) has a standard deviation of 0.21 nm; while in closed-loop operation, the position error (in green) has a standard deviation of 0.22 nm. The current in the electromagnetic drive has a root mean square (RMS) as low as 0.26 mA (see the upper right graph), and the equilibrium pressure for a mass of 4 kg approx. is bounded around 1.18 bar (see the lower left graph). Further experiments were also performed in closed-loop operation over the vertical stroke of 10 mm. In the lower right graph, the RMS positioning error and the RMS control current stay below 0.25 nm and 0.3 mA, respectively. Given the very low current, heat emission is minimised by emitting only a few nanowatts (54 nW approx.) into the measurement space.

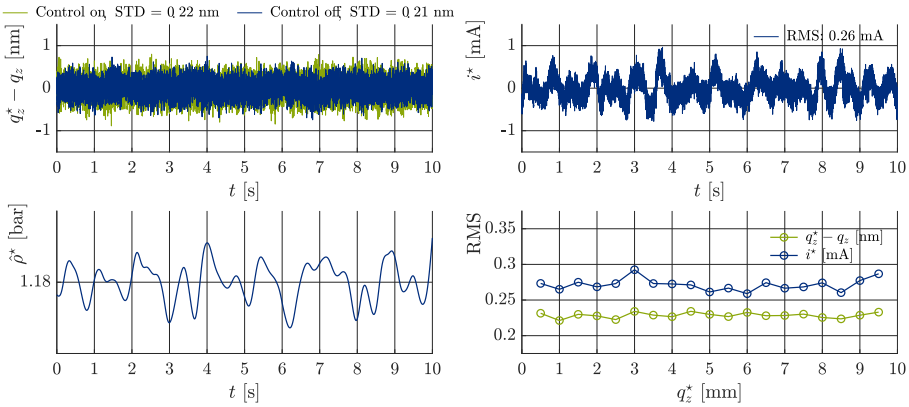

Figure 8: Time series of the closed-loop positioning error (in nm), control current (in mA), pneumatic pressure (in bar), and RMS deviation w.r.t. the vertical displacement.

These impressive results in positioning applications play a central role for future research towards a full 6D system and, additionally, validate the projected performance of an individual LAU using a modern control system in order to achieve sub-nanometer precision positioning with RMS errors below 0.25 nm while heat emission is minimised via an almost zero current in the electromagnetic actuator. Further research will address a 3D vertical motion system comprising three LAUs to provide motion in z-direction, as well as tilting angles φ_x and φ_y.

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DFG Deutsche Forschungsgemeinschaft
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The Research Training Group 2182 on Tip- and laser-based 3D-Nanofabrication in extended macroscopic working areas (NanoFab) is funded by the German Research Foundation (DFG) under the funding code DFG GRK 2182.

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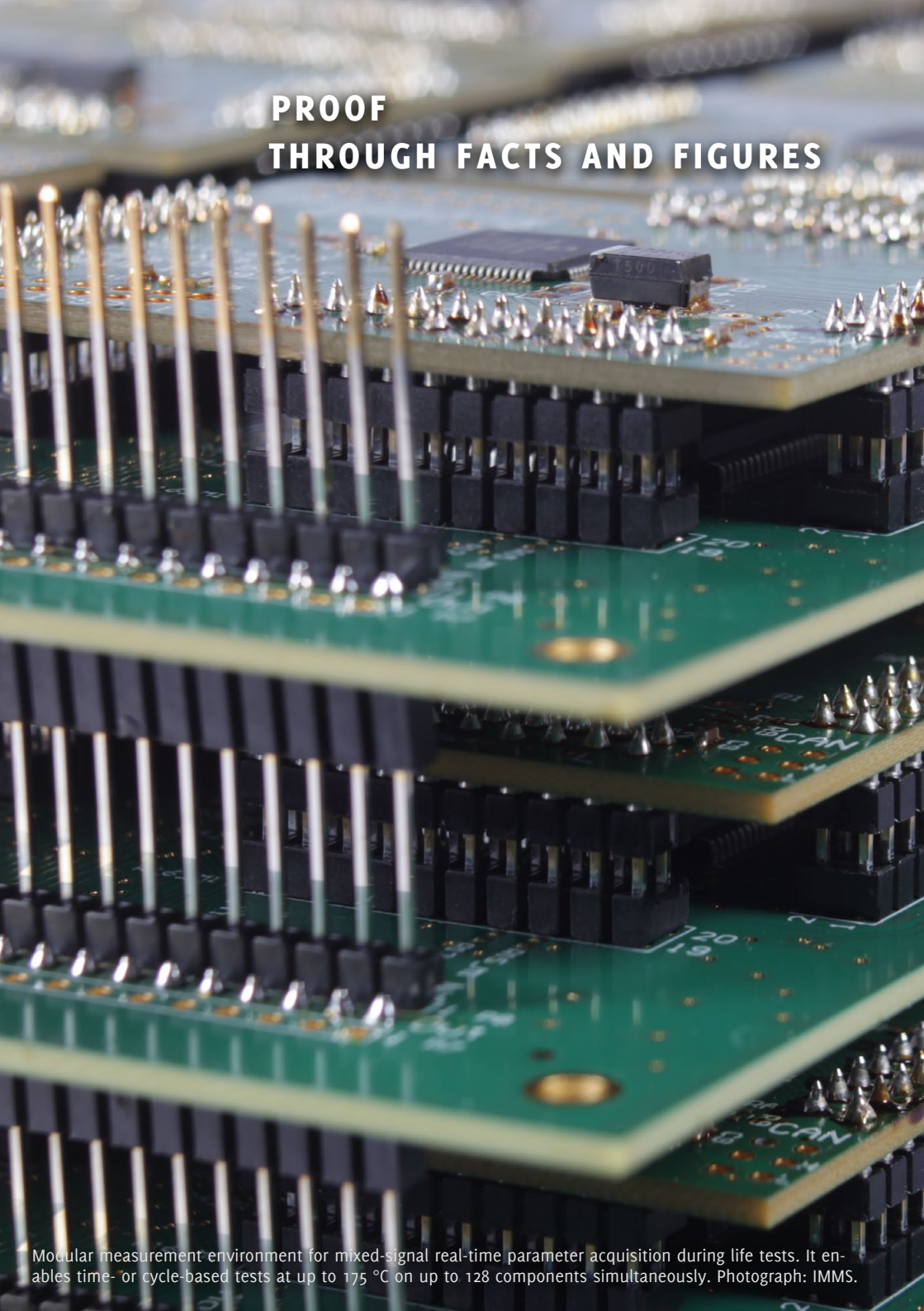
PROOF
THROUGH FACTS AND FIGURES

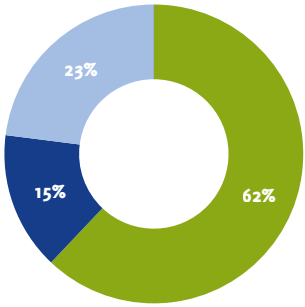


Modular measurement environment for mixed-signal real-time parameter acquisition during life tests. It enables time- or cycle-based tests at up to 175 °C on up to 128 components simultaneously. Photograph: IMMS.

At the end of the 2021 financial year, 87 people were employed at IMMS. Of these, 54 scientists and 20 students were employed in research and development. This corresponds to a share of around 85 % of all **employees**.[1]

As part of training in practice-oriented research, a total of 35 students were supervised at the IMMS in the 2021 financial year, including 1 Bachelor's thesis and 6 Master's theses, and 6 employees were enrolled as doctoral students at a university.

Staff structure



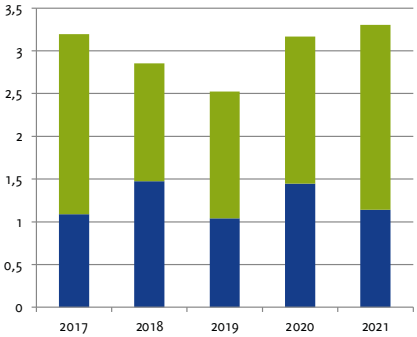
Scientists | administration/apprentice | students

The large number of nationalities represented at IMMS also promoted international exchange for research and development in 2021. Despite the noticeable increase in competition for outstanding minds, further researchers were recruited to work at IMMS in 2021. To be able to guarantee the expected increasing demand from industry for the Institute's specific research services and the associated necessary growth in the coming years, a wide range of measures and activities were undertaken to recruit new scientists.

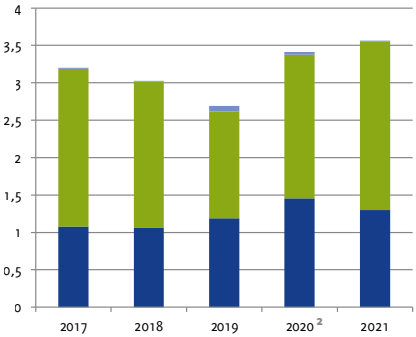
As in previous years, the financial year was characterised by conducting public research projects and by transferring research results to industry (industrial contract research). **Third-party funding** earnings (project earnings) were increased by around 4% in 2021 compared to the previous year. The high level of work in progress from publicly funded research projects (funded projects) had a particular effect here, which compensated for the restraint of industrial partners in contracting in the financial year. The publicly funded project business (funded projects) could be expanded significantly compared to the previous year, so the earnings from public project grants were 26 % higher than the previous year's value. 12 publicly funded research projects were started. Earnings from industrial contract research (industrial earnings) in 2021 remain around 21% below the high earnings of the previous year, but are still at a good level in a 5-year comparison. As in previous years, industrial

1 *As the employment figures given are actual numbers for 31.12.2021 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 €



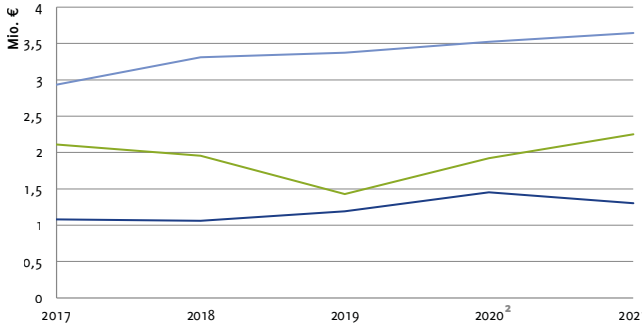
Project **revenues**
Industrial projects / funded projects / others
in million €



contract research was largely characterised by a large number of small contracts from small and medium-sized enterprises in Thüringen (approx. 58%).

The positive development of third-party funding earnings was also reflected in project revenues, which were up by a total of about 5 % over the previous year. The distribution of total third-party funding revenues (project revenues) between revenue from funded projects and revenue from industrial contract research essentially corresponds to the distribution of earnings.

Institutional funding from the German Land of Thüringen formed the basis for carrying out the research tasks of IMMS. In particular, preliminary research is an essential prerequisite for the innovative strength of the institute. The funding of the internal research groups enables IMMS to develop and work on the essential research foci for strategic further development, independently from the availability of funding through public funding offers.



Pillars of financial support
in million €

Basic funding
(institutional support)

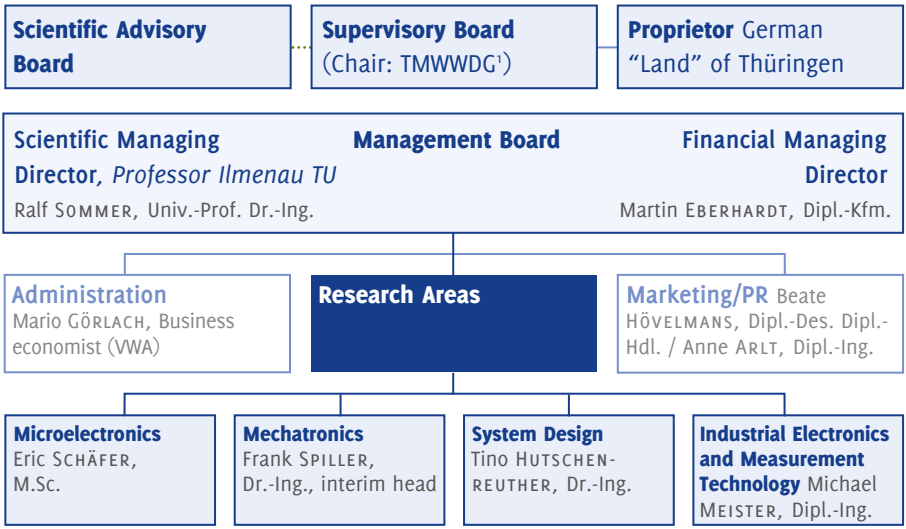
Public project funding

Revenues from industry

² Figures corrected

More on funding at www.imms.de.

Organisation*



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* as of 31 December 2021

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- Prof. Dr.-Ing. Johannes Trabert, Ernst-Abbe-Hochschule Jena, University of Applied Sciences, Department of Electrical Engineering and Information Technology, Communications Systems and Transmission Technology

* as of 31 December 2021

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

IMMS as host, organiser or co-initiator

12/01/2021 – AI Developers' Round Table, SME 4.0, *organisation, talk*, online

01/02/2021 – BarCamp at DATE 2021, *organisation, Session Chair, moderation und talk*; online

04/02/2021 – Regulars' Table "Sensors 4.0", Legal certainty in open source applications, SME 4.0, *workshop*, online

26/02/2021 – Regulars' Table "Collaboration", "Collaborative working – applications and hurdles", SME 4.0, *workshop*, Online

17/03/2021 – Cloud in practical application, presentation event by TGF GmbH, ELMUG e.G., Thuringian Competence Centre for Economics 4.0 und SME 4.0 – Competence Centre Ilmenau, *workshop*, Online

13/04/2021 – AI Developers' Round Table, SME 4.0, *organisation, talk*, online

20/04/2021 – Workshop with SONOTEC GmbH: "Developing solutions for measurement data acquisition for cutting machines and resource-efficient AI-based data evaluation", SME 4.0, *workshop*, online

Current events: www.imms.de.

18/05/2021 – Workshop with KOMOS GmbH: „AI-supported digitisation solutions 1", SME 4.0, *workshop*, KOMOS GmbH, Bürgel

20/05/2021 – Regulars' Table "Sensors 4.0", "Diagnostic solutions in industrial application", SME 4.0, *organisation, 2 talks*, online

04/06/2021 – Cooperation workshop with ZO.RRO: ZO.RRO – Innovative solutions for the CO_2-free energy supply of the future, SME 4.0, *workshop*, online

08/06/2021 – Workshop "First impressions count - even virtually", SME 4.0, *workshop*, online

08/07/2021 – Workshop "Second impressions count too", SME 4.0, *workshop*, online

14/07/2021 – Workshop with KOMOS GmbH: „AI-supported digitisation solutions 2", SME 4.0, *workshop*, KOMOS GmbH, Bürgel

19/07/2021 – SMACD 2021, International Conference on Synthesis, Modeling, Analysis and Simulation Methods, and Applications to Circuit Design, *conference chair and organisation, technical programme management; 4 talks*; online

19/07/2021 – PRIME 2021, International Conference on PhD Research in Microelectronics and Electronics (PRIME 2022), *conference organisation, 2 talks*; online

19/07/2021 – BarCamp at SMACD 2021, *organisation, session chair, moderation*; online

13/10/2021 – AI for SME – Optimising processes with artificial intelligence, presentation event by SME Digital, *organisation and talk*, online

Conferences / events with contributions by IMMS

12/01/2021 – AI Developers' Round Table, SME 4.0, *organisation, talk*, online

21/01/2021 – 3. Industrieforum „Smarte Fertigung", Integration flexibler Fertigungstechnologien und intelligenter Prozessketten, *talk*, online

01/02/2021 – DATE 2021, Presentation at the Virtual University Booth / BarCamp, *organisation BarCamp, talk*, online

22/02/2021 – TuZ 2021, 33. ITG/GI/GMM workshop on Test methods and reliability of circuits and systems, *talk*, online

22/02/2021 – SPIE 2021, Advanced Lithography Digital Forum of The International Society for Optics and Photonics, *talk*, online

26/02/2022 – Regulars' Table "Collaboration", "Collaborative working – applications and hurdles", SME 4.0, *workshop*, Online

03/03/2021 – AI Spring, event series of the Thuringian Competence Centre Economy 4.0, *moderation, talk*, online

Current events: www.imms.de.

07/03/2021 – ICM 2021, International Conference on Mechatronics, *talk*, online
08/03/2021 – 41th GIL Annual Conference, Leibniz Institute of Agricultural Engineering and Bioeconomy e.V., *talk*, online
24/03/2021 – Regulars' Table "Collaboration", "Appearing confident online", SME 4.0, *talk*, online
13/04/2021 – AI Developers' Round Table, SME 4.0, *organisation, talk*, online
14/04/2021 – Trustworthy electronics, BMBF Digital Conference on Research and Innovation for Technological Sovereignty, *2 talks*, online
14/04/2021 – Silicon Saxony e. V., Event of the Artificial Intelligence and Smart Systems & Internet of Things working groups, *talk*, online
12/05/2021 – Think Wireless IoT Day on Healthcare and Security, *talk*, online
20/05/2021 – Regulars' Table "Sensors 4.0", "Diagnostic solutions in industrial application", SME 4.0, *organisation, 2 talks*, online
07/06/2021 – MetroInd4.0&IoT 2021, 2021 IEEE International workshop on Metrology for Industry 4.0 and IoT, *talk*, online
11/07/2021 – ICSV27, 27th International Congress on Sound and Vibration, *talk*, online
19/07/2021 – SMACD 2021, International Conference on Synthesis, Modeling, Analysis and Simulation Methods, and Applications to Circuit Design, *conference chair and organisation, technical programme management; 4 talks*; online
19/07/2021 – PRIME 2021, International Conference on PhD Research in Microelectronics and Electronics (PRIME 2022), *conference organisation, 2 talks*; online
15/08/2021 – DAGA 2021, 47th Annual Conference on Acoustics, *talk*, Wien
18/08/2021 – "Digital Lunch Break", Thuringian Competence Centre Economy 4.0, SME 4.0 - Competence Centre Ilmenau, *talk*, online
23/08/2021 – SAS 2021, Sensors Applications Symposium SAS, *talk*, Sundsvall, Schweden, online
21/09/2021 – elmug4future, Sensors, systems and processes for resource optimisation, *talk*, Erfurt und online
22/09/2021 – EXPRESS Regional Conference, Mid-Germany Digital Days in Viticulture and Fruit Growing, *talk*, Meißen
30/09/2021 – MOEMS-workshop, Optical sensors and systems for fluorescence and scattered light – CiS workshop, *talk*, Erfurt (hybrid)
06/10/2021 – IEEE BioCAS 2021, Biomedical Circuits and Systems Conference (BioCAS): Restoring Vital Functions by Electronics – Achievements, Limitations, Opportunities, and Challenges, *talk*, Berlin, online

Current events: www.imms.de.

06/10/2021 – IEEE RFID-TA 2021, 11th IEEE international Conference on RFID Technology and Applications, *talk,* Delhi, India, virtual conference
13/10/2021 – AI for SME – Optimise processes with artificial intelligence, SME 4.0, *organisation und talk*, online
26/10/2021 – DVCon Europe, The Design and Verification Conference & Exhibition Europe, online
11/11/2021 – „AI talk", Event of the accompanying research of Mittelstand Digital, *talk*, online
17/11/2021 – EUSPEN 2021, Special Interest Group Meeting: Micro/Nano Manufacturing, *talk*, online
30/11/2021 – InnoCON Thüringen 2021, "Addressing the challenges of our time such as digital transformation and decarbonisation with the Thuringian Innovation Strategy 2021 – 2027.", *talk, Demonstrator*, Arena Erfurt, hybrid

Trade fairs

15/04/2021 – Hannover Messe, SME 4.0, Thuringian joint booth of LEG Thüringen, online
23/04/2021 – BUGA 2021, Federal Horticultural Show Erfurt, *demonstrator*
26/10/2021 – inova 2021, Career Forum at the Ilmenau TU
30/11/2021 – InnoCON Thüringen 2021, "Addressing the challenges of our time such as digital transformation and decarbonisation with the Thuringian Innovation Strategy 2021 – 2027.", *talk, Demonstrator*, Arena Erfurt, hybrid

Video productions for demonstrators / online events

- ***Your career at IMMS**, Recruiting-Clip für die virtuelle Ausstellung / Carrer Fair, SMACD 2021, International Conference on Synthesis, Modeling, Analysis and Simulation Methods, and Applications to Circuit Design*
- ***AnoPCB – plugin for the free PCB design tool KiCad for artificially IntelligEnt layout processing**. video tutorial, EDA Competition Award, SMACD 2021, International Conference on Synthesis, Modeling, Analysis and Simulation Methods, and Applications to Circuit Design*
- ***25 years of IMMS – We thank you very much for your congratulations!** Video summary of greetings sent to IMMS on the occasion of its 25th anniversary*

Current events: www.imms.de.

More videos at www.imms.de

- ***From one of the world's first USB hubs to AI - 25 years of IMMS.*** *Video from one of the first transfer projects launched in 1996, which advanced the worldwide USB development from Thüringen, to a selection of current AI solutions.*

Publications

Reviewed Publications

Evaluation of 2D-/3D-Feet-Detection Methods for Semi-Autonomous Powered Wheelchair Navigation, Cristian Vilar Giménez[1]. Silvia Krug[1,2]. Faisal Z. Qureshi[1,3]. Mattias O'Nils[1]. *Journal of Imaging, vol. 7, no. 12, p. 255, Nov. 2021*, **DOI: doi.org/10.3390/jimaging7120255.** [1]Department of Electronics Design, Mid Sweden University, Holmgatan 10, 851 70 Sundsvall, Sweden. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [3]Faculty of Science, University of Ontario Institute of Technology, 2000 Simcoe St. N., Oshawa, ON L1G 0C5, Canada.

Nanometergenaue Hubmodule für die Präzisionsantriebstechnik, Stephan Gorges[1]. *Konstruktion (2021) Nr. 11-12, Sonderteil Antriebstechnik, Seite 36 – 40,* **www.ingenieur.de/fachmedien/konstruktion/antriebstechnik/hubmodule-fuer-die-praezisionsantriebstechnik/.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Filterless TRF Reader with CMOS Sensor ASIC for Lateral Flow Immunoassays, Alexander Hofmann[1]. Peggy Reich[1]. Martin Grabmann[1]. Georg Gläser[1]. Max Trübenbach[2]. Alexander Rolapp[1]. Marco Reinhard[1]. Friedrich Scholz[2]. Eric Schäfer[1]. *2021 IEEE Biomedical Circuits and Systems Conference (BioCAS), 2021, 6 – 9 October 2021, Berlin, Germany, virtual conference, pp. 1 – 6.* **DOI: doi.org/10.1109/BioCAS49922.2021.9645000,** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Senova Gesellschaft für Biowissenschaft und Technik mbH, Weimar, Germany.

All publications: www.imms.de

A UHF RFID to I2C Bridge IC with Configurable Power Storage Unit for Flexible RFID Sensor Applications, Jun TAN[1]. Muralikrishna SATHYAMURTHY[1]. Hani ABDULLAH[1]. Jonathan GAMEZ[1]. Bjoern BIESKE[1]. Benjamin SAFT[1]. Martin GRABMANN[1]. Jacek NOWAK[2]. Sylvo JÄGER[2]. Eric SCHÄFER[1]. *2021 IEEE International Conference on RFID Technology and Applications (RFID-TA), 6 – 8 October 2021, Dehli, India, pp. 301 – 304,* **DOI: doi.org/10.1109/RFID-TA53372.2021.9617266.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Microsensys GmbH, Erfurt, Germany.

Comparing BLE and NB-IoT as Communication Options for Smart Viticulture IoT Applications, Silvia KRUG[1,2]. Sebastian MIETHE[1]. Tino HUTSCHENREUTHER[1]. *2021 IEEE Sensors Applications Symposium (SAS), 23 – 25 August 2021, virtual conference.* **DOI: doi.org/10.1109/SAS51076.2021.9530069,** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Mid Sweden University Sundsvall, Sweden.

Tip- and Laser-based 3D Nanofabrication in Extended Macroscopic Working Areas, Ingo ORTLEPP[1]. Thomas FRÖHLICH[1]. Roland FÜßL[1]. et al. *Nanomanufacturing and Metrology, 132–148 (2021).* **DOI: doi.org/10.1007/s41871-021-00110-w.** [1]Technische Universität Ilmenau, Germany.

Impact of Input Data on Intelligence Partitioning Decisions for IoT Smart Camera Nodes, Isaac Sánchez LEAL[1]. Irida SHALLARI[1]. Silvia KRUG[1,2]. Axel JANTSCH[1,3]. Mattias O'NILS[1]. *Electronics 2021, 10, 1898.* **DOI: doi.org/10.3390/electronics10161898.** [1]Department of Electronics Design, Mid Sweden University, Holmgatan 10, 851 70 Sundsvall, Sweden. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [3]Institute of Computer Technology, TU Wien (Vienna University of Technology), Gusshausstrasse 27-29/384, 1040 Vienna, Austria.

Trash or Treasure? Machine-learning based PCB layout anomaly detection with AnoPCB, Henning FRANKE[1]. Paul KUCERA[1]. Julian KUNERS[1]. Tom REINHOLD[2]. Martin GRABMANN[2]. Patrick MÄDER[1]. Marco SEELAND[1]. Georg GLÄSER[2]. *2021 17th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), 19 – 22 July 2021, Erfurt, Germany, online. Proceedings in: 423 Seiten, 140 x 124 mm, Slimlinebox, CD-Rom, ISBN 978-3-8007-5588-2, E-Book: ISBN 978-3-8007-5589-9,* **https://ieeexplore.ieee.org/document/9547913** [1]Technische Universität Ilmenau, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Machine Learning in Charge: Automated Behavioral Modeling of Charge Pump Circuits, Martin GRABMANN[1]. Christian LANDROCK[2]. Georg GLÄSER[1]. *2021 17th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), 19 – 22 July 2021, Erfurt, Germany, online. Proceedings in: 423 Seiten, 140 x 124 mm, Slimlinebox, CD-Rom, ISBN 978-3-8007-5588-2, E-Book: ISBN 978-3-8007-5589-9,* **https://ieeexplore.ieee.org/document/9547918**, [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]X-FAB Global Services GmbH, Erfurt, Germany.

Modeling and Optimization of Supply Sensitivity for a Time-Domain Temperature Sensor, Jun TAN[1]. *2021 17th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), 19 – 22 July 2021, Erfurt, Germany, online. Proceedings in: 423 Seiten, 140 x 124 mm, Slimlinebox, CD-Rom, ISBN 978-3-8007-5588-2, E-Book: ISBN 978-3-8007-5589-9,* **https://ieeexplore.ieee.org/document/9547935**, [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Design and Optimization of a Control Algorithm for a Digital Low-Dropout Regulator in System-on-Chip Applications, Benedikt OHSE[1]. Jun TAN[2]. *2021 17th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), 19 – 22 July 2021, Erfurt, Germany, online. Proceedings in: 423 Seiten, 140 x 124 mm, Slimlinebox, CD-Rom, ISBN 978-3-8007-5588-2, E-Book: ISBN 978-3-8007-5589-9,* **https://ieeexplore.ieee.org/document/9547956**, [1]Ernst-Abbe-Hochschule Jena, Jena, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany.

Make Some Noise: Energy-Efficient 38 Gbit/s Wide-Range Fully-Configurable Linear Feedback Shift Register, Christoph WAGNER[1]. Georg GLÄSER[2]. Thomas SASSE[1]. Gerald KELL[3]. Giovanni DEL GALDO[1,4]. *2021 16th Conference on PhD Research in Microelectronics and Electronics (PRIME), 2021, 19 – 22 July 2021, Erfurt, Germany, online. Proceedings in: 423 Seiten, 140 x 124 mm, Slimlinebox, CD-Rom, ISBN 978-3-8007-5588-2, E-Book: ISBN 978-3-8007-5589-9,* **https://ieeexplore.ieee.org/document/9547997**, [1]Technische Universität Ilmenau, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [3]Technische Hochschule Brandenburg, Germany. [4]Fraunhofer IIS, Ilmenau, Germany.

Every Clock Counts – 41 GHz Wide-Range Integer-N Clock Divider, Christoph Wagner[1]. Georg Gläser[2]. Gerald Kell[3]. Giovanni Del Galdo[1,4]. *2021 16th Conference on PhD Research in Microelectronics and Electronics (PRIME), 19 – 22 July 2021, Erfurt, Germany, online. Proceedings in: 423 Seiten, 140 x 124 mm, Slimlinebox, CD-Rom, ISBN 978-3-8007-5588-2, E-Book: ISBN 978-3-8007-5589-9,* **https://ieeexplore.ieee.org/document/9547998,** [1]Technische Universität Ilmenau, Germany. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [3]Technische Hochschule Brandenburg, Germany. [4]Fraunhofer IIS, Ilmenau, Germany.

A Case Study on Suitability of Machine Learning for Predictive Drill Bit Sharpness Estimation, Umut Onus[1]. Stefan Marr[2]. Sebastian Uziel[1]. Silvia Krug[1]. *2021 IEEE International workshop on Metrology for Industry 4.0 and IoT, 7 – 9 June 2021, Rome, Italy, online,* **DOI: doi.org/10.1109/MetroInd4.0IoT51437.2021.9488429,** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]GFE Gesellschaft für Fertigungstechnik und Entwicklung Schmalkalden e.V.

Investigations on the positioning accuracy of the Nano Fabrication Machine (NFM-100), Jaqueline Stauffenberg[1]. Ingo Ortlepp[2]. Ulrike Blumröder[2]. Denis Dontsov[3]. Christoph Schäffel[4]. Mathias Holz[5]. Ivo W. Rangelow[6]. Eberhard Manske[2]. *tm – Technisches Messen. 2021, 88(9): 581 – 589.* **DOI: doi.org/10.1515/teme-2021-0079.** [1]Technische Universität Ilmenau, Institute for Process Measurement and Sensor Technology, Ilmenau, Germany. [2]Technische Universität Ilmenau, Institute for Process Measurement and Sensor Technology, Ilmenau, Germany. [3]SIOS Meßtechnik GmbH, Ilmenau, Germany. [4]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [5]nano analytik GmbH, Ilmenau, Germany. [6]Technische Universität Ilmenau, Nanoscale systems Group, Ilmenau, Germany

Light Absorption Measurement with a CMOS Biochip for Quantitative Immunoassay Based Point-of-Care Applications, Alexander Hofmann[1]. Michael Meister[1]. Alexander Rolapp[1]. Peggy Reich[1]. Friedrich Scholz[2]. Eric Schäfer[1]. *in IEEE Transactions on Biomedical Circuits and Systems,* **DOI: doi.org/10.1109/TBCAS.2021.3083359.** [1]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [2]Senova Gesellschaft für Biowissenschaft und Technik mbH, Weimar, Germany.

All publications: www.imms.de

Design space exploration for an IoT node: Trade-offs in processing and communication, Irida SHALLARI[1]. Isaac S. LEAL[1]. Silvia KRUG[1,2]. Axel JANTSCH[1,3]. Mattias O'NILS[1]. *in IEEE Access, vol. 9, pp. 65078-65090, 2021,* **DOI: doi.org/10.1109/ACCESS.2021.3074875.** [1]Department of Electronics Design, Mid Sweden University, Sundsvall 85170, Sweden. [2]IMMS Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH, 98693 Ilmenau, Germany. [3]TU Wien, Karlsplatz 13, 1040 Vienna, Austria.

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Abbreviations

AI *Artificial ntelligence*
API *Application programming interface*
ASIC *Application-specific integrated circuit*

CMOS *Complementary metal–oxide semiconductor*
CRS *Cytokine release syndrome*
DNA *Deoxyribonucleic acid*
DOF *Degree of freedom*

EDA *Electronic design automation,*
FET *Field effect transistor*
FFT *Fast Fourier transform, algorith*
FPGA *Field programmable gate array*

I²C *Inter-integrated circuit*
IC *Integrated circuit*
IEEE *Institute of Electrical and Electronics Engineers*
IoT *Internet of things*

LAU *Lifting and actuating unit*
LIF *Laser interferometer*
LoC *Lab on chips*
LQ *Linear-quadratic*

MEMS *Microelectromechanical systems*
ML *Machine learning*

PCB *Printed circuit board*
PCR *Polymerase chain reaction*
PID *Proportional-integral-derivative controller*
POCT *Point-of-care test system for on-site diagnostics*

REST *Representational state transfer, paradigm for software architecture of distributed systems*
RF *Radio frequency*
RFID *Radio-frequency identification*
RMS *Root mean square*

SiCer *Silicon (Si) ceramic (Cerium) composite substrate*
SME *Small and medium-sized enterprises*
SPAD *Single photon avalanche diodes*
SPARCL® *Spatial proximity analyte reagent capture luminescence*

TSV *Through-silicon vias*
ULP *Ultra low power*
USB *Universal serial bus*

WFC *Weight-force compensation*

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