Fraunhofer

IPM

FRAUNHOFER INSTITUTE FOR PHYSICAL MEASUREMENT TECHNIQUES IPM

2019 2020

ANNUAL REPORT

FRAUNHOFER IPM

ORGANIZATION

<< **Cover:** *Our new building in close vicinity to Freiburg University's technical campus offers a modern working environment in addition to excellent technical conditions for our research (Read more on pages 10 to 12).*

MEASURING · MONITORING · OPTIMIZING

OUR BUSINESS UNITS

PRODUCTION CONTROL

OBJECT AND SHAPE DETECTION

GAS AND PROCESS TECHNOLOGY

THERMAL ENERGY CONVERTERS

INFRASTRUCTURE AND SUSTAINABILITY

**Dear customers,
dear partners,**

Moving into our new building on the University of Freiburg's Faculty of Engineering campus is the greatest step forward for our institute since it was founded and moved into its first dedicated building in Heidenhofstraße in 1973. We are very grateful to the state of Baden-Württemberg and the German federal government, as well as the European Union, which has helped fund construction via the European Regional Development Fund (ERDF), for this tangible proof of how much they trust and value us! We are also deeply indebted to the University of Freiburg, which has been a valuable partner day after day and allowed us to build on its campus as an integral part of Freiburg's renowned research community.

We worked to ensure that durable materials with a low carbon footprint were used for our new facility. The building automation and other technology, as well as heating and cooling systems using industrial waste heat and ground water, ensure highly efficient operation — and not just for our own building. When the new SC Freiburg stadium is running at full load in winter, our system can contribute half a megawatt of heat if needed. (You can read more about the sustainability of our new building and about its technical equipment on the pages 10 to 12.)

Planning and monitoring infrastructure — measurement technology is worth the investment

Buildings and infrastructure in general are also a focus of our research. There are many different applications for measurement technology in this field, with major RoI potential for the operators and the environment! Huge investments are required for the planning, construction and maintenance of rails, roads, and waterways, as well as electricity, gas, heating and water networks, and ports and airports. Market studies forecast global investments of 80,000 billion US dollars in the expansion of public infrastructure over the next twenty years. This is more than Germany's predicted gross domestic product for the same period. These investments will have a significant carbon footprint – making it even more important to plan carefully, build efficiently and ensure long-term, reliable operation. Our measurement systems are used around the world in order to fulfill this goal. Our Object and Shape Detection unit works on applications such as automated route planning for expanding fiber-optic networks, construction site monitoring, and assessing the condition of rails and roads. The Gas and Process Technology unit contributes innovations including sensors for early fire detection and for gas pipeline monitoring, while the Thermal Energy Converters unit develops caloric heat pumps for a sustainable heat supply, for example. Meanwhile, in the Production Control unit, we work on areas including straightness measurement for essential building materials such as rods, bars and beams.

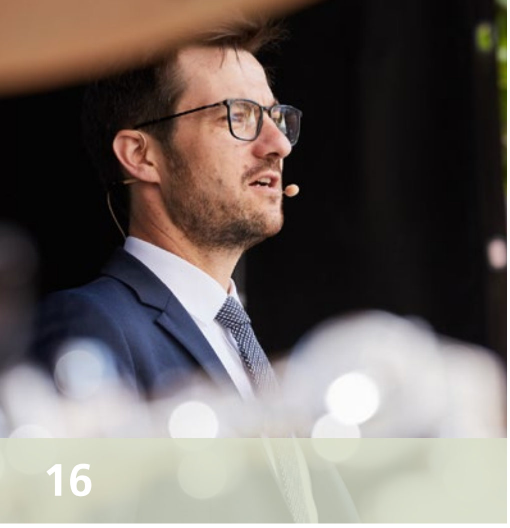
Our new building will allow us to produce even better results across all of our business units. We look forward to putting our expertise and our new technical facilities to good use in further exciting research and development projects — perhaps including yours.

I very much hope you enjoy browsing through our annual report and discovering our innovations.

Yours,

Karsten Buse

Prof Dr Karsten Buse, Executive Director.



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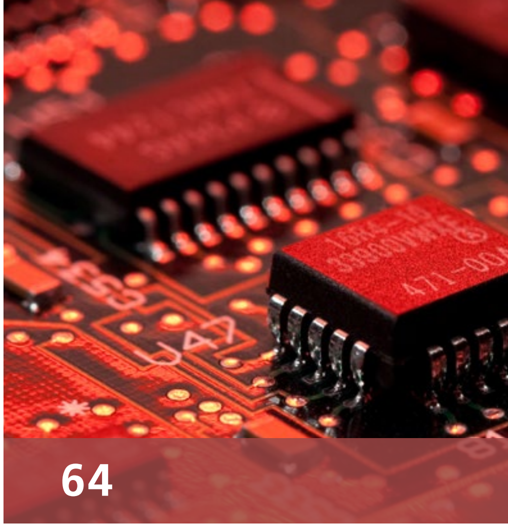
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MANAGEMENT

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Prof Dr Karsten Buse

Deputy Director
Dr Daniel Carl

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Holger Kock

Research
Dr Rosita Sowade

Organizational Development
Dr Heinrich Stülpnagel

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Anneliese Zwölfer

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Head of Technical Services
Clemens Faller

Mechanics and Construction
Thomas Hinrichs

Facility Management
Clemens Faller

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Head of Department
Dr Daniel Carl

Optical Surface Analytics
Dr Albrecht Brandenburg

Inline Vision Systems
Dr Tobias Schmid-Schirling

Geometrical Inline Measurement Systems
Dr Alexander Bertz

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Head of Department
Prof Dr Alexander Reiterer

Airborne and Underwater Scanning
Simon Stemmler

Smart Data Visualization
Prof Christoph Müller

Mobile Terrestrial Scanning
Prof Dr Alexander Reiterer

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Head of Department
Prof Dr Jürgen Wöllenstein

Integrated Sensor Systems
Dr Marie-Luise Bauersfeld

Spectroscopy and Process Analytics
Dr Raimund Brunner

Thermal Measurement Techniques and Systems
Martin Jägle

Nonlinear Optics and Quantum Sensing
Dr Frank Kühnemann

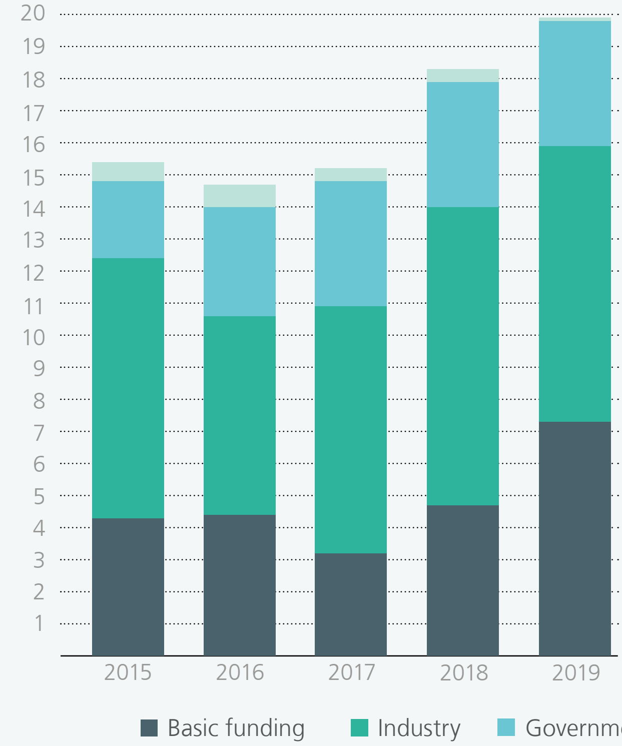
THERMAL ENERGY CONVERTERS page 58

Head of Department
Dr Olaf Schäfer-Welsen

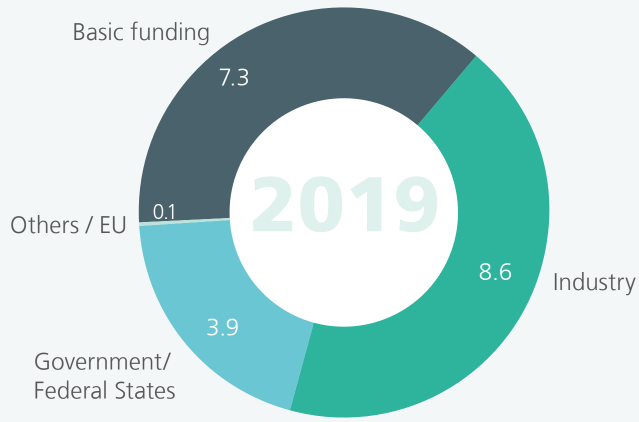
Caloric Systems
Dr Kilian Bartholomé

Thermoelectric Systems
Dr Olaf Schäfer-Welsen

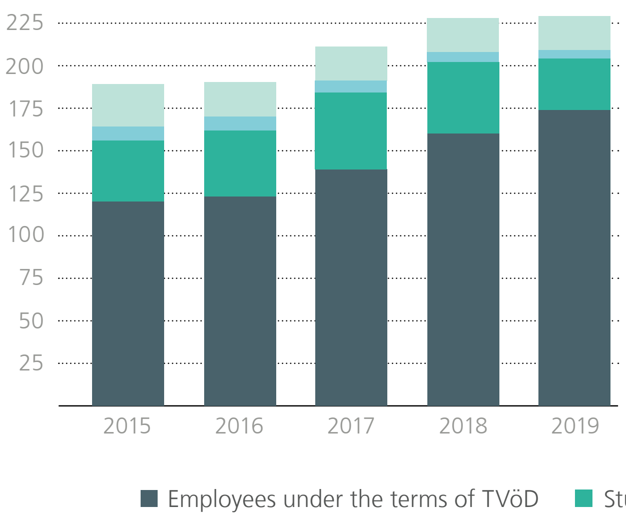
Operating budget in million euros



19.9 million
Operating budget



Personnel



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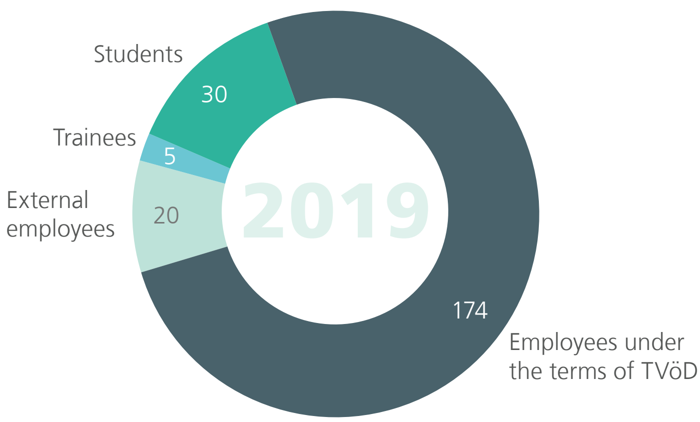
Employees



HIGH LEVEL OF EXCELLENCE UPHELD

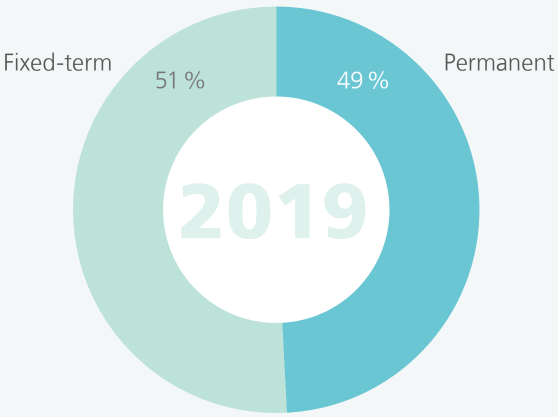
A survey of institute employees showed an extraordinarily high level of job satisfaction for the second time in a row.

LOGIT Effectory, the company responsible for conducting the survey, deemed the institute to be extremely fit in terms of strategy, with long-term employee dedication having risen slightly in comparison to 2015, demonstrating outstanding commitment to the institute. An amazing 99 percent of the staff are prepared to give their best for the success of the institute, 97 percent would recommend Fraunhofer IPM as an employer, 95 percent support the institute's goals and 90 percent of the staff have confidence in the managers. In all other questions, too, the values of Fraunhofer IPM are consistently well above the values of external benchmarks.

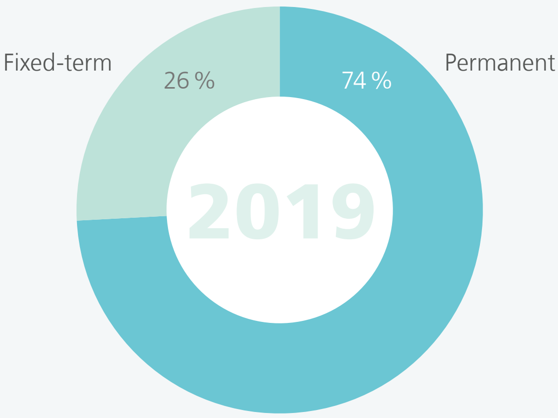
The 94-percent participation rate (160 employees) and over 500 open-ended comments provide evidence of how dedicated the employees are to the institute. In terms of room for improvement, employees pointed to project planning and the at times very high workload.

A Fraunhofer-wide survey was conducted back in 2015. Executive Director Karsten Buse opted to maintain a four-year cycle as originally planned, initiating the 2019 survey of his own accord.

Staff under the terms of the Collective Agreement for the Public Service TVöD: percentages of fixed-term/permanent contracts of employment



Scientifc

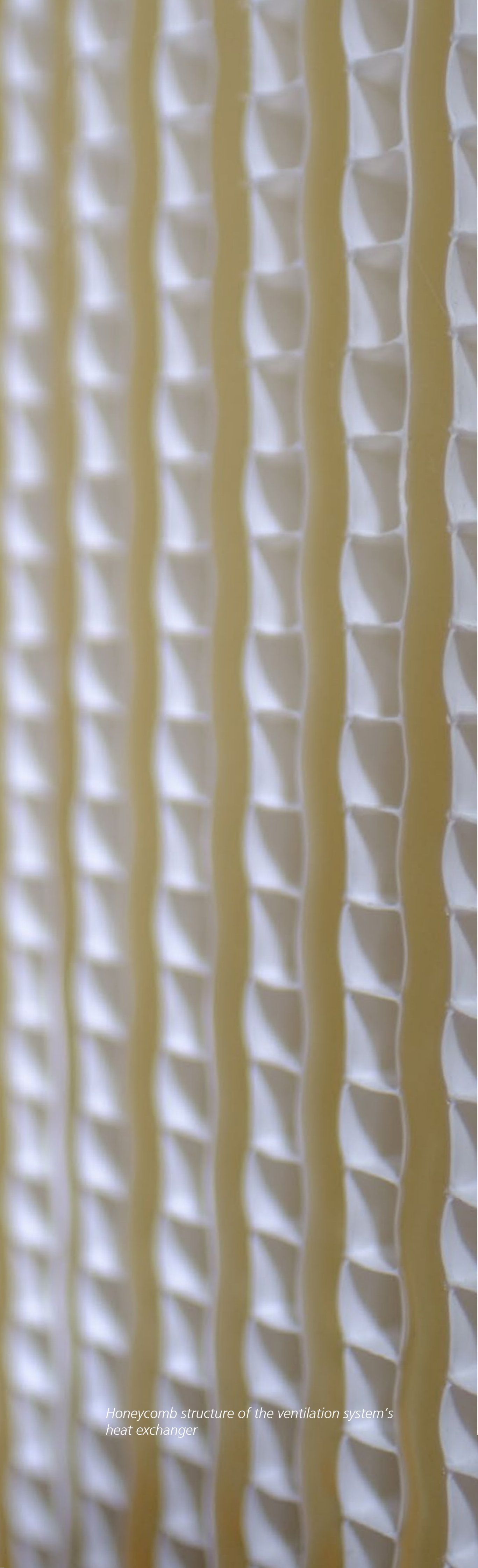


Non-scientific

THE ROLE OF SUSTAINABILITY IN OUR NEW BUILDING

Sustainability has taken on a central role in our new building – from the choice of materials used to the building's energy consumption, we have favored the most environmentally friendly and energy-efficient design possible.

The result is a modern building that in many respects goes beyond the usual standard in sustainability, featuring innovative technical installations.



Honeycomb structure of the ventilation system's heat exchanger

SMART USE OF INDUSTRIAL WASTE HEAT

The institute uses a low temperature system to source district heating from a neighboring industrial plant. District heating is typically sufficient for normal heating purposes, but it does reach its limit in certain situations, for instance on cold winter mornings when everyone arrives at work and turns up their heaters at around the same time.

District heating feed-in point with an output of 500 kW

In order to balance out – or shave – these peak loads, badenova-WÄRMEPLUS offers its customers smart load management, and Fraunhofer IPM is amongst the first district heating customers to take advantage of this service. When loads are not very high, e.g. at night, the building is used for thermal energy storage. It is slowly preheated using the available heat from district heating, optimizing heat flow and relieving the infrastructure.

INNOVATIVE VENTILATION SYSTEM

Adiabatic cooling is high-performing and energy efficient. This we already know. But particularly in situations where contaminated or corrosive exhaust air can form – for example in our research laboratories – it is important to take precautions. Damage caused by corrosion leads to leakages in the surface materials of heat exchangers, e.g. aluminum. Seven ventilation systems with countercurrent plate heat exchangers made of corrosion-resistant material were therefore chosen for installation in the new building.

The devices' large cross section slows down the airflow, thus enabling efficient heat transfer. Innovative technology is also at the center of adiabatic cooling in the system. In contrast to conventional evaporative coolers with downstream heat transfer, the system takes the water created through evaporation and sprays it directly onto the heat exchangers. This guarantees particularly effective heat absorption.

CHOICE OF MATERIALS

- Steel windows and sand-lime brick walls to reduce the use of aluminum and concrete, which require large quantities of energy during production
- Outer façade in durable ceramic
- Polymer-free thermal insulation
- Extensive greenery: roof garden for urban gardening, more than 3000 sqm of vegetation on the roof and façade, abundance of trees
- Approx. 13,000 sqm of flooring made of natural raw materials (wood and rubber)

LIGHTING

- Translucent doors and transom windows which let in natural light, meaning reduced artificial lighting
- Windows with opening transom sections for individual night-time cooling
- Artificial lighting provided by energy-efficient LED lights with motion sensor technology

ENERGY, HEATING AND COOLING

- Triple-glazed windows with sun protection coating
- Groundwater-based thermo-active building system which enables 380 kW of carbon-free building and process cooling
- Photovoltaic installation with 30 kWp
- Ten charging stations for electric vehicles

TECHNICAL EQUIPMENT

With a usable floor area of around 7500 sqm, the new building offers a comfortable, modern working environment in addition to excellent structural and technical conditions for our research.

- Two specialist technical facilities with a ceiling height of 9 meters
- 500-sqm workshop
- Two state-of-the-art gas measurement laboratories
- 400-sqm clean laboratory with working environment similar to cleanroom conditions: low energy requirements and costs, in part due to low air volumes and lack of drop ceilings
- Excellent technical laboratory resources: high efficiency and cost-effectiveness thanks to a well-controlled working environment with regard to temperature, cleanliness and supply systems
- Generous event space with room for up to 250 people

Examples of new large-scale equipment

- Coordinate measuring machine
- Micro-CT
- Magnetically shielded room (MSR)

LARGE-SCALE PROJECTS 2019

A total of thirteen research projects, in which Fraunhofer IPM is involved with more than one million euros each, were carried out by our scientists in 2019. With ElKaWe, Fraunhofer IPM took over the coordination of a Fraunhofer lighthouse project for the first time.

MagCon Magnetocalorics: Development of coolant-free, highly efficient heat pumps for heating and cooling
Project duration: 2/1/2016–12/31/2019
Funding: Fraunhofer-Gesellschaft

Freifall 100 percent quality testing of semi-finished parts by geometry and surface analysis in free fall
Project duration: 4/1/2017–9/30/2020
Funding: Fraunhofer-Gesellschaft

TOXIG Color change based sensors for toxic gas detection
Project duration: 3/1/2017–8/31/2020
Funding: Fraunhofer-Gesellschaft

MagMed Development of a coolant-free, efficient cooling technology, sub-project: System development and measurement technology
Project duration: 6/1/2017–5/31/2020
Funding: BMWi, project-executing organization: Forschungszentrum Jülich GmbH

eHarsh Sensor systems for extremely harsh environments
Project duration: 7/1/2017–6/30/2020
Funding: Fraunhofer-Gesellschaft (Lighthouse project)

QUILT Quantum methods for advanced imaging solutions
Project duration: 9/1/2017–6/30/2021
Funding: Fraunhofer-Gesellschaft (Lighthouse project)

FLuMEMS MEMS based catalytic thermal sensors for gas and liquid detection
Project duration: 4/1/2018–3/31/2021
Funding: Fraunhofer-Gesellschaft

MultiVIS Visualization of multi-dimensional data
Cooperation with Furtwangen University HFU
Project duration: 7/1/2018–12/31/2023
Funding: Fraunhofer-Gesellschaft

Elasto-Cool Elastocalorics: Development of highly efficient heat pumps for cooling and heating without the need for harmful coolants
Project duration: 8/1/2018–7/1/2021
Funding: BMBF, project-executing organization: VDI/VDE Innovation und Technik GmbH

ISLAS Intracavity laser spectroscopy for highly sensitive trace gas detection
Project duration: 3/1/2019–2/28/2022
Funding: Fraunhofer-Gesellschaft

QMag Development of two complementary quantum magnetometers to measure smallest magnetic fields with high resolution and high sensitivity at room temperature
Project duration: 3/21/2019–3/31/2024
Funding: Fraunhofer-Gesellschaft (Lighthouse project)

LaserBeat Impact hammer test using light: non-contact, extensive inspection of tunnels based on laser-induced structure-borne sound
Project duration: 4/1/2019 – 3/31/2022
Funding: Fraunhofer-Gesellschaft (WISA)

ElKaWe Electrocaloric heat pumps
Project duration: 10/1/2019 – 9/30/2023
Funding: Fraunhofer-Gesellschaft (Lighthouse project)

> The members of our advisory board provide the institute with strategic advice, not only during its annual meeting but also in our day-to-day business.

PROFESSORSHIPS AT UNIVERSITIES AND UNIVERSITIES OF APPLIED SCIENCES

Fraunhofer IPM maintains connections with the University of Freiburg in the form of three associated professorships and two lectureships. Through the close university connection, we can draw on the latest results from basic research in our project work. Since 2019, the institute has also been cooperating with the Furtwangen University of Applied Sciences (HFU) as part of the Fraunhofer-University Cooperation Program.

UNIVERSITY OF FREIBURG

Department of Microsystems Engineering – IMTEK

Laboratory for Optical Systems
Prof Dr Karsten Buse
www.imtek.de/laboratories/optical-systems

Research foci
- Nonlinear optical materials
- Optical whispering gallery resonators
- Miniature solid-state lasers
- Optical frequency converters (optical parametric oscillators OPO)
- Frequency combs
- Fast tuning of laser frequencies
- Integrated optics

Laboratory for Gas Sensors
Prof Dr Jürgen Wöllenstein
www.imtek.de/laboratories/thin-film-gassensors

Research foci
- Micro structured gas sensors
- Micro structured IR emitters for the mid infrared spectral range
- Laser spectroscopy
- Compact optical gas measuring systems
- Photoacoustics
- Catalytic sensors for flammable gases
- Systems integration

Department of Sustainable Systems Engineering – INATECH

Chair for Monitoring of Large-Scale Structures
Prof Dr Alexander Reiterer
www.inatech.de/alexander-reiterer

Research foci
- Inspection and monitoring of artificial and natural objects
- Development and implementation of innovative sensor concepts based on laser scanners and cameras
- Data analysis and interpretation with a focus on linkages to influence parameters, causative forces and changes measured
- Development and implementation of complete system chains – from data acquisition to data evaluation

"Each year is better than the last. It's a fantastic experience, a real highlight of our annual calendars."
Gerhard Kleinpeter

FURTWANGEN UNIVERSITY

Faculty of Digital Media

Professorship of Computer Graphics
Prof Christoph Müller

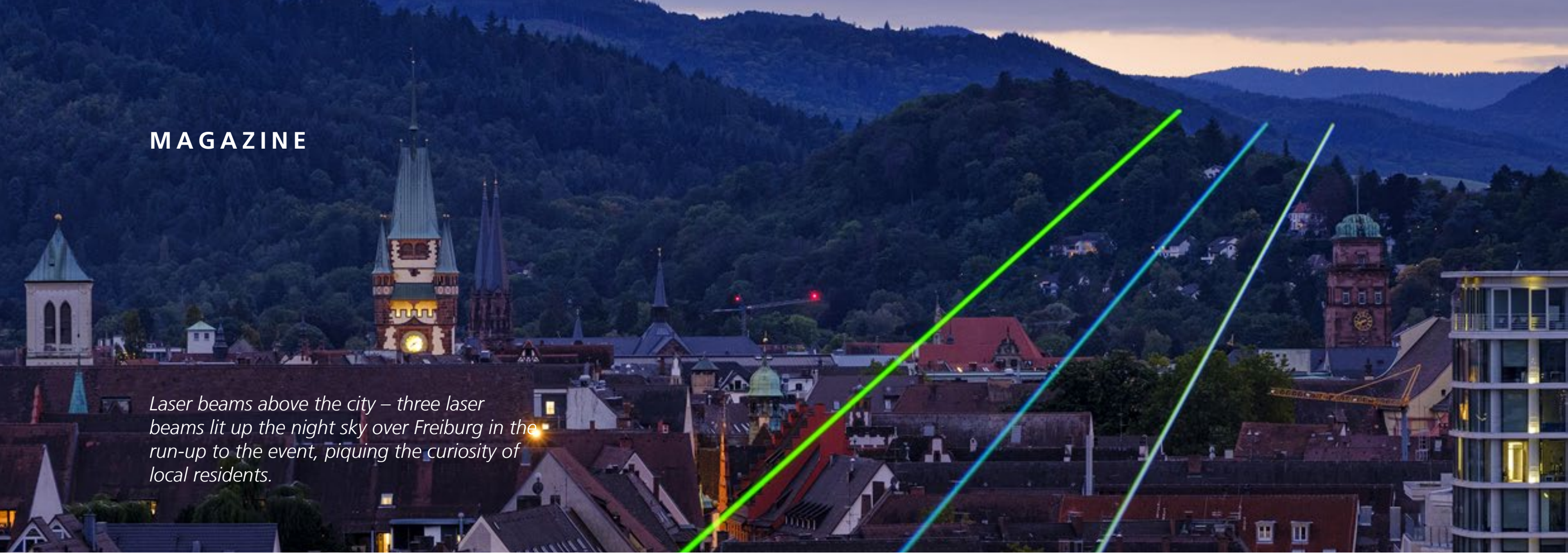
https://www.hs-furtwangen.de/en/faculties/digital-media

Research foci

- Real-time 3D visualization for industrial and medical applications
- Interactive visualization solutions for measuring technology
- Photorealism in real-time computer graphics
- Software engineering in 3D computer graphics
- Synthetic training data for AI-based image classification

OUR ADVISORY BOARD

A distinguished and dedicated board of trustees advises and supports the institute in strategic issues and decisions for the future.



Laser beams above the city – three laser beams lit up the night sky over Freiburg in the run-up to the event, piquing the curiosity of local residents.

FREIBURG CELEBRATES 70 YEARS OF FRAUNHOFER

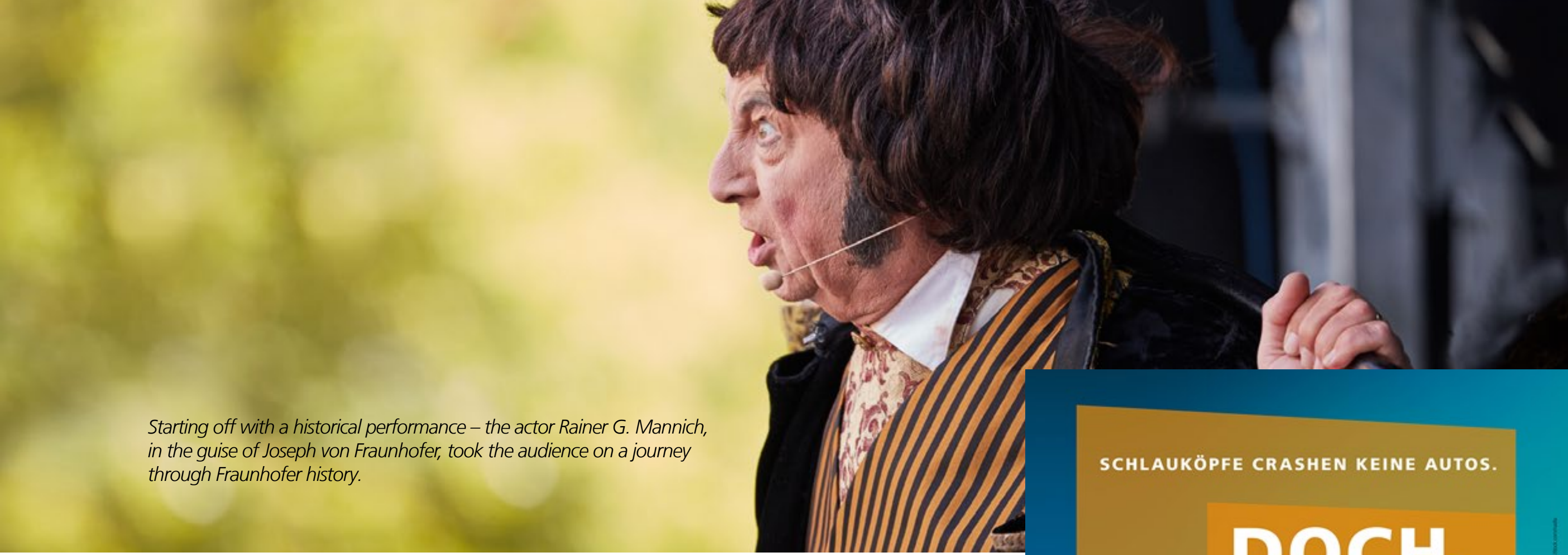
The five Freiburg Fraunhofer institutes organized a very special celebration in the city center on September 28 to mark the Fraunhofer-Gesellschaft's 70th anniversary.

The week beforehand, three laser beams lit up the night sky above Freiburg to announce the event. On the day itself, proceedings centered around the university courtyard, with institute staff as well as the general public invited to attend. More than 5000 people took up the invitation and enjoyed a varied and exciting program with talks, interactive experiments, live music, a laser show, and an escape game.

The actor Rainer G. Mannich, in the guise of Joseph von Fraunhofer, took the audience on a journey back in time through the history of Fraunhofer research. Scientists from the Freiburg Fraunhofer Institutes gave accessible presentations of their research topics – from crash research using x-ray technology, to caloric cooling systems and optimized power electronics, to innovations in photovoltaic coatings.

Two heads are better than one – students worked together to find a way out of the escape room.

"The university and Fraunhofer have a key role to play in implementing Freiburg's ambitious sustainability goals. The Fraunhofer-Gesellschaft is one of our city's largest employers and attracts world-class research to the area," said Mayor Martin Horn at the opening ceremony.



Starting off with a historical performance – the actor Rainer G. Mannich, in the guise of Joseph von Fraunhofer, took the audience on a journey through Fraunhofer history.

Fraunhofer proves misconceptions wrong day in, day out – a poster series based on the Fraunhofer motto "Does work" announced the topics to be explored by the individual Freiburg institutes.

A range of themed exhibit tents offered attendees the opportunity to learn more about the topics of sensors and data, materials and functions, light and outer space, and mobility and sustainability. For children, there was a varied program with interactive experiments, craft activities, and face painting. Also popular was the escape game for students, which required teamwork and collaborative problem-solving.

The daytime events closed with a spectacular laser show but the guests continued to celebrate late into the night with cocktails, a DJ, and bands. The Freiburg festival was one of the largest events held across Germany to celebrate the anniversary of the Fraunhofer-Gesellschaft and proved extremely popular with local residents.

Celebratory spirit at Platz der Weißen Rose – the courtyard hosted the evening's entertainment, with a DJ as well as bands including a number of Fraunhofer musicians.

More than 5000 people attended the Fraunhofer anniversary festival in Freiburg and celebrated into the night.

LAUNCH OF TWO FRAUNHOFER LIGHTHOUSE PROJECTS

Fraunhofer IPM is involved in ElKaWe and QMag, two lighthouse projects that launched in 2019.

For the project "Quantum Magnetometry" (QMag), six Fraunhofer institutes are working together to develop quantum magnetometers for industrial applications. These magnetometers are designed to provide images of extremely small magnetic fields with a never-before-seen spatial resolution and unprecedented sensitivity at room temperature. The research centers on two complementary systems in which a scanning probe quantum magnetometer is used for nanoelectronic applications. Research at Fraunhofer IPM focuses on novel applications for optically pumped magnetometers (OPM). These extremely sensitive sensors are intended to be applied in the area of low field nuclear magnetic resonance, or low field NMR, for chemical process analytics and materials testing. The QMag project, coordinated by the Fraunhofer Institute for Applied Solid State Physics IAF, has received ten million euros in funding and will wrap up in 2024.

The "Electrocaloric heat pumps" (ElKaWe) project has received eight million euros in funding to find an alternative to compressor-based heat pumps. As part of the project, six Fraunhofer institutes led by Fraunhofer IPM are working to develop a prototype of an electrocaloric heat pump within the next four years. The core of the team's work entails the design of the materials and system based on a novel systems approach patented by Fraunhofer IPM. This approach involves the use of a thermal diode for facilitating heat transfer through a combination of vaporization and condensation of an innocuous fluid in heat pipes. Electrocaloric polymer-based materials, coatings, and a special electric control element are also in development. The highly efficient electrocaloric heat pumps are intended to be used for both heating and hot water in buildings as well as in industrial cooling technology, vehicle air conditioning systems, server and control cabinet cooling, and laboratory refrigerators.

^ As part of the ElKaWe lighthouse project, six Fraunhofer institutes under the direction of Fraunhofer IPM are cooperating to develop efficient electrocaloric heat pumps.
www.elkawe.org

< In the context of the QMag lighthouse project, Fraunhofer IPM explores novel applications for highly sensitive optically pumped magnetometers.
www.qmag.fraunhofer.de

International quantum physics meeting: More than 40 researchers from Germany, elsewhere in Europe, the USA, and Singapore came together at the German Physical Society's Physikzentrum in Bad Honnef to take part in the "Sensing with Quantum Light" symposium.

INTERNATIONAL SYMPOSIUM ON QUANTUM SENSOR TECHNOLOGY

In September 2019, Fraunhofer IPM joined together with Fraunhofer IOF to organize the workshop "Sensing with Quantum Light".

The event was held at the Physikzentrum Bad Honnef and brought together both renowned and early career researchers in the field of quantum sensor technology for discussions of their work. Guided by the question "How can photonic quantum states be used to expand the frontiers of conventional measurement technology used in imaging, spectroscopy and analytics?", contributions addressed everything from physical principles to the assessment of technology in industry.

Infrared measurement technology using nonlinear interferometers represented one focal point, with contributions from Berlin, Singapore, and the consortium of the Fraunhofer lighthouse project "Quantum methods for advanced imaging solutions" (QUILT). A report on the first interferometer in the terahertz range and a quantum FTIR developed by Fraunhofer IPM were among the highlights of the symposium. As part of QUILT, the Fraunhofer-Gesellschaft provided financial support for the event. The QUILT project involves research on new methods in quantum sensor technology and quantum imaging which has been conducted at six Fraunhofer institutes since 2017.

TRIPLE THE NETWORKING OPPORTUNITIES – OUR WORKSHOPS IN 2019

With three workshops in the fields of thermoelectrics, caloric systems, and gas sensor technology, attracting many international attendees, Fraunhofer IPM once again offered a major platform for networking, knowledge sharing, and innovation in 2019.

Between 60 and 70 scientists and industry experts attended each of the three workshops to explore the latest technology in the individual fields.

The first event was the inaugural industry workshop on thermoelectrics, held in March in cooperation with the German Thermoelectric Society. Expert presentations and an accompanying exhibition looked at thermoelectric materials and systems as well as researchers' efforts to refine Peltier technology and thermoelectric generators. The discussions focused on ways to open up new applications, including industrial waste heat utilization and energy harvesting.

A few days later, calorics experts came together to share their knowledge around solid-state systems for heating and cooling at the second Caloric Systems Workshop. This event was held in cooperation with the German Society of Refrigeration and Air Conditioning as well as Innovationsnetzwerk Magnetokalorik (Magnetocalorics Innovation Network), which is funded by the federal program ZIM for small and medium-sized enterprises. The whole spectrum of caloric technologies was covered with talks on magnetocalorics, elastocalorics, and electrocalorics. An exhibition highlighted the major disruptive potential of these technologies, displaying no fewer than four operative caloric systems for the first time.

The third event on the agenda, the Gas Sensor Workshop, was held in October. Experts in gas measurement technology met here for the eighth time to share knowledge and ideas via presentations and an exhibition. The event focused on topics including environmental measurement technology as well as gas detection in industrial applications. Fraunhofer IPM presented the project GAS-O-CHROM, which involves the development of optical gas sensors for early fire detection.

The three workshops are held every other year.

Prof Dr Alexander Reiterer (2nd from left), Dr Katharina Wäschle (center), and Dominik Störk (2nd from right) were presented with the Fraunhofer Prize by jury member Prof Dr Gerd Müller (left) and the Fraunhofer President Prof Dr Reimund Neugebauer (right).

JOSEPH VON FRAUNHOFER PRIZE 2019

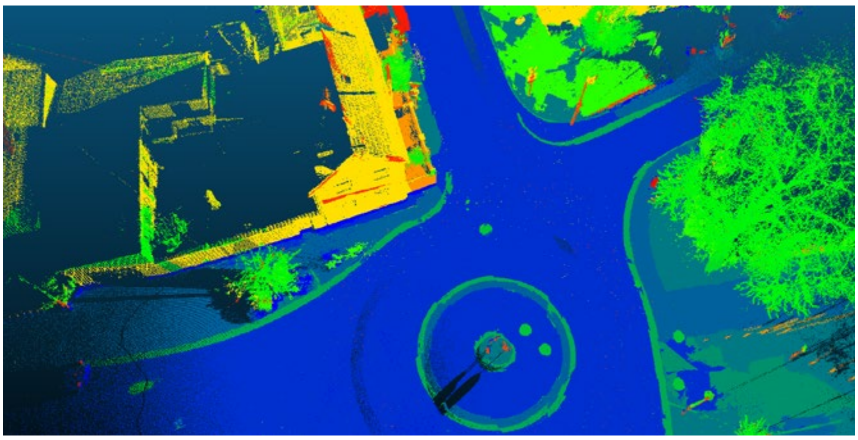
Fraunhofer IPM receives the Joseph von Fraunhofer Prize for the fourth time in seven years

In 2019, the institute won the Fraunhofer Prize in recognition of a software tool for creating digital planning data to support the expansion of fiber-optic networks. Deutsche Telekom is the first company to use the tool, which will help make its planning process much more efficient. It will now take days rather than weeks to complete the route planning for a town. The company will be able to rely on its own 2D and 3D digital measurement data instead of the land registry plans, aerial photographs, and manually collected data that it currently uses. The data interpretation is fully automated thanks to a smart algorithm based on machine learning techniques. The team behind the tool trained a neuronal network to independently identify 30 different classes of objects, such as vehicles, curbs, manhole covers, signs, trees, and hedges. To make this possible, they built up their own training dataset with around one hundred thousand example images covering different objects, seasons, and weather and lighting conditions. The tool is part of a process chain developed at the institute which covers the generation of geo-mapping data using optical measurement technology as well as data processing and fully automated data interpretation.

NEW CUSTOMER MAKES MILLION-EURO ORDER

Thanks to an industry commission worth 1.2 million euros, the research team headed by Prof Dr Alexander Reiterer once again won the Fraunhofer-Gesellschaft's award for customer acquisition of the month in November.

The Fraunhofer IPM team had already proved especially successful at closing major industry deals in recent years. The latest new order was from DeTeFleetServices GmbH, a subsidiary of Deutsche Telekom AG. The team was commissioned to develop two fully equipped mobile urban mapping vehicles. Each vehicle is to be fitted with a 3D laser scanner and four cameras to document the entire street space, providing a solid foundation of planning data for the expansion of fiber-optic networks. “Best customer acquisition” is an internal Fraunhofer ranking which identifies the largest deal closed with a private company each month.



The mapping vehicles use optical measurement technology to provide data in the form of 3D point clouds as a basis for efficient route planning.

Enjoying the trip to Fraunhofer IPM's new building.

A CYCLE TOUR WITH MAYOR MARTIN HORN

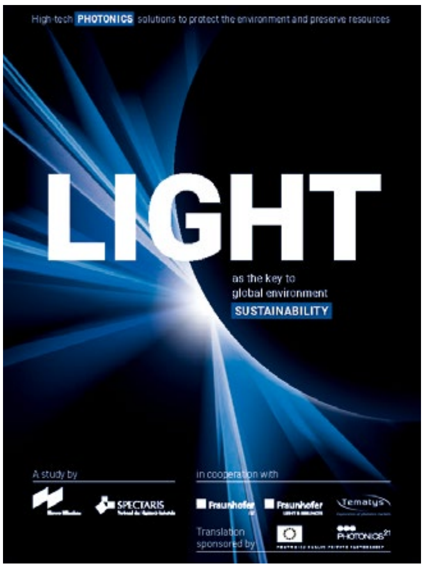
On June 12, Freiburg's mayor, Martin Horn, took part in a cycle tour to visit all five Fraunhofer institutes in Freiburg.
It was a glorious summer's day as the mayor joined the institutes' directors on a trip across the city to learn more about research in one of Germany's largest Fraunhofer hubs. The first stop was Fraunhofer EMI, where the cyclists were presented with drinks holders for their bicycles from the 3D printing laboratory and enjoyed some lupin ice cream – a Fraunhofer invention. Thoroughly refreshed, the group then continued on to the other institutes. Mayor Horn inspected the progress of construction work on Fraunhofer IPM's new building and also took a look at a range of measurement systems which had been brought over specially for the occasion.
He was highly impressed, describing the Fraunhofer institutes as "an important driving force for an ambitious sustainability policy" in the scientific and economic hub that is Freiburg.

KARSTEN BUSE HEADS FRAUNHOFER GROUP FOR LIGHT & SURFACES

The Fraunhofer Senate appointed Prof Karsten Buse as Chair of the Fraunhofer Group for Light & Surfaces as of October 1, 2019.
He had previously been unanimously elected to this position by the group's members. Buse took over the position from Prof Reinhart Poprawe, Director of the Fraunhofer Institute for Laser Technology ILT. The new position also entails Buse's appointment to the twelve-member Fraunhofer Presidential Council. The Fraunhofer Group for Light & Surfaces brings together expertise from six Fraunhofer institutes in the areas of laser, optical, measurement, and coating technology.

STUDY ON GREEN PHOTONICS

Fraunhofer IPM was involved in a study on "green photonics", which highlighted the important role that optical technologies play in achieving climate protection goals.
Published as a 100-page paper entitled "Light as the Key to Global Ecological Sustainability", the study illustrates how photonics contributes to the protection of our environment and resources. According to the study, photonics already prevents more than one billion tons of carbon dioxide emissions today, and this number is set to increase to three billion tons by 2030. The publication demonstrates the technology's vast potential for protecting the environment. As part of the study, Fraunhofer IPM presents 3D laser scanners for maintaining infrastructure, laser spectroscopy for measuring exhaust gas, and digital holography for quality control in industrial production.
The paper was published by the German Industry Association for Optics, Photonics, Analytical and Medical Technology – SPECTARIS in cooperation with Messe München, Fraunhofer ILT, and the Fraunhofer Group for Light & Surfaces.



www.spectaris.de/verband/themen/greenphotonics/

BUDDING RESEARCHERS PAY A VISIT TO THE INSTITUTE

Students from Freiburg's ANGELL Akademie visited Fraunhofer IPM not once but twice this year.

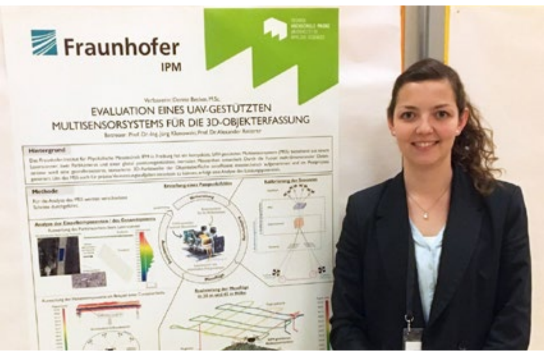
A seventh-grade class enjoyed a hands-on introduction to the different areas of research at the institute during a science- and technology-themed field trip in April. The students circulated around six different stations admiring laser scanners for measuring railway tracks, image processing systems for production control, and innovative cooling systems that eliminate the need for harmful refrigerants. They were also able to touch, test and explore many different parts and systems themselves.

For the school's Green Campus Day on November 15, students from grades 10 through 12 with an interest in the environment were invited to visit the institute. This event was organized by the foundation ANGELL Schulstiftung to give the students a closer look at different aspects of sustainability. One group visited Fraunhofer IPM to learn about technologies and ideas in the fight against climate change. The focus was on the institute's new building, where the students were able to see sustainable materials and building techniques in use by attending a guided tour and took the chance of estimating CO_2 savings.

AWARD-WINNING MASTER'S THESIS

The company ÖbVI Petersen awarded a prize to Denise Becker, a former Master's student with Fraunhofer IPM, for the poster presentation of her thesis.

Denise Becker worked with Fraunhofer IPM until September 2019 while completing her Master's. For her thesis, she evaluated a UAV-assisted multi-sensor system developed at the institute for mapping objects from the air. Becker was presented with the annual ÖbVI Petersen prize in December 2019 at a seminar on terrestrial laser scanning held by DVW e.V. German Association for Geodesy, Geoinformation and Land Management. ÖbVI is the German abbreviation for "publicly appointed surveyor". In Germany, these professionals perform official tasks on behalf of the state and are thus subject to state oversight. Denise Becker's thesis was jointly supervised by Prof Dr Jörg Klonowski at Mainz University of Applied Sciences and Prof Dr Alexander Reiterer at Fraunhofer IPM.



Denise Becker won the ÖbVI Petersen prize for her Master's thesis.

FEMALE CAREER

Four female staff members from Fraunhofer IPM take part in the Fraunhofer-Gesellschaft's TALENTA career program.

PhD students Nora Bachmann, Laura Engel, Chiara Lindner, and Lena Maria Maier are supported as part of TALENTA *start*. The program supports female scientists at an early stage in their career. In addition to qualification offers, the "career time" program aims to provide the necessary freedom for doctoral studies or professional development. Around 30 TALENTA start places are awarded annually.

Lena Maria Maier is conducting research on caloric systems in her doctoral thesis. "Thanks to TALENTA, I was able to attend some additional training courses and I am now in regular contact with other female doctoral students."

< Seventh graders were fascinated by the laser scanners and other equipment.

THREE QUESTIONS FOR… CLEMENS FALLER

Clemens Faller has led the Technical Services Department at Fraunhofer IPM since 2014. The department, which also houses the mechanical workshop, is staffed by 20 employees who ensure a seamless operation. Faller has over 30 years of experience in erecting and operating research units, most recently as the Technical Director at the Fraunhofer Institute for Solar Energy Systems ISE.

Clemens Faller at the groundbreaking ceremony of the institute's new building in 2017. As the Technical Director, Clemens Faller ensures that technical support runs smoothly – in the building, in the labs, and in the workshop. He has been a key figure in organizing and steering the planning and construction of the institute's new building.

Mr. Faller, the institute's new building is being constructed under your direction with an investment of about 45 million euros. What were the greatest challenges in this project? Have you lived through moments of desperation?

The greatest challenge was finding out what was required for the essential functionality of the laboratories. In order to provide a building infrastructure that ultimately works just the way we need it to, I needed to grasp exactly what my colleagues were looking for. The worst moments in the construction process are always the ones where we realize that not everything was taken into consideration during the planning phase, or that essential functions and conditions were overlooked. Plus in this project, severe water damage took a huge toll in terms of time and budget, and we had to dismiss a few companies due to inadequate performance. On top of that, another company became insolvent right when we urgently needed its services.

What does a scientific institution require in terms of building technology?

A research institution requires a lot in the way of building technology, as this technology has to be able to accommodate all laboratory operations. My personal goal – and that of the institute – was to achieve precisely that, while also minimizing our environmental impact as much as possible with the funds we were provided, which means achieving the highest possible efficiency.

You have decades of experience in technical building management. What has remained constant in this time and what has undergone the most change?

Building technology has developed at a staggering pace in recent years. Unsurprisingly, it has also taken a big step in the direction of digitalization – a process that has already been underway for about ten years now, but is just now becoming very involved. The technology for building management is becoming smarter and more connected.

> Boehringer Ingelheim microParts GmbH manufacturing facilities in Dortmund.

>> Dr Bastian Knabe (left) heads the Engineering Standards, Services and Innovations department. His colleague Dr Manuel Kemmler (right) is the Senior Project Manager.

"Getting down to business"

Several years ago, the pharmaceutical company Boehringer Ingelheim microParts GmbH achieved a technical innovation with its RESPIMAT® inhaler: It works without a propellant. The core element is a special micro-nozzle which atomizes the medication. Fraunhofer IPM was commissioned to develop an optical in-process inspection system to precisely control the quality of this microfluidic component during production. Dr Bastian Knabe and Dr Manuel Kemmler, the persons responsible for the project at Boehringer Ingelheim microParts GmbH, have discussed this innovation with us in detail.

How did you come to work with Fraunhofer IPM?
Kemmler: At the beginning of 2011, we opened a general inquiry with the Fraunhofer Vision Alliance regarding the direct quality control of a microfluidic component during production. Fraunhofer IPM offered a compelling solution.

How did you proceed?
Kemmler: Following the initial feasibility study on using autofluorescence to detect silicone, we really got down to business in the subsequent projects: We wanted to also be able to detect other component materials, various plastics, glass, and silicon. But there was nothing on the market for this. So Fraunhofer IPM developed systems for us that we now use to conduct quality controls in a three-shift cycle.
Knabe: Meanwhile, we have collaborated on many other projects together in a tremendous effort that spans our entire value chain. I think that Fraunhofer IPM knows our company in and out by now.

The RESPIMAT® inhaler: Boehringer Ingelheim microParts GmbH uses measurement systems from Fraunhofer IPM for automated quality assessment of key components.

What do you look for in a development partner?
Knabe: When we take complex problems that require customized solutions and add yet another element to them, that's where we need Fraunhofer IPM. The regulations governing medical device manufacturing require that inspection systems be put through their paces. In order to prove this, we rely on scientific methods: hypotheses, experiments, series of tests, etc. When statistic methods must be applied as a matter of principle and your partners are also scientists, it's easier to join forces and come up with the necessary tests relatively quickly. That's where I see the greatest advantage to working together with Fraunhofer IPM.

Boehringer Ingelheim microParts GmbH manufactures the RESPIMAT® product range in Dortmund. RESPIMAT® is a propellant-free pocket inhaler which has been available in a reusable format since 2019. With a production capacity of 45 million devices, the approximately 650 employees in Dortmund provide for the world market exclusively on behalf of Boehringer Ingelheim. The main working steps in production are the creation of the plastic parts via injection molding, the etching and separation of the nozzles, and the final assembly of the device including quality control.

What determines a project's success?

Knabe: The most important thing is that our project partner is truly interested in the problems at hand and in finding a solution. A deep understanding and commitment to a given development project – particularly when it is so complex – is critical, as is a sense of responsibility for the final result. Only then can a project succeed.

Is there something in particular that makes your collaboration with Fraunhofer IPM special?

Kemmler: If you are looking for a special, customized solution for your existing customized solution, there are few partners who compare to Fraunhofer IPM, particularly when it comes to image capturing and processing.

Knabe: Since we work so closely with each other, we also come into contact with other industry sectors via measurement technology. We leave joint meetings with a lot of food for thought. That's something unquantifiable that we can't get anywhere else on such an outstanding level.

To what extent is it worth investing in measurement technology?

Kemmler: You might think that new products only catch on if they're less expensive than what's already available on the market, but that's only true to a certain extent. In manufacturing medical products, quality plays a huge role. In general, a higher-quality product will cost more money.

Knabe: Amortization is an important variable, but not the only one. There are also projects that have been implemented without it. However, the projects that we've most recently conducted together with Fraunhofer IPM saw both amortization and an increase in quality.

What technological challenges do the pharmaceutical and medical technology industry face?

Knabe: I view sustainability as the most important topic. And I think it will continue to be very relevant in the industry moving forward. I also believe that the market will reward companies for improving sustainability. For instance, we have recently released a new version of our inhaler with precisely this vision in mind. The inhaler can now be reused, massively reducing its carbon footprint. Other manufacturers are becoming more concerned with hygiene. And this is another area where measurement technology comes into play: How can sterility be quickly verified using simple resources?

Kemmler: Another trend is that software is becoming increasingly important in measurement technology. These days, there's more and more talk about artificial intelligence. The question is: How can such software be validated in a regulated environment? Until now, validating the functionality of software has always required the existence of a viewable source code. In the world of neural networks, however, this doesn't exist. We have to find a different solution.

BUSINESS UNIT
PRODUCTION CONTROL

"We develop customized inspection systems for a changing production environment."

For production control, Fraunhofer IPM develops optical systems and imaging methods. The systems can be used to precisely inspect surfaces and measure complex 3D structures during production and thus to control processes. The systems measure fast and accurately so that small defects or impurities can be detected and classified in real time, even at high production speeds. Combined with (mark-free) individual component tracking, 100 percent real-time control and direct feedback into production is possible against the backdrop of the fourth industrial revolution.

A wide range of methods is used, including digital holography, infrared reflection spectroscopy and fluorescence methods, with fast, low-level image and data processing. The systems, optimized to meet customer specifications, are used in applications such as forming technology in the automotive industry and for quality assurance in medical products through to electronics production.

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Group **Optical Surface Analytics**

- Detection and classification of particulate impurities
- Analysis of filmic coatings and impurities
- Element analysis in complex multilayer systems

Group **Geometrical Inline Measurement Systems**

- High-precision measurement of functional surfaces at production speed
- Optical gearwheel measurement
- Dynamic deformation measurement

Group **Inline Vision Systems**

- Surface inspection shape measurements of semi-parts and components
- Inspection of long products
- Marker-free component identification

< Optical measurement systems detect even tiny defects on component surfaces.

GROUP **OPTICAL SURFACE ANALYTICS**

Dr Albrecht Brandenburg, P +49 761 8857-306, albrecht.brandenburg@ipm.fraunhofer.de

The research focus of the group is the development of turnkey devices for inspecting surfaces. We use various in-house developments based on fluorescence measurement techniques to check for contamination on surfaces and to inspect oil coatings and other surface coatings. We inspect both rollstock and complex components in production. The surfaces of components of any shape are fully scanned in free fall using a fluorescence measurement imaging technique that does not require any further handling of the components. To measure the geometry and analyze the composition of non-transparent coatings contactlessly, we rely on laser-induced breakdown spectroscopy, which is also used for monitoring laser machining processes. With shortwave infrared analysis, we use the spectral dependence of absorption and scattering properties to analyze materials. Our inline microscopy systems inspect the geometry and surfaces of micro-components at the rate of production with outstanding accuracy, for instance for medical devices. Our wealth of experience in system development covers optical units, image capturing, and image processing.

Group Manager: Dr Albrecht Brandenburg

FLUORESCENCE ANALYSIS FOR CLEANLINESS AND COATING INSPECTIONS

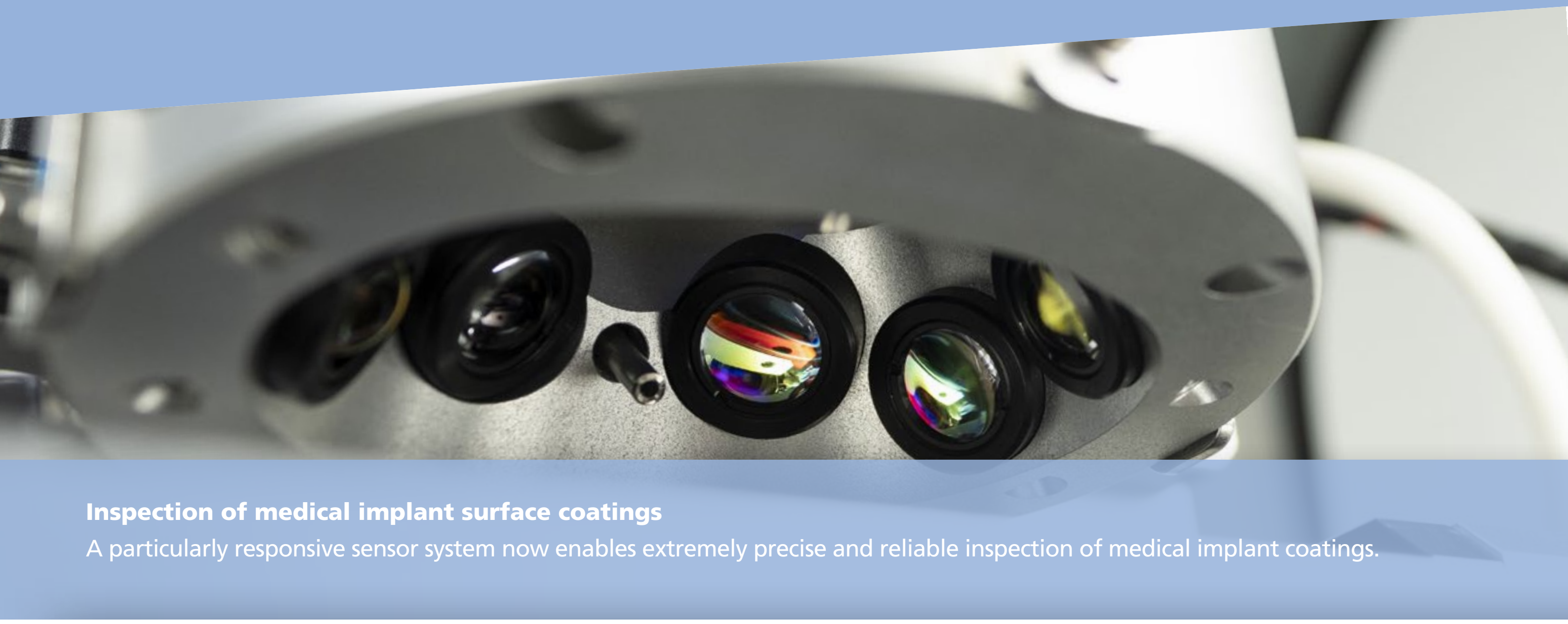
- Evaluation of position, form, and amount of film-like contamination at the rate of production
- Measurement of processing aids such as oils, greases, or cleaning agents (detection limit for standard oils: 0.01 g/m^2) as well as thin coatings using imaging techniques
- F-Camera: field of view covering several cm^2, 20-µm resolution
- F-Scanner: field of view covering several cm^2, 500-µm resolution
- F 360°: free fall system, 100-µm resolution

INLINE MICROSCOPY FOR HIGH-DEFINITION CHARACTERIZATION OF SMALL COMPONENTS

- Characterization of complex 3D microstructures
- Detection of structural defects, impurities, scratches, and incorrect external dimensions
- Repeatability of distance measurement down to the sub-micrometer
- Highly accurate measurement of component dimensions
- Cycle time of approx. one second

LASER-INDUCED BREAKDOWN SPECTROSCOPY FOR COATING ANALYSIS

- Non-contact surface material analysis
- Thickness measurement of micrometer-thin functional coatings
- Monitoring of laser structuring and laser cleaning processes
- Detection of coating components down to the ppm range



Inspection of medical implant surface coatings
A particularly responsive sensor system now enables extremely precise and reliable inspection of medical implant coatings.

Sensor differentiates metallic and non-metallic particles
A new type of sensor for inline particle detection which enables innovative image analysis has been developed in cooperation with an industrial partner. The sheen of metallic particles is used to differentiate between particles. The compact sensor can be placed directly on surfaces and communicates wirelessly with the control unit.

Strong presence at industry trade fairs
At the Control and parts2clean international trade fairs as well as the Automotive Engineering Expo, we presented our current research findings and products, including the inline particle detector and the F-Scanner.

BUSINESS UNIT PRODUCTION CONTROL

GROUP **INLINE VISION SYSTEMS**

Dr Tobias Schmid-Schirling, P +49 761 8857 - 281, tobias.schmid-schirling@ipm.fraunhofer.de

The group's research focus is on highly accurate customized inspection systems that inspect component surfaces down to the micrometer during production. The multi-camera systems inspect the components for compliance with quality criteria using fast, low-level image processing driven by state-of-the-art algorithms. Our inspection systems for quality control of sheeting and long products detect flaws in production at high feeding rates. A free-fall inspection system developed by the group enables us to completely inspect complex shaped components in a matter of seconds without further handling. At the same time, we utilize the image data of a component's surface microstructure to generate an individual digital fingerprint that is used for tracking. This marker-free Tracking & Tracing procedure is combined with individual inspection data to pave the way for the comprehensive digitalization of production processes in line with Industry 4.0.

Group Manager: Dr Tobias Schmid-Schirling

100 PERCENT CONTINUOUS MONITORING

- Surface monitoring of wires, cables, and bands as well as pipes, rods, and profiles
- In real time up to 30 m/s
- Inline defect detection down to 50 µm
- Automatic defect detection, classification, and documentation

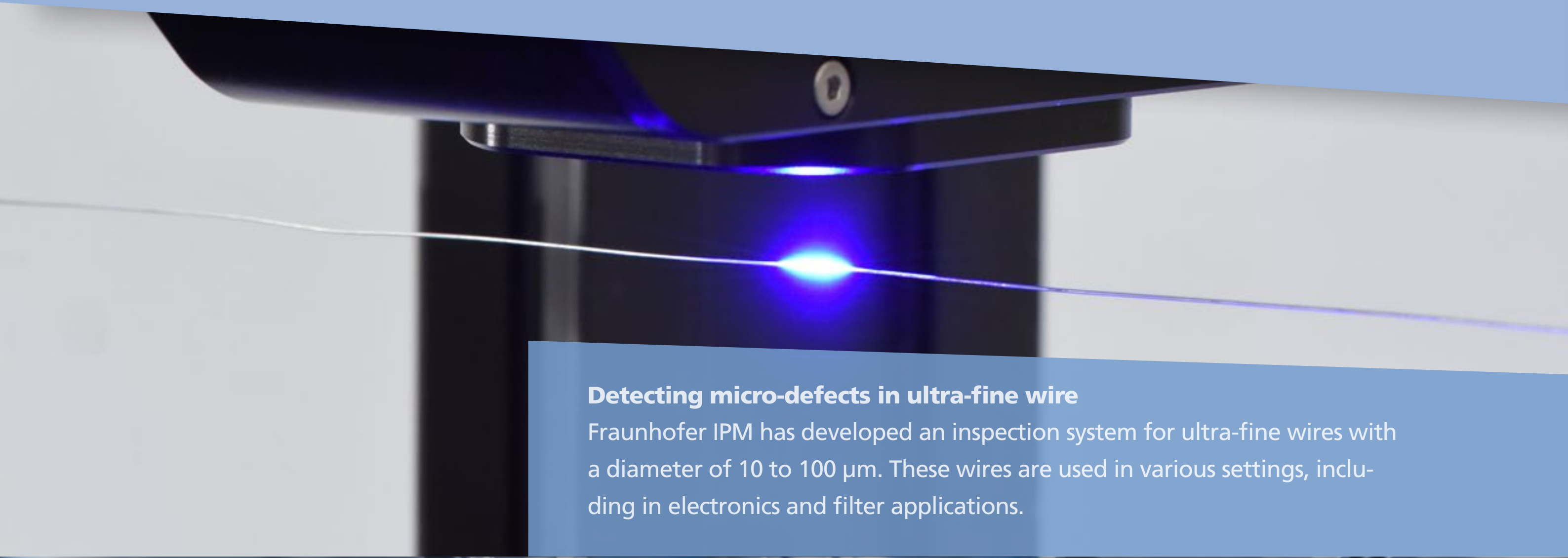
INSPECT 360°: COMPONENT INSPECTION IN FREE FALL

- Full inspection of the component surface for geometric defects and surface defects
- Inline inspection of different components with no need for specific handling or adjustment
- Defects larger than 100 µm detectable in one-second intervals

TRACK & TRACE FINGERPRINT: MARKER-FREE COMPONENT TRACING

- Reliable image-based tracing of mass-produced parts in batches of many millions
- Can withstand local surface damage and impurities
- Small signature IDs (of only a few kB) enable rapid identification at the rate of production

Sensor system enables marker-free tracking in the automobile industry
With pilot installations for tracking individual components via Track & Trace Fingerprint, Fraunhofer IPM has made it possible for various automobile industry customers to compare hundreds of thousands of components in their respective production environments.



Detecting micro-defects in ultra-fine wire
Fraunhofer IPM has developed an inspection system for ultra-fine wires with a diameter of 10 to 100 µm. These wires are used in various settings, including in electronics and filter applications.

Testing complex components in free fall
As part of a study on 3D-printed components for BMW, Fraunhofer IPM succeeded in demonstrating the operational readiness of a system developed specifically for testing complex components. The multi-camera system enables full contactless inspection of the texture and geometry of the components in free fall.

GROUP **GEOMETRICAL INLINE MEASUREMENT SYSTEMS**

Dr Alexander Bertz, P +49 761 8857 - 362, alexander.bertz@ipm.fraunhofer.de

The group's research focuses on developing measurement systems that perform contactless, high-precision inline measurements on the geometry and 3D surface structure of complex components, providing measurement data in real time. To do this, ultra modern optical measurement techniques, such as digital holography and speckle correlation, are combined with exceptionally fast evaluation procedures. This creates systems that, for the first time, are allowing gear geometries to be optically scanned in just a few seconds, workpieces to be measured directly in machine tools with the utmost precision, and the smallest stress-induced component deformations and cracks to be identified.

Group Manager: Dr Alexander Bertz

INLINE COMPONENT TESTING

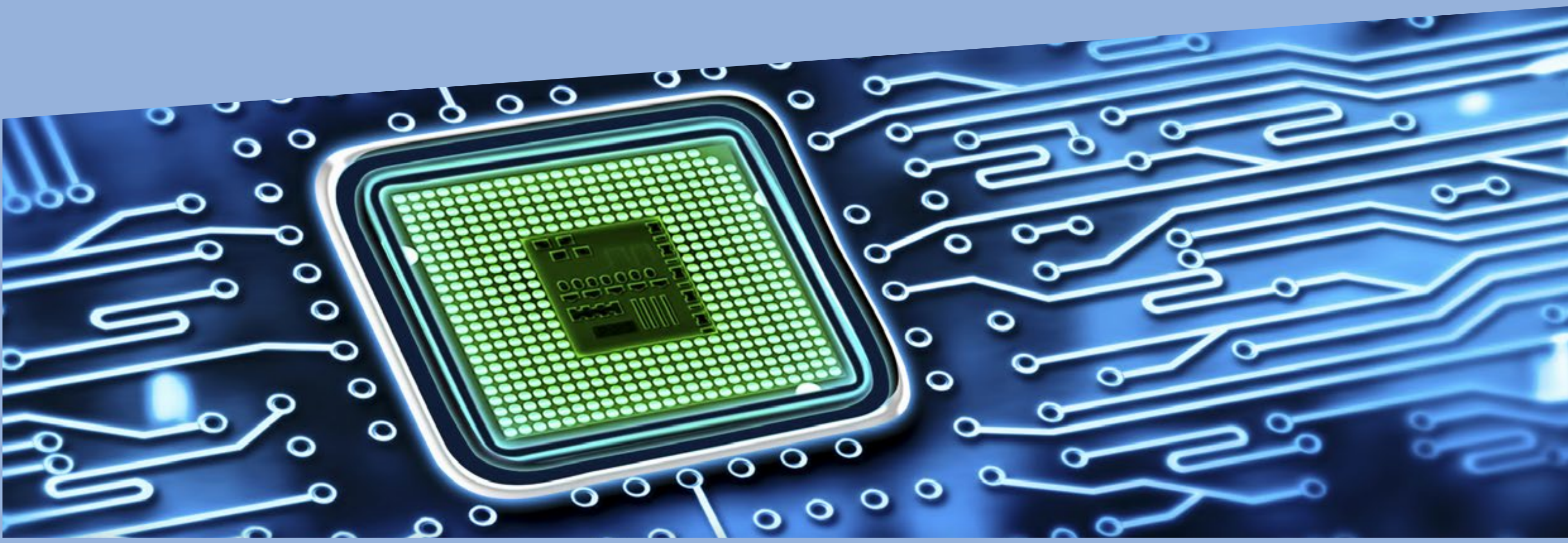
- Topography measurement of precision parts
- Measurement field size can be scaled to suit specific applications (currently available 15 × 15 mm² to 190 × 150 mm²)
- Measurement accuracy: axial below 0.2 µm, lateral depending on size of image field and camera option 3 µm to 30 µm
- Measurement time: below 0.1 s for 3D images with 10 mio. points
- Flexible working distance up to approx. 300 mm, mechanical focusing eliminated

GEAR MEASUREMENT

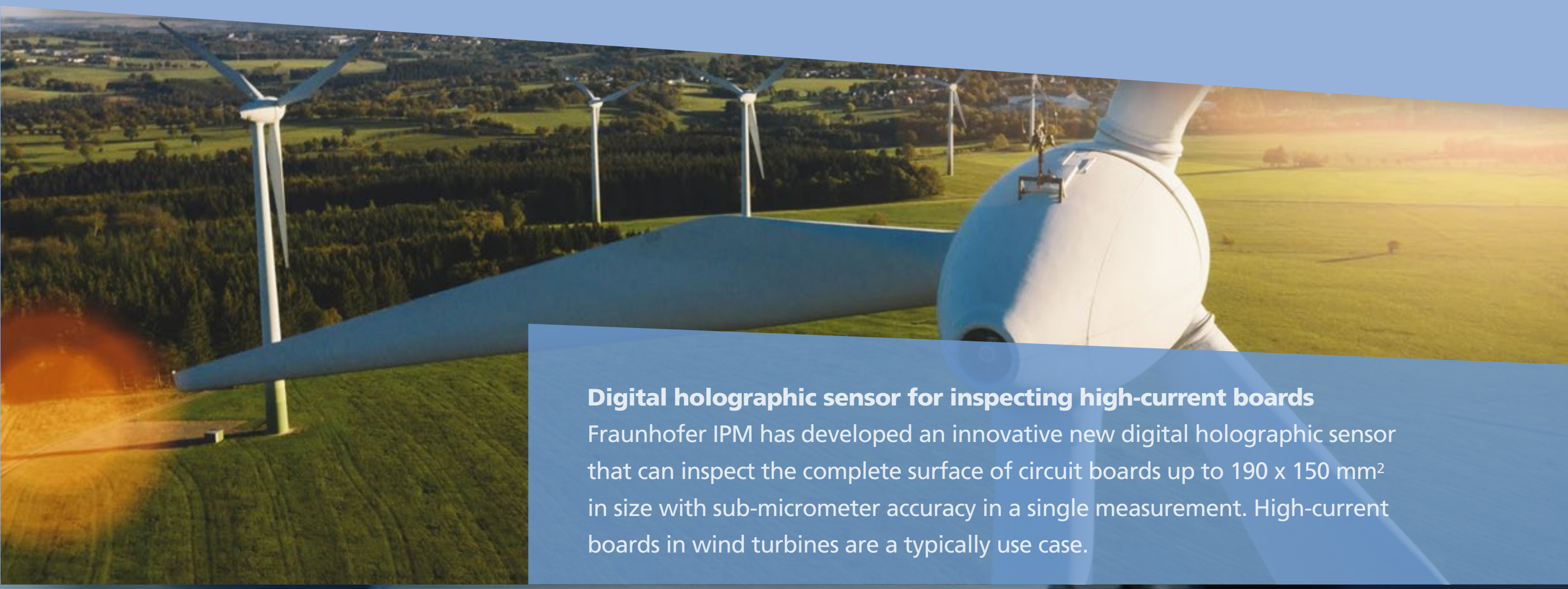
- 100% inspection of entire gear in just a few minutes
- Single spot measurement accuracy below 1 µm
- Spur and helical gears captured
- Active suppression of multiple reflections on the gear flanks
- Contactless measurement, even on moving objects

DYNAMIC DEFORMATION MEASUREMENT

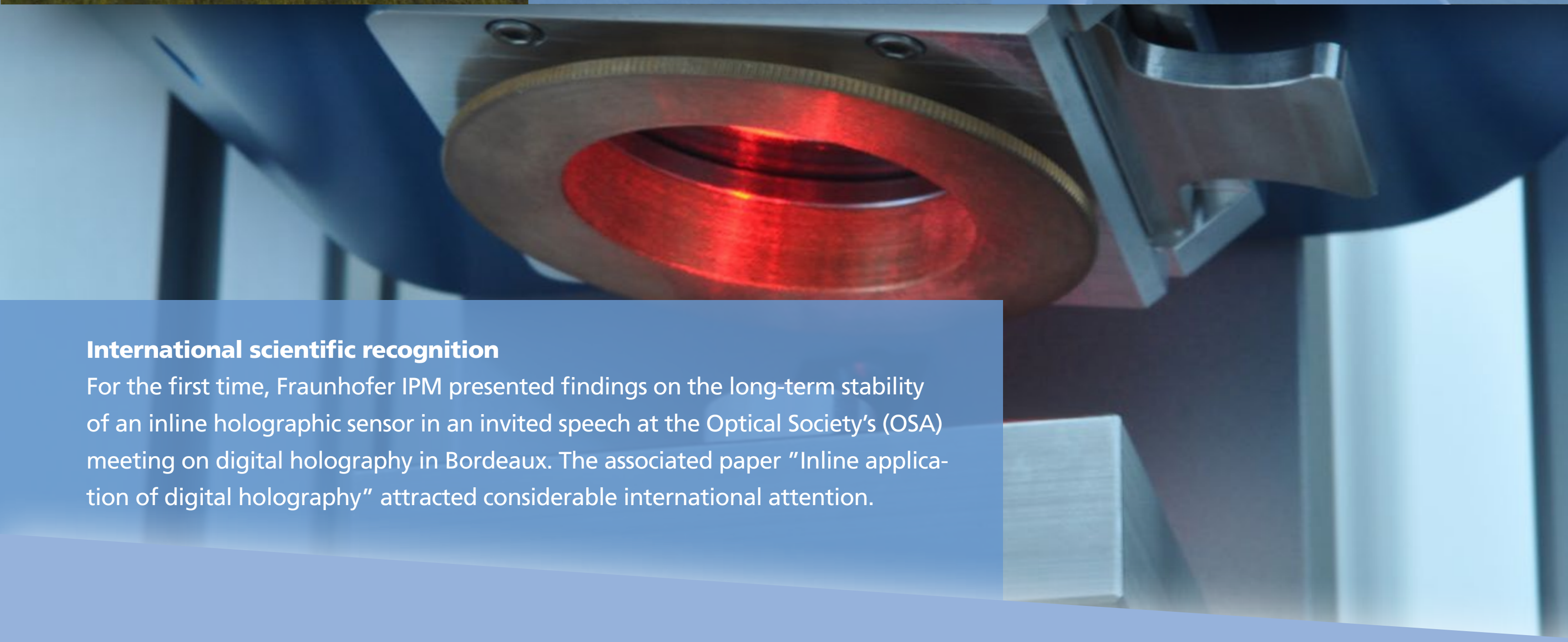
- Temporally resolved imaging measurements with a frame rate of up to 1 kHz
- Image field of 10 × 10 mm²
- Measurement accuracy below 0.5 µm
- Non-contact and marker-free up to 1000 °C
- Strain-controlled short cycle strength analysis, load measurement, and crack assessment
- Standard-compliant fatigue testing in just one hour of measurement time
- Electronic Speckle Pattern Interferometry (ESPI) and Digital Image Correlation (DIC)



Measuring microbumps quickly and with maximum precision
For the first time, a holographic surface sensor can measure electronic microbump structures with a height accuracy of less than 0.2 µm (3σ) and a lateral scanning capacity of less than 3 µm. Very high cycle speeds can be achieved thanks to a data rate of 150 million 3D points per second.



Digital holographic sensor for inspecting high-current boards
Fraunhofer IPM has developed an innovative new digital holographic sensor that can inspect the complete surface of circuit boards up to 190 x 150 mm² in size with sub-micrometer accuracy in a single measurement. High-current boards in wind turbines are a typically use case.



International scientific recognition
For the first time, Fraunhofer IPM presented findings on the long-term stability of an inline holographic sensor in an invited speech at the Optical Society's (OSA) meeting on digital holography in Bordeaux. The associated paper "Inline application of digital holography" attracted considerable international attention.

New drive systems require new approaches to quality assurance

Nearly all German car manufacturers now offer standard vehicles with electric or hybrid drives. This profound shift in vehicle production is not just transforming value chains and production structures, it also introduces new requirements for quality assurance. To this end, Fraunhofer IPM develops suitable optical inspection systems.

For car manufacturers, far-reaching changes in mobility mean shorter development cycles and small batch sizes, which presents major challenges for quality assurance. The German automotive industry is now tackling the changes in production head on, setting an example for other industries facing similar upheaval. For several years, Fraunhofer IPM has been hard at work on solutions to especially demanding inspection tasks – in particular for automotive suppliers. The projects are focused on quality assurance for power electronic components and connectors as well as for electric motors and their housings.

Vehicle power electronics must be both highly specific and durable

Power electronics ensure that the battery, motor, control unit, converter, and auxiliary systems of an electric vehicle are interconnected. If these central components fail, the vehicle comes to a complete stop. As a result, quality criteria such as durability, service life, and power density are of utmost importance. In order to reduce weight and save space, power electronics are sometimes integrated into the housing of the electric motor – hardly a favorable location for electronics. Components installed there must be able to withstand strong vibrations and high heat for the entire life of the vehicle.

Fraunhofer IPM is developing inspection systems to provide quality assurance for power electronics. For example, the HoloTop sensor system not only detects potential debonding of the conductive layer in direct bonded copper (DCB) components, it can also identify particles, point defects, and cracks with sub-micrometer accuracy directly in the production line. Using multiwavelength digital holography, the optical 3D sensor can inspect and classify an area of 200 × 150 mm^2 in less than half a second. Inspection isn't limited to geometric defects. Often, even the smallest impurities, such as tiny dirt particles or films on copper foil, can cause issues with electronics. Fraunhofer IPM's fluorescence measurement systems, such as the F-Scanner or F-Camera, can be used directly in the production line to detect impurities, that could affect quality, quickly and without contact.

It's also important that the housing of power electronics fit precisely. Power electronics always generate heat, which is typically transferred to heat sinks through thermal contact with housing surfaces. Fraunhofer IPM checks these contact surfaces for surface defects by recording images in free fall. The Inspect 360° free fall inspection system reliably detects chip residue, pins, perforations, or grooves that could interfere with optimal thermal contact right in the production line, eliminating the need for costly handling.

< HoloCut in machine tools: The spindle grips the 3D sensor like a tool and simply moves it to the workpiece for measurement.

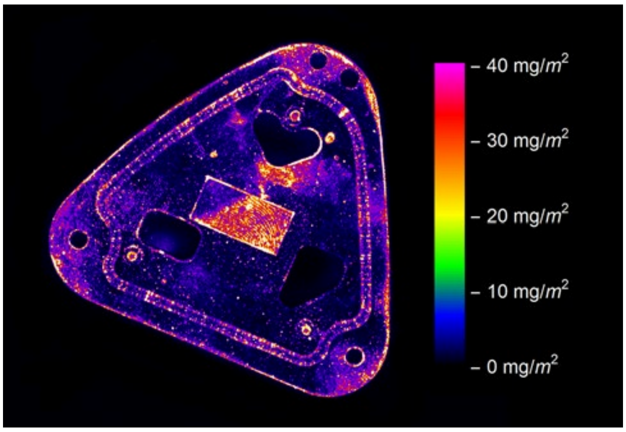
Fraunhofer IPM's **2D and 3D INSPECTION SYSTEMS** are developed for difficult production conditions. The systems provide our industrial partners with very precise measurement data in real time. This offers many advantages, including the ability to control new manufacturing processes as they are being established – an increasingly common occurrence given the changes in the automotive industry. By targeting our development of inline optical measurement techniques for a wide variety of production applications and by combining them with extremely fast evaluation methods, we have made 100% inspection possible for even the shortest production cycles. Drawing on our many years of experience in optics, electronics, imaging, and data processing, we develop turnkey inspection systems for production.

Even simple, mass-produced connectors are highly specialized parts

The requirements for geometry and surface properties are often similarly high for inexpensive mass-produced parts. This may seem surprising, since such small parts typically have little monetary value, but they are still highly specialized components. Connectors in particular sometimes have very low tolerances. Since even low-cost components fulfill important functions in the vehicle, a cost-effective approach to checking for dimensional accuracy and surface defects is needed. To this end, Fraunhofer IPM's free fall inspection systems – such as Inspect 360° – offer a clear advantage over traditional image processing solutions: they eliminate the need for expensive handling systems.

Precision is also required for housing, gearing, drill holes, and sealing surfaces

Electric vehicles are far quieter than vehicles with a combustion engine. Even the smallest surface defect, for example in the gearing, results in audible noise that previously would have gone unnoticed. Here, too, multiwavelength digital holography can be used to ensure that geometry and surfaces meet the requirements for precision. Compact sensor heads that have been specifically tailored to the application are used to record the quality of sealing surfaces, drill holes, or gearing directly in the processing center, making it possible to rework components as needed without reclamping the workpiece. The spindle grips the sensor like a tool and simply moves it to the workpiece for measurement. Another typical task is the detection of particles or filmic contamination, for example in the battery housing. Unwanted films can impede the thermal connection to the battery stack. The F-Scanner and the F-Camera prevent this disruptive effect by reliably determining the cleanliness of such surfaces.



F-Scanner and F-Camera: Imaging fluorescence measurement systems quantitatively detect residual contamination in the form of films and particles. The false-color display facilitates the rapid analysis of the component surface.

BUSINESS UNIT
OBJECT AND SHAPE DETECTION

“We develop optical measurement systems for efficient infrastructure monitoring.”

In the “Object and Shape Detection” business unit, we serve the entire process chain for mapping, referencing and visualizing the shape and position of infrastructure objects. For this purpose, we develop laser scanners and custom-made lighting and camera systems. These devices are able to perform measurements with high levels of speed and precision, particularly from moving platforms. Measurement data are evaluated in a fully automated process and interpreted by specially developed software. To this end, we employ techniques from the field of artificial intelligence (AI), such as deep learning. Data that are edited and visualized for specific applications provide experts with a sound basis for decision-making, for instance where the planning of infrastructure is concerned.

We focus specifically on speed, robustness and long service life of the systems. Objects and shapes are mapped three-dimensionally with a wide range of sizes covered – from a few centimeters to a scale of some 100 meters. The measurement systems are in use worldwide, their tasks ranging from monitoring rail infrastructure to surveying road surfaces. New areas of application include mobile data collection both from the air and underwater.

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Group **Mobile Terrestrial Scanning**

- Rail systems
- Road systems
- Systems for meteorological applications (incl. wind LiDAR)
- Rapid and robust systems
- Software for data interpretation

Group **Airborne and Underwater Scanning**

- Systems for unmanned aerial vehicles
- Systems for underwater applications
- Miniaturization of measurement systems
- Systems based on low-cost and consumer products (incl. smartphones)
- Software for data interpretation

Group **Smart Data Visualization**

- Real-time visualization of spatial data
- Creation of synthetic measurement data (incl. for machine learning)
- Flexible function libraries
- Platform-independent systems

< Camera optics of the Contact Wire Inspection Systems CIS-LS for high precision measurement of contact wire wear and position.

BUSINESS UNIT **OBJECT AND SHAPE DETECTION**

GROUP **MOBILE TERRESTRIAL SCANNING**

Prof Dr Alexander Reiterer, P +49 761 8857 - 183, alexander.reiterer@ipm.fraunhofer.de

The research focus of the group is the development of time-of-flight measurement-based optical measurement systems for mobile use on rail and road vehicles. The systems determine distances to objects with great speed and submillimeter precision. Combined with a scanning unit, they can also capture three-dimensional object geometries. For precise position and location detection, the group is developing special camera-based techniques which – either when used in isolation or in combination with conventional inertial sensors – allow data to be assigned to a fixed system of local or global coordinates. Our robust measurement systems are installed on road and rail measurement vehicles or on driverless vehicles for surveying difficult-to-access objects. The systems survey and monitor rail infrastructure and inspect road surfaces or tunnel constructions with high precision. For a fully automated analysis and classification of 2D and 3D data, we are developing self-learning algorithms based, among others, on the concept of deep learning.

Group Manager: Prof Dr Alexander Reiterer

RAIL SYSTEMS

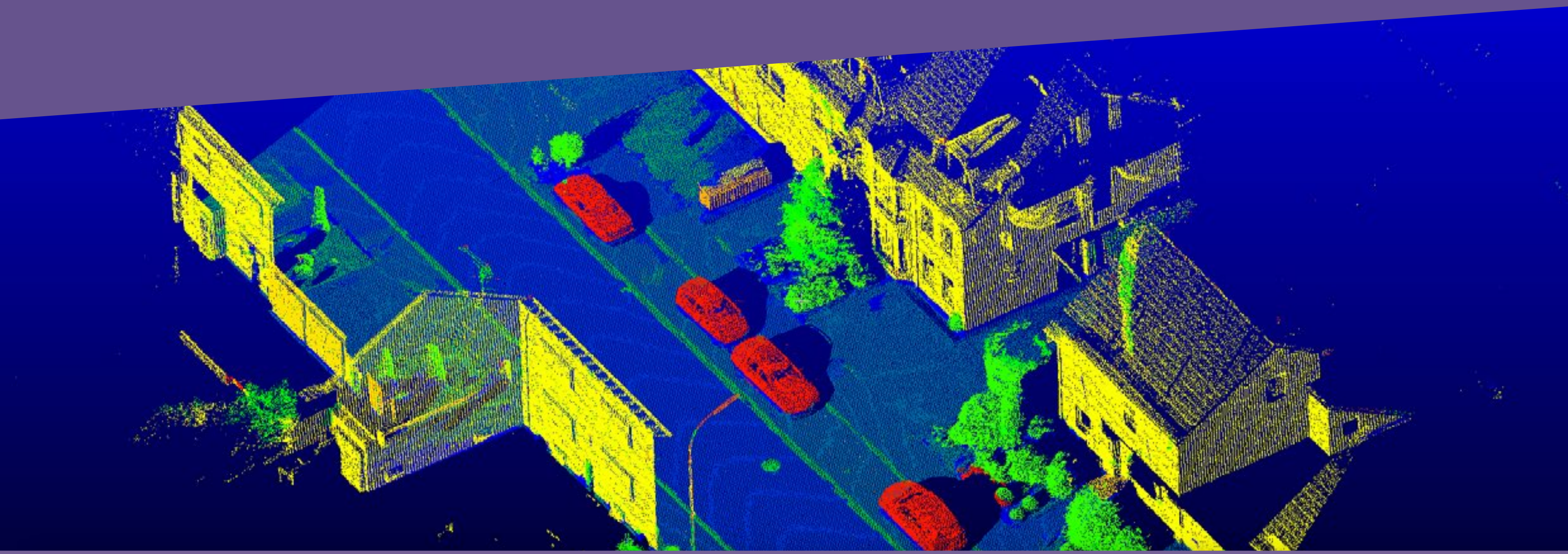
- Overhead wire surveying at speeds of up to 250 km/h
- Railway line clearance monitoring with 3 mm precision
- Environment scanning with up to 800 profiles per second
- Track profile measurement with 0.3 mm precision
- Tunnel inspection: 360° 3D-geometry scanning, crack detection with millimeter resolution, moisture detection

ROAD SYSTEMS

- Measuring transverse evenness of roads with 0.3 mm precision
- Mapping of 2 million measuring points per second
- Surveying road corridors of up to 300 m in width with 3 mm precision
- Detecting cracks in road surfaces at driving speeds of 80 km/h with a resolution of 1 mm

AUTOMATED DATA INTERPRETATION

- Interpreting 2D and 3D measurement data fully automatically, incl. by means of deep learning
- Implementing cloud-based solutions for data processing
- Building comprehensive training datasets for the automated training of algorithms

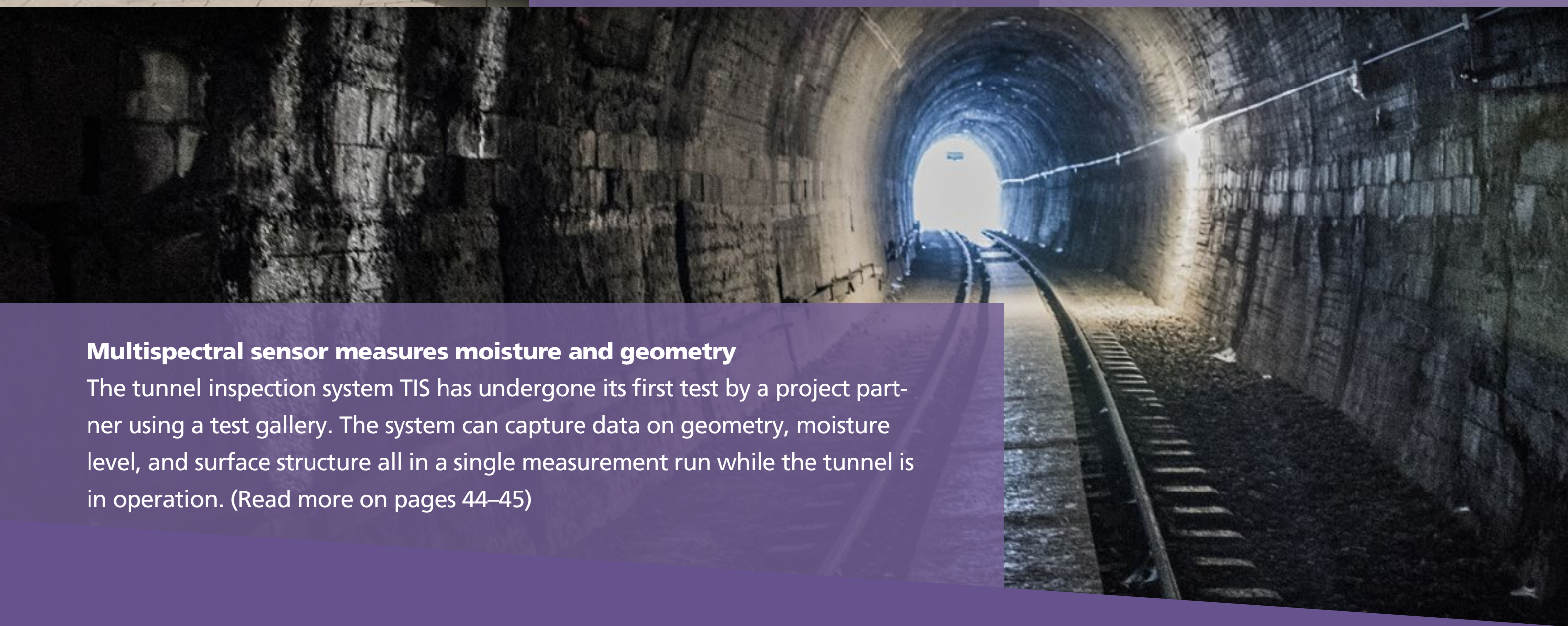


Fully automated classification of 3D measurement data

Fraunhofer IPM received the Joseph von Fraunhofer Prize 2019 for its 3D AI software with a unique process chain for the automated classification of 3D measurement data. The system is used by companies such as Deutsche Telekom and STRABAG. (Read more on page 22)

Delivery of a mobile mapping vehicle

For a project commissioned by Geotechnik GmbH, Fraunhofer IPM has manufactured a mobile mapping vehicle capable of generating digital 3D road topology and topography data for infrastructure planning at speeds of up to 100 km/h.



Multispectral sensor measures moisture and geometry

The tunnel inspection system TIS has undergone its first test by a project partner using a test gallery. The system can capture data on geometry, moisture level, and surface structure all in a single measurement run while the tunnel is in operation. (Read more on pages 44–45)

BUSINESS UNIT **OBJECT AND SHAPE DETECTION**

GROUP **AIRBORNE AND UNDERWATER SCANNING**

Simon Stemmler, P +49 761 8857-211, simon.stemmler@ipm.fraunhofer.de

The main research foci of the group are the development of lightweight optical measurement systems for use on UAV and the adaptation of LiDAR technology for capturing 3D data of large under water structures. Our UAV scanner systems use time-of-flight measurement techniques to measure distances to objects with high accuracy and generate three-dimensional data in combination with cameras. This makes them suitable for condition monitoring of construction sites, buildings, bridges, or vegetation areas. In the future, remotely operated underwater vehicles (ROV) equipped with our LiDAR systems will be used for surveying underwater constructions such as pipeline foundations and offshore wind farms. The group is also working to develop lean 3D measurement technology solutions based on low-cost and consumer products, e.g. smartphones.

Group Manager: Simon Stemmler

AIRBORNE SYSTEMS

- Measurement systems (laser scanner and cameras) weighing under 2.5 kg
- Measurement precision 1 cm
- Typical measurement distances of up to 100 m
- Measurement frequencies of up to 60 kHz
- Position measurement using visual odometry as well as positioning and orientation systems

UNDERWATER MEASUREMENT SYSTEMS

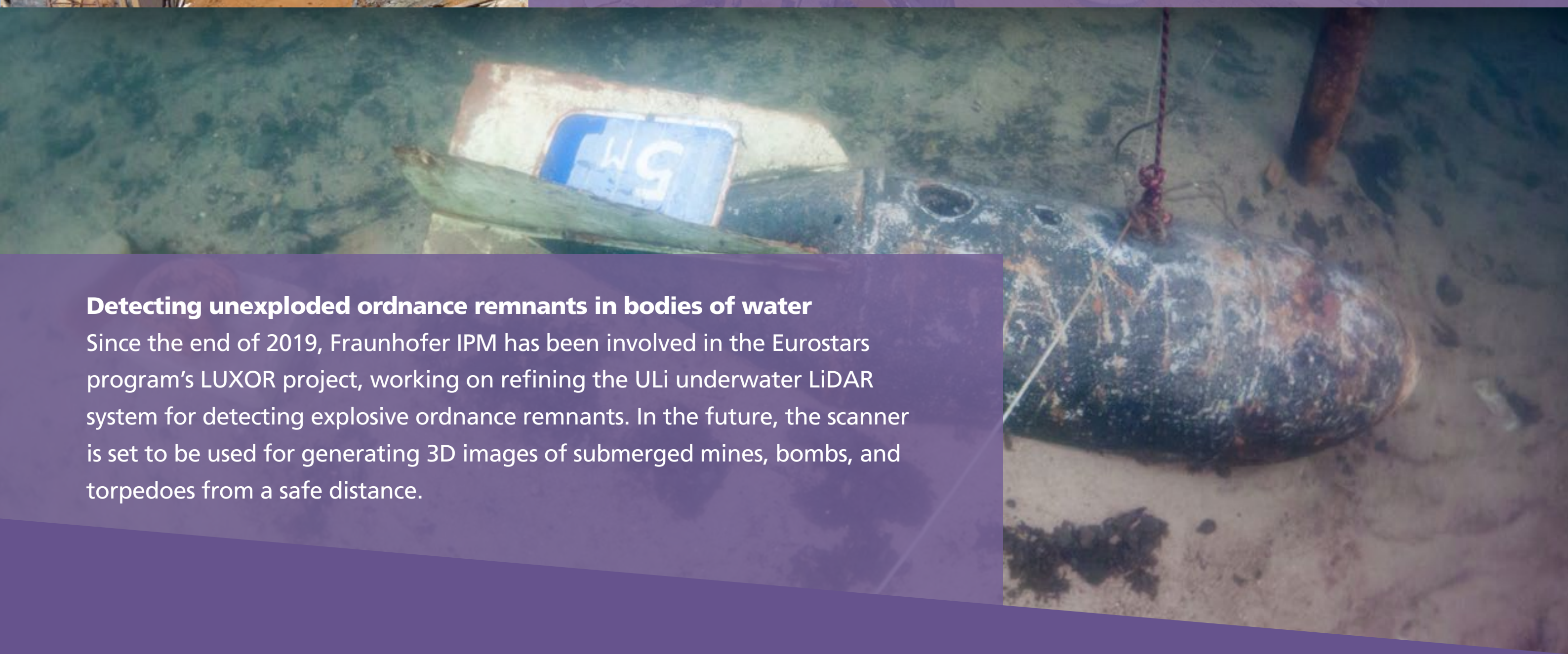
- 3D surveying with subcentimeter resolution, even in turbid water
- Measurements irrespective of light conditions and depth
- Measurement frequency up to 40 kHz
- Scanning frequency 800 Hz
- Measurement distance up to 40 m (depending on the turbidity of the water)
- Stationary and mobile surveying

DATA PREPARATION

- Fusion of 3D and 2D data incl. positioning and texturizing
- Derivation of metadata from texturized 3D data
- Automated data interpretation, e.g. based on "Deep Learning"
- Automation of surveying tasks

Cameras record condition of crop plants for farmers
A camera system for fast, high-resolution multispectral imaging was constructed as part of the Fraunhofer lighthouse project "Cognitive Agriculture" (COGNAC). The cameras are designed to record the condition of crop plants. Testing is set to begin during the 2020 growing season.

Geopositioning and digitalization of infrastructure on-site
Fraunhofer IPM has developed a mobile application for use in digitalizing infrastructure (e.g. mapping structural elements) which enables real-time 3D reconstruction using stereo camera images as well as automated data analysis based on deep learning.



Detecting unexploded ordnance remnants in bodies of water
Since the end of 2019, Fraunhofer IPM has been involved in the Eurostars program's LUXOR project, working on refining the ULi underwater LiDAR system for detecting explosive ordnance remnants. In the future, the scanner is set to be used for generating 3D images of submerged mines, bombs, and torpedoes from a safe distance.

BUSINESS UNIT **OBJECT AND SHAPE DETECTION**

GROUP **SMART DATA VISUALIZATION**

Prof Christoph Müller, P +49 761 8857 - 236, christoph.mueller@ipm.fraunhofer.de

The research focus of the group is the customized visualization of spatial measurement data. Smart data visualization provides the foundations for rapidly gathering complex measurement data and deriving targeted actions from this information. To this end, we develop interactive applications which enable users to navigate in compiled measurement data and which act as a visual aid in complex analyses and decision-making processes. Depending on the application, an enormous variety of visualization options and suitable platforms may be required to do this. In any situation where processes have to be adjusted interactively, measurement results must be visualized in real time. We therefore develop algorithms and methods for smart data concentration to enable optimal handling of extensive measurement data. This creates the foundation necessary for using both existing and future measurement techniques in new areas.

Measurement data must be culled during collection, in particular for mobile devices with limited processing power, before they can be interpreted and subsequently visualized. The ability to visualize measurement data on mobile devices makes it possible to conduct quality control and completeness checks during data collection rather than afterwards. We also draw on extensive knowledge surrounding the underlying data and the generation of images from 3D models to create synthetic training data – for AI-based object recognition, for example. In doing so, we are also laying the foundation for the iterative optimization of measurement techniques with a view to machine data interpretation in the future.

Group Manager: Prof Christoph Müller

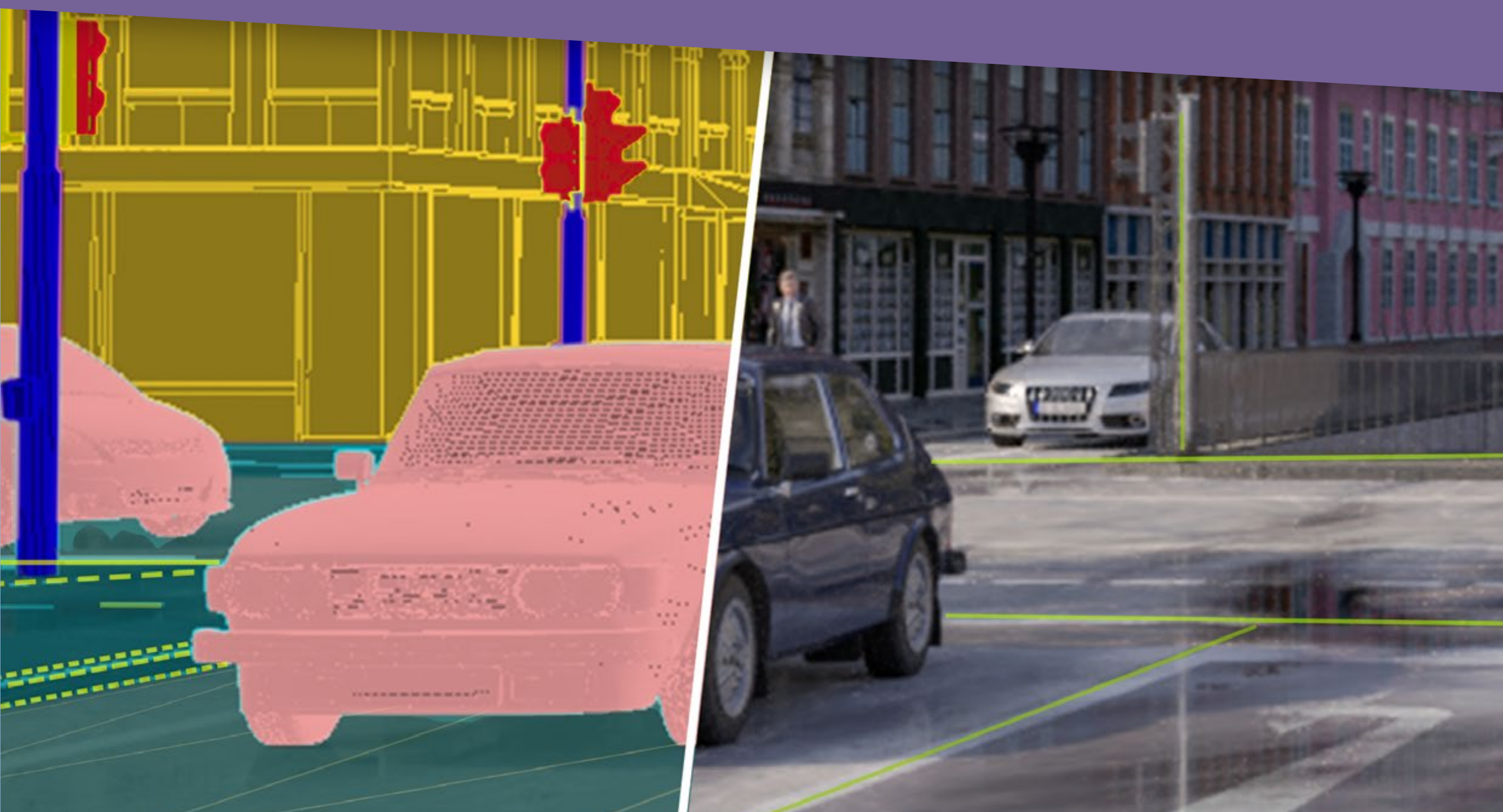
VISUALIZATION

- Display of massive point clouds
- Real-time rendering with more than 20 frames per second
- Various visualization techniques for intuitive presentation of complex information, e.g.
  - Calculation of lighting conditions on a surface visually reconstructed in real time in order to identify structures
  - Color-coding of edges to visually separate entities within the point cloud
  - False-color representation of other measurement data channels (intensity, hit count) or other information derived in real time (distance, height, fissuring of the surface)

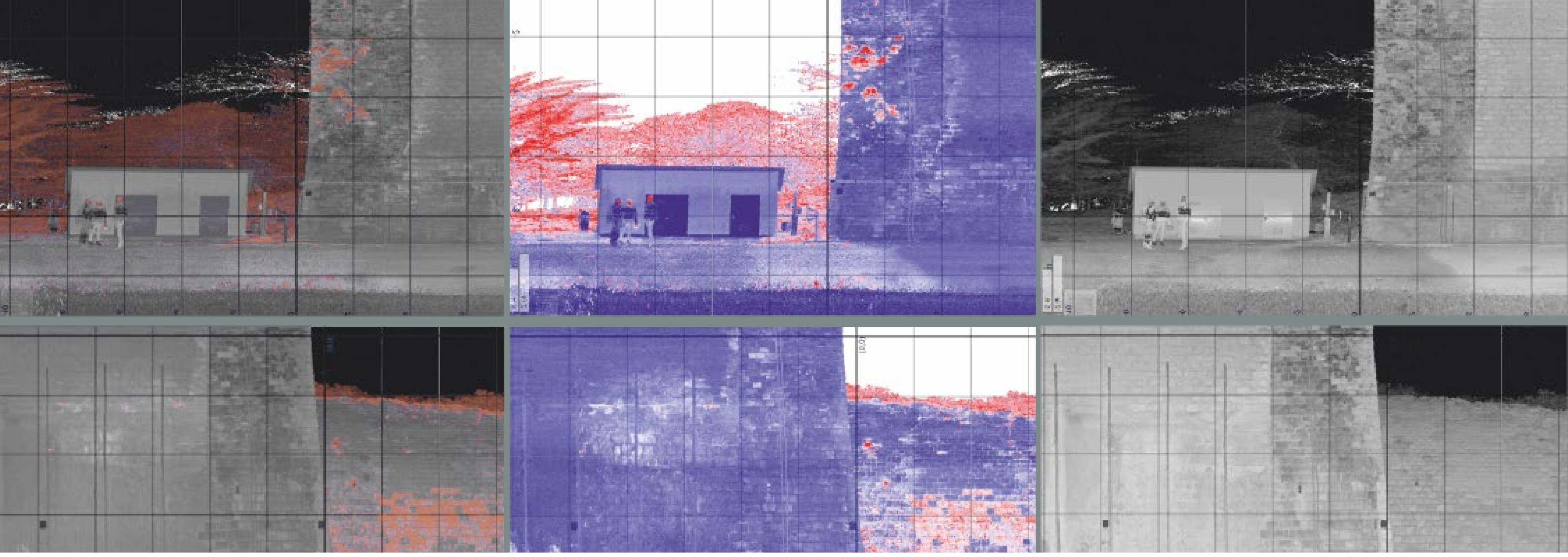
SYNTHETIC TRAINING DATA

- Creation of 3D scenes including material properties, lighting conditions, weather phenomena, and dynamic properties
- Algorithmic generation of 3D models from parameterizable components
- Creation of simulated measurement data: photo-realistic images and 3D point clouds

Interactive display of 3D point clouds
As part of the MultiVIS project, a software application was developed that can interactively display unstructured point clouds at over 20 frames per second – a very high display quality. Different types of visualization are possible.



Efficient data training: cityscapes
Artificial neural networks (ANNs) are used for the automated interpretation of measurement data and can be trained very efficiently with the support of synthetic training data. The team created the first 3D model of urban settings, consisting of photo-realistic images and classification of these images, as the basis for the generation of artificial training datasets.



Multispectral laser scanner detects moisture in tunnels

In addition to geometry and surface condition, moisture is another important parameter measured in tunnel condition monitoring. Fraunhofer IPM has now updated its Clearance Profile Scanner CPS, originally designed for railway inspection down to the millimeter, with an additional multispectral phase scanner. The CPS^2 is capable of measuring objects' moisture levels in addition to their geometry.

In Germany alone, over four hundred road, rail, and subway tunnels require regular inspections – and many of these are several decades old. Every year, the costs of maintaining and repairing these tunnels amount to nearly one billion euros. What's particularly astonishing is that the condition of these structures is still surveyed manually for the most part, requiring them to be fully closed off. Due to the different measurement techniques used, the data obtained are not uniform and not always available in a digital format. Mobile scanners – some of which are already in use today – promise to resolve this issue, offering many advantages over conventional measurement techniques. They are quick and accurate, they can be operated under any lighting conditions, and they deliver digital, location-referenced measurement data.

First multispectral phase scanner

While LiDAR (light detection and ranging) solutions based on the ToF (time-of-flight) method are typically used for generating rough representations of objects, Fraunhofer IPM uses phase shift measurement for its CPS. With a relative measuring precision of 1 to 5 mm at a measuring rate of 2 MHz, it offers much higher performance than ToF-based systems and is thus suited to producing accurate digital representations of structures or their surroundings.

Until now, laser scanners that measure using multiple different wavelengths have only been marketed by a few companies, exclusively as ToF systems and primarily for use in airborne applications such as vegetation mapping as well as bathymetry. At about one cubic meter in size and over 70 kg, these systems are cumbersome and heavy. As well as offering lower resolution and measuring rates than phase shift measurement solutions, they have proven to be insufficiently eye-safe (laser safety Class 4) in practice. With the CPS^2, the team has managed to develop the first multispectral phase scanner that can scan quickly and accurately from mobile platforms. The system is compact and easy to handle, measuring about 30 cm × 30 cm × 30 cm, and features an eye-safe Class 1 laser scanner.

The first-generation CPS carries out geometric measurements using a near-infrared laser with a wavelength of 1500 nm. With the next generation CPS^2, designed for measuring moisture, the laser wavelength was reduced to 1450 nm corresponding to the spectral signature of water. An additional laser with a wavelength of 1320 nm has been integrated into the CPS^2. Water does not exhibit any absorption at this wavelength, allowing this laser to serve as a reference. A comparative measurement of the two wavelengths – within and directly next to the absorption band of

< In order to enable the automated measurement of moisture in tunnels, Fraunhofer IPM is using multispectral laser scanning for the first time. Wet areas at the tunnel entrance (upper row) and on a tunnel wall (lower row) are revealed by the absorption information (color-coded red).

The CPS² relies on near-infrared (NIR) differential optical absorption spectroscopy (DOAS). DOAS is a common method for determining the moisture levels of food products, for example. Two collinear laser beams of different wavelengths scan the surface of the measurement object. These beams are specifically absorbed by water. The measuring beam with a wavelength of 1450 nm is selected to correspond with the absorption band of water. The second laser with a wavelength of 1320 nm lies outside of this absorption band and serves as a reference. An intensity analysis of the two signals gives the moisture value. The recorded intensities of both wavelengths are compared with the standardized target intensities of an ideal, dry Lambertian scatterer with a reflectance of about 90 percent. This makes it possible to differentiate even between different moisture levels (e. g. high, intermediate, low) extremely accurately, taking into account the reduction of the overall intensity due to material changes, color, debris, etc.

water – shows whether water is present on the surface of the measurement object. Geometric measurements can be taken by both lasers simultaneously.

On the right track – tests prove the system's usability

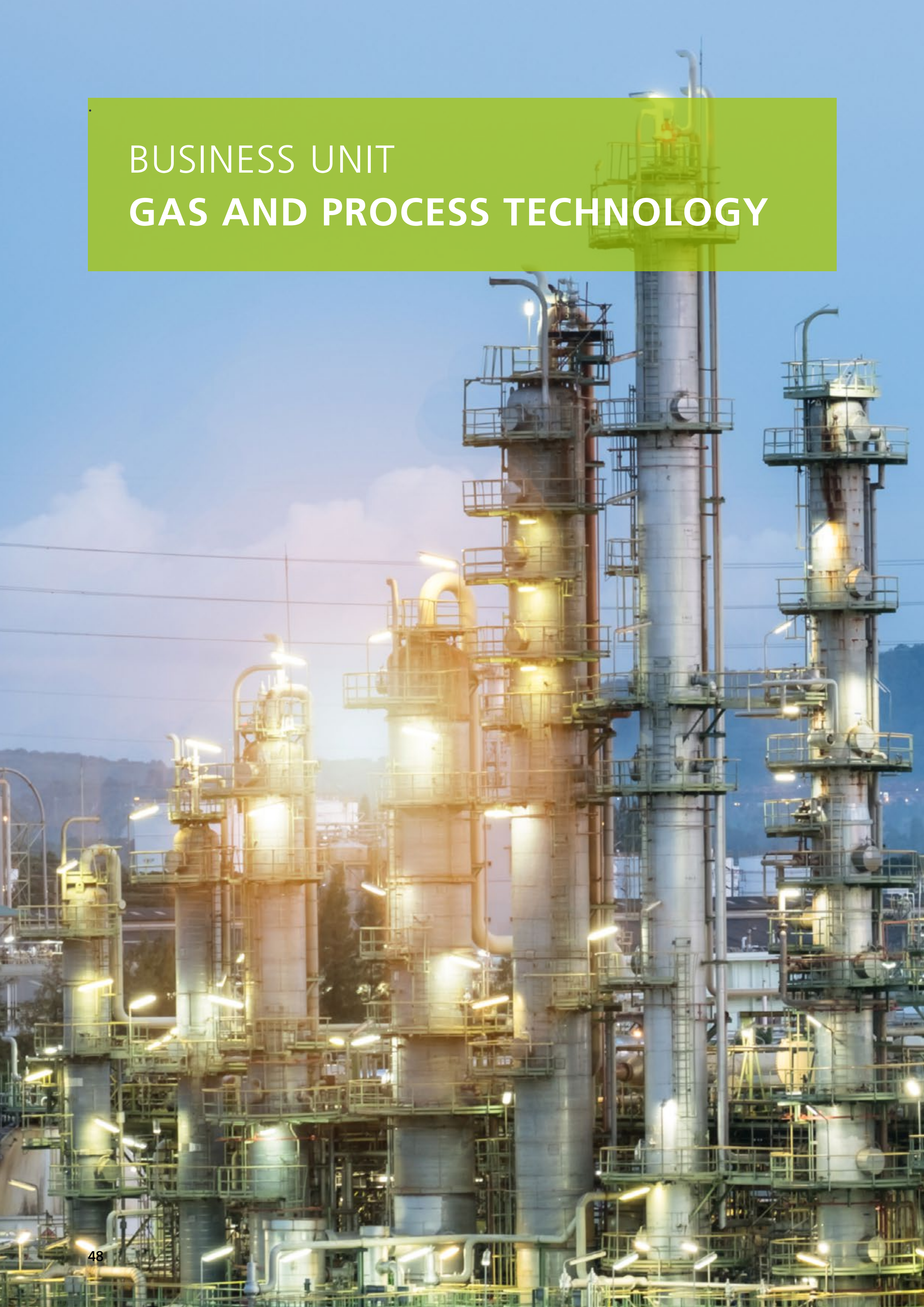
In 2019, test measurements were taken in multiple locations across Europe as part of a cooperative effort with tunnel inspection companies and railway operators. The CPS² was equipped with positioning sensor technology and driven through tunnels atop a hand-pushed, rail-mounted platform. This configuration allowed for a measurement rate for both wavelengths of 2 MHz. Moving at 5 km/h, the scanner mapped the tunnel wall with a lateral resolution of approximately 3 mm × 7 mm. High-resolution test measurements at a tunnel entrance and on a tunnel wall show that the moisture on the surface of the structure is reliably detected (image above center). In addition to moisture, the geometry and surface of the tunnel walls are mapped down to the millimeter, enabling deformations, cracks and chipped-off surface material to be identified. The CPS² is the first system to enable simultaneous digital and location-referenced mapping of water ingress, surface defects, and geometry in a single pass through a tunnel. Moreover, the system clearly recognizes vegetation (image above, upper row), since this also contains a lot of water and therefore exhibits a spectral signature in the infrared range. The CPS² is thus also suited to detecting vegetation along railroad tracks, for example.

Novel deflection unit for higher speeds

As part of the Eurostars OpOrTunIty project, Fraunhofer IPM is currently working with a number of European companies on an expanded version of the CPS², the tunnel inspection system TIS. A novel deflection unit is intended to enable the combination of multiple lasers, the ultimate goal being to increase the speed at which measurements are taken in order to record water ingress, surface defects, and geometry simultaneously at a lateral resolution in the millimeter range and at a speed of 80 km/h through the tunnel. This would eliminate the need for tunnel closures during measurement.

Prof. Dr. Alexander Reiterer, P + 49 761 8857 - 183, alexander.reiterer@ipm.fraunhofer.de

BUSINESS UNIT
GAS AND PROCESS TECHNOLOGY



"Our know-how opens up new possibilities for gas and process measurement technology."

In its "Gas and Process Technology" business unit, Fraunhofer IPM develops and manufactures measuring and control systems to meet customer requirements. The main features of these systems are short measurement times, high precision and reliability, even in extreme conditions.

Our expertise includes laser spectroscopic methods for gas analysis, energy-efficient gas sensors, particle measuring technology, thermal sensors and systems as well as nonlinear optics and, as of late, quantum sensing. The scope of applications is massive – it extends from flue gas analysis and transport monitoring for food to sensors and systems for measuring very small temperature differentials.

Prof Dr Jürgen Wöllenstein
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Group **Integrated Sensor Systems**
- Gas sensitive materials
- Micro-optical components
- Miniaturized gas sensor systems

Group **Spectroscopy and Process Analytics**
- Spectroscopic analytics
- Optical systems
- Data evaluation methods

Group **Thermal Measurement Techniques and Systems**
- Custom-made microstructures
- Thermal measurement systems
- Simulation of physical processes

Group **Nonlinear Optics and Quantum Sensing**
- Nonlinear optics
- Laser absorption spectroscopy
- Quantum sensing

< Gas sensors for the process industry must withstand extreme environmental conditions. We develop and test robust measuring systems for industrial use.

BUSINESS UNIT GAS AND PROCESS TECHNOLOGY

GROUP **INTEGRATED SENSOR SYSTEMS**

Dr Marie-Luise Bauersfeld, P +49 761 8857 - 290, marie-luise.bauersfeld@ipm.fraunhofer.de

The group's research focuses on developing functional, gas-sensitive materials and surfaces as well as miniaturized gas sensor systems. We always keep the specific application in mind when synthesizing and processing gas-sensitive materials and surfaces. We construct miniaturized gas sensor systems by integrating sensor technology and electronics into compact and cost-effective microsystems. One example is microstructured infrared emitters which are integrated into micro-opto-electro-mechanical systems (MOEMS) as light sources. We develop particularly small, inexpensive and energy-efficient gas sensors to be embedded in wireless sensor networks or mobile end devices. They can be used for ventilation applications, toxic gas detection, and quality control for food in storage or during transportation, as well as for smart applications such as in smart homes.

Group Manager: Dr Marie-Luise Bauersfeld

GAS SENSITIVE MATERIALS

- Materials synthesis and processing: layers of a few nm to some µm, coatings of micro-structured substrates (MEMS)
- Semiconductor gas sensors: metal oxide layers such as SnO_2, WO_3 or $Cr_{2-x}Ti_xO_{3+z}$ with catalytic additives
- Colorimetric gas sensors: e. g. color change materials for CO, NO_2, NH_3, H_2S, and volatile organic compounds (VOC)

MICRO-OPTICAL COMPONENTS

- IR emitters for a wavelength range of 5 to 12 µm, can be modulated if desired
- IR detectors (e.g. made of PbSe) for a wavelength range of 3 to 5 µm
- Diffractive optics, e. g. Fresnel lenses made of silicon or components for IR emitters

MINIATURIZED GAS SENSOR SYSTEMS

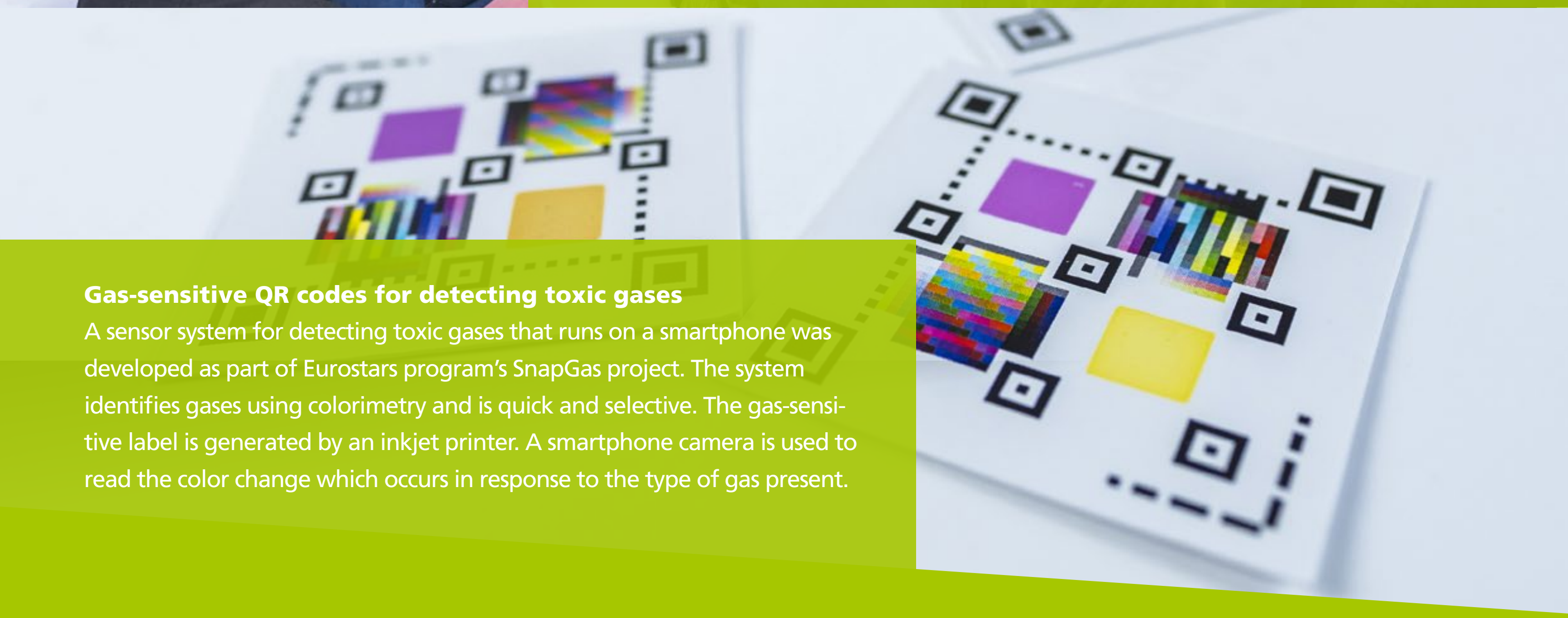
- Detection of gas concentrations from ppb to percent according to measurement principle applied; modular systems by combining various sensor principles
- Sensor technology for energy self-sufficient systems with wireless communication
- Photoacoustic systems, filter photometers, and miniaturized gas chromatography systems

Gas sensor measures the purity of refrigerants

In the CONTECT-R project, funded by the German Federal Ministry of Education and Research (BMBF), scientists of the group developed a photoacoustic gas sensor for detecting refrigerants which contain fluorine. The sensor forms part of an analysis system for checking the purity of environmentally friendly refrigerants, which is the product of co-development with research partners.

8th Gas Sensor Workshop

Over 70 experts participated in the eighth Gas Sensor Workshop, which took place at Fraunhofer IPM on October 24, 2019. The ninth workshop is planned for 2021.
www.gassensoren.fraunhofer.de



Gas-sensitive QR codes for detecting toxic gases

A sensor system for detecting toxic gases that runs on a smartphone was developed as part of Eurostars program’s SnapGas project. The system identifies gases using colorimetry and is quick and selective. The gas-sensitive label is generated by an inkjet printer. A smartphone camera is used to read the color change which occurs in response to the type of gas present.

GROUP **SPECTROSCOPY AND PROCESS ANALYTICS**

Dr Raimund Brunner, P +49 761 8857 - 310, raimund.brunner@ipm.fraunhofer.de

The group's research focuses on developing spectroscopy systems for the detection and analysis of liquids and gases, with methods including Raman, FTIR, ATR, and laser spectroscopy. We use simulation tools as well as suitable analysis methods such as Fourier and energy dispersive X-ray spectroscopy (EDX) to develop optical components and electronics modules and to characterize them, for instance by inspecting degradation and stability. The group has many years of experience in exhaust gas measuring technology and calorific value analytics, covering rapid gas analyzers for engine test benches used in engine development and systems for monitoring calorific value in natural gas pipelines. Our remote gas detection systems rely on laser spectroscopy and infrared imaging measurement technology to locate leaks and are used in remote safety monitoring for industrial facilities and gas lines. In the area of liquid analysis, we develop ATR process spectrometers for quality control in beverage industry and fermenting processes.

Group Manager: Dr Raimund Brunner

SPECTROSCOPY ANALYTICS

- Optical trace gas analyzers based on laser spectroscopy: sensitivity in the ppb range for N_2O and NH_3, in the ppm range for O_2
- Raman spectroscopy: analysis of liquids, biological samples, solid-state materials, or gases
- ATR spectroscopy: measurement of dissolved substances in liquids down to the ppm range
- Photoacoustic measurement methods, individual acoustic resonator tuning

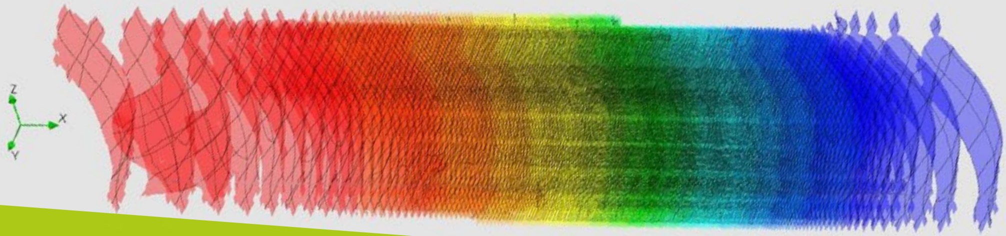
OPTICAL SYSTEMS

- Simulations: optics, mechanics, flow, electronics
- Detection of optical backscattering
- Systems for laser spectroscopy in the NIR / MIR with mirror optics
- Special optical setups: long-path absorption cells, EUV diffraction gratings, laser packages including collimators, reference systems
- In-situ measurement methods

EVALUATION METHODS

- Chemometric methods for analyzing measurement data
- Determining the measurement accuracy and reliability of gas sensors and laser systems under different conditions
- Modeling as a basis for linearization and calibration-free spectroscopy

Nitrous oxide soil sensor – initial field tests successfully completed
As part of the Fraunhofer lighthouse project COGNAC (Cognitive Agriculture), the group is developing a compact soil sensor for taking high-resolution measurements of gases which contribute to climate change. A nitrous oxide sensor laboratory system based on laser spectroscopy has been constructed and initial field measurements have been successfully completed.



Tried-and-tested Quantum cascade laser (QCL) analyzer is enhanced
The exhaust gas measurement system developed for AVL Emission Test Systems GmbH is now equipped to detect ammonia thanks to a new laser and a high-temperature measurement cell. Interband cascade lasers (ICL) make for even higher performance. A new compact single-channel system is now being produced using innovative, highly efficient methods for manufacturing individual components.

Automated, in-process cleaning of ATR elements
The team has succeeded for the first time in integrating adapted hollow sapphire cylinders into Varivent® process flanges as ATR elements. The scientists have thus paved the way for automated, in-process cleaning of these elements. Initial tests indicate a detection limit of lower than 50 ppm toluene diisocyanate in chlorobenzene. Isocyanates are needed for manufacturing polyurethanes, lacquers, adhesives, and foams.

BUSINESS UNIT **GAS AND PROCESS TECHNOLOGY**

GROUP **THERMAL MEASUREMENT TECHNIQUES AND SYSTEMS**

Martin Jägle, P +49 761 8857 - 345, martin.jaegle@ipm.fraunhofer.de

This group's research focus is on thermal sensors made of various materials and systems for temperature dependent materials characterization. Flexible substrates allow very small temperature differentials to be measured using so-called calorimeter chips and a wide range of material parameters, such as thermal and electrical conductivity, to be determined using press-on measuring structures. We develop microstructures and microsystems for temperature dependent determination of material parameters, e.g. thermopiles, tailored to specific applications. Fluid sensor technology on polymer substrates developed by the group are used for oil quality monitoring, our fouling sensors detect the degree of scaling in production plants. In the context of thermal impedance analysis, we employ coupled thermal-electrical finite element models. A further research focus of the group is on modelling and validation of coupled thermal-electric-mechanical effects in microsystems as well as in larger systems such as energy storage systems for geothermal applications.

Group Manager: Martin Jägle

CUSTOM-MADE MICROSTRUCTURES

- Microstructures for organic electronics, heaters, and microfluidics with structures of typically 1 µm
- Thermopile sensors, fouling sensors, calorimetric sensors
- Thermal sensors for determining material parameters, especially thermal conductivity
- Electronic tongues

THERMAL MEASUREMENT SYSTEMS

- Systems for determining electrical conductivity, charge carrier concentration, Seebeck coefficient, majority charge carriers, e.g. by way of Hall measurements on semiconductors from –200 to 800 °C
- Systems for measurement of thermal properties of solids, liquids, and gases by employing electric and thermal impedance measurement (3 omega method)

SIMULATION OF PHYSICAL PROCESSES

- Coupled finite element models (FEM)
- Computational fluid dynamics (CFD) with thermal analysis
- Simulation of geothermal processes and design of energy storage devices
- Thermal management for systems validation

Laboratory for characterizing thermo-physical material properties

At our measuring stations we determine a large number of temperature-dependent parameters of functional materials. In addition to Hall and Seebeck performance measurements, we are now capable of conducting simultaneous thermal analyses (STA measurements). The group develops its own measuring systems and carries out measurements on behalf of customers – for research applications as well as for industrial quality assurance.

HE-Lab: measuring at the limit

In our "Harsh Environment Laboratory" we test sensors at temperatures up to 200 °C and pressures up to 2000 bar.
The first test stand was put into operation in 2019. The new building will house customized test rigs for both small electronic components and systems with several liters of volume.

BUSINESS UNIT **GAS AND PROCESS TECHNOLOGY**

GROUP **NONLINEAR OPTICS AND QUANTUM SENSING**

Dr Frank Kühnemann, P +49 761 8857 - 457, frank.kuehnemann@ipm.fraunhofer.de

Innovative new measurement technologies are at the core of the group's research: What types of sensors will we use tomorrow? And what sorts of opportunities will this open up? In close cooperation with partners in basic research, the group is working on innovative laser-based measurement principles and methods for spectroscopy. This includes continuous-wave (cw) laser light sources with customized wavelengths for spectroscopy, for which the group has a leading position worldwide, as well as wavelength converters for efficient infrared detection. They expand the possibilities of measurement technology, for example, in gas spectroscopy for investigating combustion processes or in the characterization of components for high-power lasers. In addition, they are used in quantum optics research laboratories and for interferometric holography. Frequency combs, on the basis of which new methods of infrared spectroscopy are being developed, are another example of nonlinear optical light sources.

The group is also active in the field of quantum sensor technology: Pairs of photons with different wavelengths, which are "entangled" in terms of their properties, form the basis of the quantum Fourier transform infrared spectrometer, which is designed to enable particularly sensitive measurements. Alkali atoms in specially prepared spin quantum states, for example, can be used as highly sensitive magnetic field sensors. The team is exploring new fields of application for these sensors in industrial process measuring technology.

Group Manager: Dr Frank Kühnemann

NONLINEAR OPTICS

- Optical parametric oscillators – wavelengths tunable from 450 nm to 5 µm with power outputs from 10 mW up to many watts (wavelength-dependent) and a linewidth of less than 1 MHz
- Frequency doubling – conversion efficiency of over 50 percent
- MIR-NIR conversion – MIR process data recorded at more than 5000 spectra per second
- Spontaneous parametric fluorescence for quantum sensors

NEW SPECTROSCOPIC MEASUREMENT TECHNIQUES

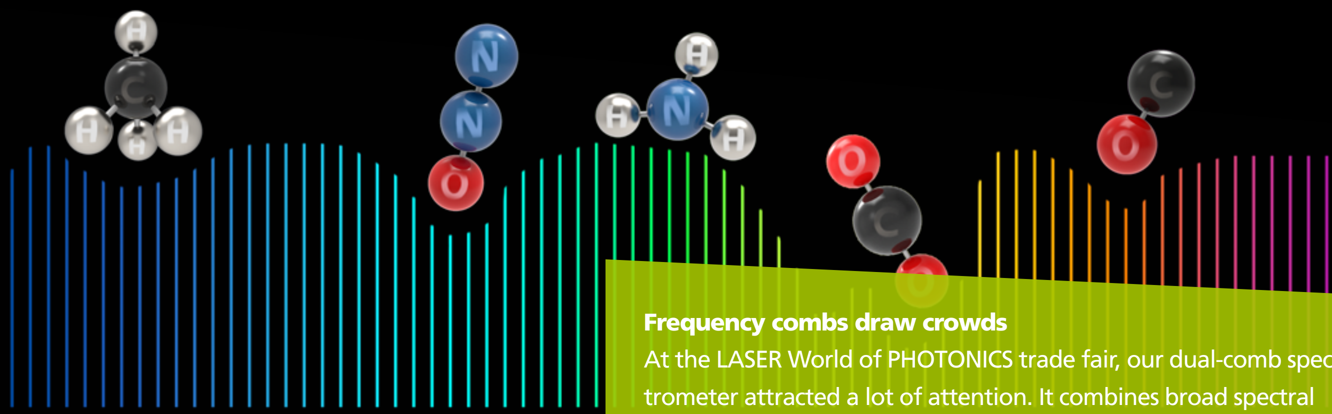
- Photothermal techniques for highly sensitive absorption spectroscopy in solids and gases
- Dual-comb infrared gas spectroscopy
- VIS, NIR, and MIR spectroscopy
- Spectroscopy for detecting residual absorption in materials down to 1 ppm

QUANTUM SENSOR TECHNOLOGY

- Spectroscopy with entangled photon pairs – quantum Fourier transform infrared spectrometer
- Magnetic field sensors with optically pumped magnetometers – NMR at ultra-low magnetic fields

Quantum FTIR makes its debut

Fraunhofer IPM co-organized the scientific workshop “Sensing with Quantum Light,” which drew more than 40 scientists from Germany, elsewhere in Europe, the USA, and Singapore to the Physikzentrum Bad Honnef in September. At the workshop, our quantum FTIR spectrometer was presented to the scientific community for the first time.



Frequency combs draw crowds

At the LASER World of PHOTONICS trade fair, our dual-comb spectrometer attracted a lot of attention. It combines broad spectral coverage in the mid-infrared range with high resolution, making it especially suitable for the analysis of complex gas mixtures.

IsoNova project – advances in characterizing absorption

New optical materials specifically for high-power lasers are the goal of this publicly funded project. Our team developed a highly sensitive spectrometer for characterizing optical absorption. We could confirm excellent properties for the first batches of new crystals produced by the consortium.

Micro-pellistors – new sensors for combustible gases

Is a gas atmosphere explosive or not? This question commonly arises in industrial process metrology, for example to ensure that processing equipment runs safely. Catalytic combustion sensors, known as pellistors, are often used to detect combustible gases and explosive gas mixtures. Fraunhofer IPM has developed innovative micro-pellistors based on new materials which make combustible gas detection especially reliable and both, energy and cost efficient.

What is the distinguishing characteristic of combustible gases? That's right, they burn! But while it may initially seem straightforward, detecting these gases proves more complex in practice. After all, sensor systems have to be able to determine the combustibility of a gas without triggering a fire or an explosion. Pellistors are an example of a safe sensor. They detect combustible gases such as methane, propane, or hydrogen by adsorbing the gas on the surface of a catalyst, where it oxidizes in a contained reaction process. The catalytic oxidation of the gas causes the temperature to rise, which in turn changes the resistance of a platinum-based heater. In a predefined application scenario, the presence of a specific combustible gas and a rough estimate of its concentration can be derived from this measurement signal.

Catalytic sensors – inexpensive and reliable, but not without drawbacks

Catalytic sensors offer three main advantages. They are easy to install, can be calibrated reliably, and operate based on a simple principle. But even cutting-edge pellistors have several drawbacks, including high operating temperatures of more than 400 °C, high power consumption, and a high susceptibility to catalyst poisons. Due to their significant power consumption, pellistors have found only limited use in mobile applications, where battery life is short. Fraunhofer IPM' s goal was thus not just to develop a miniature pellistor, but in particular to lower the operating temperature and with it the power consumption.

Since pellistors primarily rely on a catalytic layer for detecting gases, reducing the operating temperature requires the use of highly active catalysts. Methane is one of the most inert combustible gases, meaning that either especially active catalysts or very high operating temperatures (over 450 °C) are needed for its detection. These high operating temperatures cause the difficulties in reliable methane detection.

New materials for new sensors

To lower the operating temperature of pellistors, new catalytic materials have to be found – in particular for methane detection. Only with the introduction of catalytic materials offering improved activity will it be possible to design new, highly energy-efficient pellistors with the same level of stability. However, developing such catalysts is anything but easy, for three reasons. Firstly, the catalysts used in sensors are complex systems consisting of a catalytic material and various additives that are essential for integration into the sensor and for the mechanical stability of the catalytic layer.

< Sensors for detecting combustible gas mixtures, such as those used in the process industry, traditionally operate at high temperatures. In order to tap into new markets such as electric vehicles, hydrogen technology, or safety monitoring in technologically advanced buildings, decentralized, low-power sensors are needed.

A **SIMULTANEOUS THERMOGRAVIMETRY-DIFFERENTIAL THERMAL ANALYSIS SYSTEM** enables the characterization of new catalytic materials. Thermogravimetry is used to measure the change in a material's mass during a known heating or cooling process. At the same time, a differential thermal analysis is performed, which involves recording the quantity of heat emitted or absorbed by a material when it is heated or cooled.

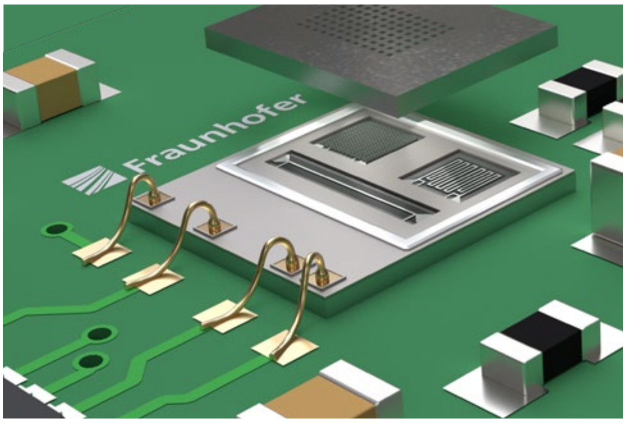
Not only can these additives influence both the activity and the stability of the catalyst, but their effect is difficult to identify using gas sensor characterization. Secondly, the reaction captured by a sensor is itself a complex reaction that is determined by the entire sensor system. And thirdly, preparing individual sensors is a very extensive process.

Reliable measurement methods for analyzing catalytic materials

To overcome these limitations affecting the development of pellistor gas sensors, Fraunhofer IPM turned to a simultaneous thermogravimetry-differential thermal analysis system in combination with a quadrupole mass spectrometer. This enables a systematical analysis of how the particle size distribution and morphology of Co_3O_4 influence its thermal stability and its catalytic activity for methane oxidation. The results achieved with this measurement technology demonstrate the method's reliability as a way of narrowing down the potential catalysts for use in catalytic gas sensors. Metal oxides with spinel structures, such as Co_3O_4, $Ni_xCo_{3-x}O_4$, $Co_{3-x}Cu_xO_4$ or $Co_{3-x}Zn_xO_4$, are particularly suitable for the catalytic combustion of methane, allowing innovative new micro-pellistors to achieve significant reductions in temperature for catalytic reactions.

Promising applications

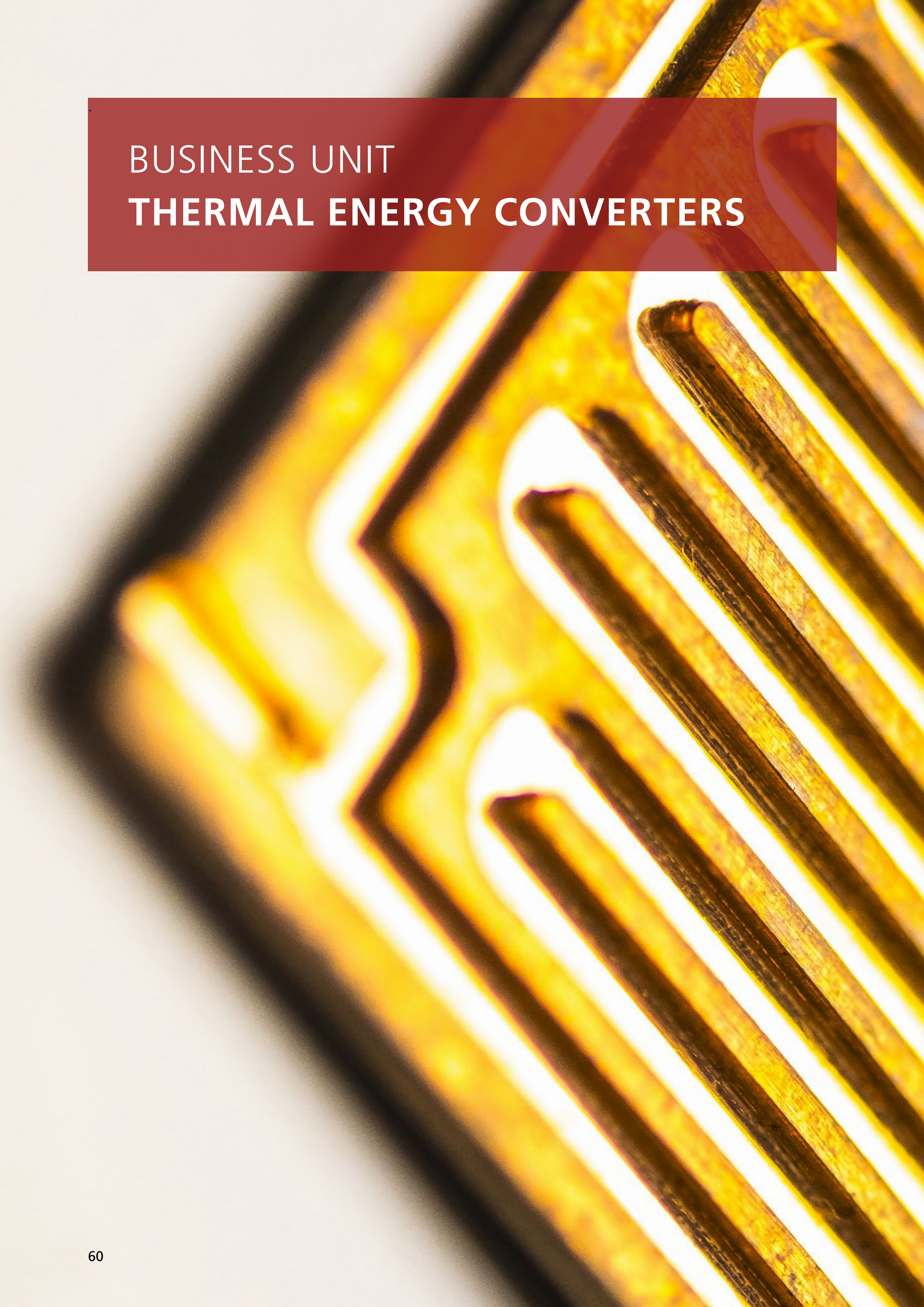
With these innovative methods for designing new catalytic materials, Fraunhofer IPM has laid the foundation for the next generation of micro-pellistors that operate at temperatures of under 350 °C. This makes it possible to design especially energy-efficient sensors that can function with less than 100 mW of power. Dimensions of under 3 mm² and the option of cost-efficient series production open up excellent opportunities in traditional markets such as mining, gas and fuel storage, and the petrochemical industry. But there are also good prospects in growth markets including smart home and consumer applications, electromobility, hydrogen technology, and infrastructure protection.



This is how it shall look like: Close-up of the low-power radio system's micro-pellistor for the detection of combustible gases.

Prof Dr Jürgen Wöllenstein, P +49 761 8857 - 134, juergen.woellenstein@ipm.fraunhofer.de

BUSINESS UNIT
THERMAL ENERGY CONVERTERS



“We pump, convert, conduct and switch heat – tailored to novel applications.”

Functional materials with special physical properties are a focus of the research performed by the “Thermal Energy Converters” business unit. We use caloric and thermoelectric materials to build innovative systems for cooling, temperature control, and converting heat into electricity.

Using these materials in heat pumps, cooling systems, and generators makes the systems we develop especially environmentally friendly, cost-efficient and durable. Beyond that, we devise, build, and characterize new types of heat pipes, especially pulsating heat pipes, for efficient heat transfer.

Dr Olaf Schäfer-Welsen
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Group **Thermoelectric Systems**

- Waste heat recovery (electric output in the kilowatt range)
- Direct waste heat recovery in furnaces (electric output in the watt range)
- Energy harvesting (electric output in the milliwatt range)
- Peltier cooling

Group **Caloric Systems**

- Efficient cooling and heating (magnetocalorics, elastocalorics, electrocalorics)
- Efficient heat transfer by means of latent heat (heat pipes)
- Thermal management
- Efficient hotspot cooling for high-performance electronics

< Pulsating heat pipes – here in planar design – dissipate heat very efficiently. This makes them suitable for cooling high-performance electronics, for example.

BUSINESS UNIT **THERMAL ENERGY CONVERTERS**

GROUP **THERMOELECTRIC SYSTEMS**

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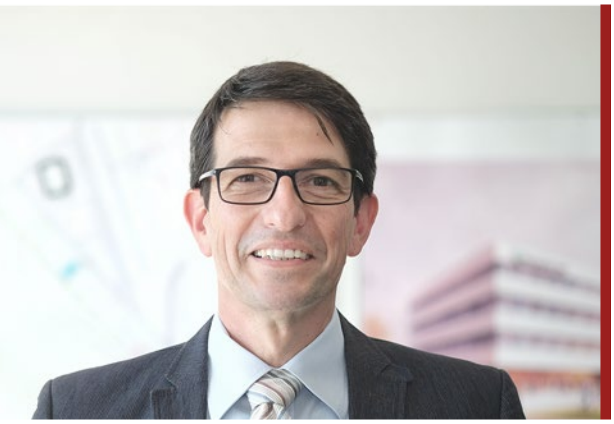
The group's research focuses on thermoelectric modules and systems, with activities ranging from system construction for demonstrators to functional testing on our own test beds or in the field to simulation calculations and validation measurements for optimally designed thermoelectric modules. The team draws on more than 20 years of experience in materials and module development, measurement technology, simulation processes, and system construction. One of the group's core areas of expertise is the development of electrical and thermal contacts that remain stable at high temperatures. A positioning robot developed at the institute enables cost-effective semi-automatic production of thermoelectric modules.

Our thermoelectric generators are used in high-temperature processes to convert waste heat into electricity. In energy harvesting, they exploit minuscule differences in temperature to generate power, for example to operate sensors and transfer sensor data. In addition, the modules can be used as Peltier modules in cooling applications where extremely precise temperature control is needed.



Group Manager: Dr Olaf Schäfer-Welsen

WASTE HEAT RECOVERY

- Thermoelectric modules for use at high temperatures
- Thermoelectric modules to improve the electric efficiency of combined heat and power plants
- Conversion of waste heat into electricity in combustion engines and industrial processes

USING WASTE HEAT IN FURNACES

- Thermoelectric modules for low electric output
- Self-powered operation of electric system components
- Self-powered measurement technology and control engineering for low-emission operation

ENERGY HARVESTING

- Converting waste heat into smallest electric output
- Power management
- Data transfer and analysis
- Comprehensive solutions suitable for IoT applications

PELTIER COOLING

- Precise temperate control of processes and components
- Materials optimized for use at specific temperatures
- System solutions tailored to the requirements of the customer and the application

Using waste heat in furnaces

When integrated into a furnace, a TEG can produce more electrical energy from waste heat than is needed to run the furnace. The excess electricity can be fed into the grid or used to power the furnace's sensors, for example. The group has equipped a pellet stove with this technology.

Turning waste heat into electricity – successful field test of thermoelectric generators

To improve the energy efficiency of combined heat and power plants (CHPs), the group is developing and building thermoelectric generators (TEGs) that turn waste heat into energy. Three TEG systems for different types of CHPs successfully completed long-term testing in the field in 2019. The electrical output of the CHPs has been increased by approximately 1 to 1.5 percent thus far.

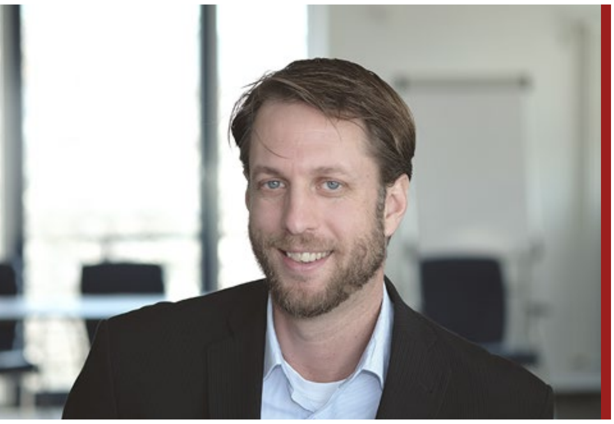
BUSINESS UNIT **THERMAL ENERGY CONVERTERS**

GROUP **CALORIC SYSTEMS**

Dr Kilian Bartholomé, P +49 761 8857 - 238, kilian.bartholome@ipm.fraunhofer.de

Innovative caloric systems for heating and cooling represent a key area of research for the group. Our work comprises the development, conception and assembly of efficient heat pumps and cooling systems based on magnetocaloric, electrocaloric or elastocaloric materials without the use of harmful refrigerants. We draw on more than 20 years of experience working with functional materials, in particular the characterization, simulation, and system integration thereof.

Novel concepts for efficient heat transfer based on pulsating heat pipes (PHPs) represent another field of work for the group. PHPs transfer heat considerably more efficiently than copper, for example, and they offer several advantages over conventional heat pipes. The PHPs we develop are used for electronic component cooling and targeted thermal management. Moreover, we are conducting research on heat pipe-based thermal switches for precisely regulating heat flows.



Group Manager: Dr Kilian Bartholomé

EFFICIENT HEATING AND COOLING

- Reduced energy needs thanks to efficient technology
- Heating and cooling without harmful refrigerants
- Compact design resulting from high energy density of caloric materials
- Low-maintenance systems

THERMAL MANAGEMENT

- Fast, precise temperature control with Peltier elements
- Passive cooling of electronic components using heat pipes
- Efficient heat distribution thanks to pulsating heat pipes
- Effective thermal conductivity higher than 3000 W/mK

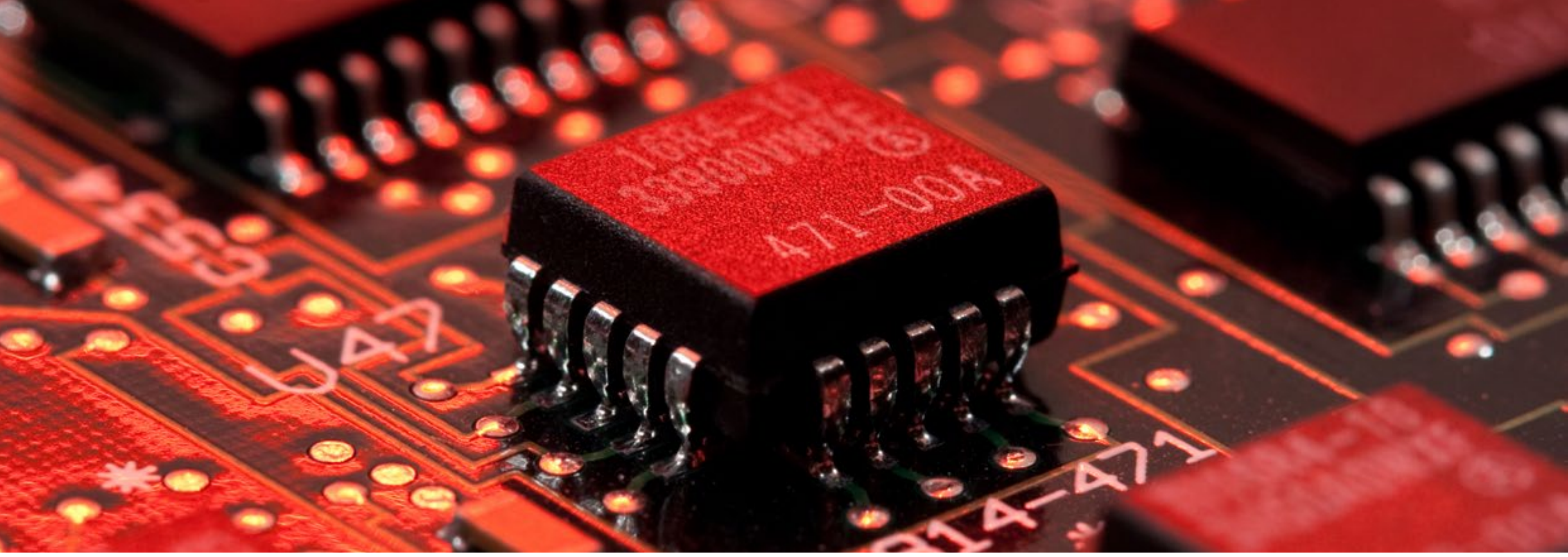
HIGH EFFICIENCY HEAT TRANSFER WITH LATENT HEAT

- Heat transfer via evaporation and condensation
- Heat transfer coefficient of higher than 10^5 W/($m^2 \cdot$ K)
- Extremely fast and efficient heat transfer for system frequencies up to 20 Hz

2nd Caloric Systems Workshop
Around 70 experts from science and industry came together at the second Caloric Systems Workshop to discuss the state of the art and the potential that caloric systems have to offer. The third Caloric Systems Workshop will take place in 2021.

Energy-efficient electrocaloric heat pumps without harmful refrigerants
Since October 2019, Fraunhofer IPM has been working together with five other Fraunhofer institutes on the "ElKaWe" lighthouse project, which centers on the development of electrocaloric heat pumps. These highly efficient systems can operate without harmful refrigerants and could be a disruptive innovation in the field of heating and cooling technology.

Elastocaloric cooling system with record-breaking long-term stability
One of the greatest challenges in creating elastocaloric systems is ensuring their long-term stability. Fraunhofer IPM has succeeded in developing the first elastocaloric system with a long-term stability of over 10^7 cycles – well above the international state of the art.



Effectively conducting and switching heat

Many industrial sectors have a keen interest in the ability to precisely and effectively regulate temperatures. Heat pipe-based cooling offers an especially efficient option for the thermal management of highly integrated electronic components. Specialized thermal switches can even improve the efficiency of traction batteries, shorten the cold start time for combustion engines, and optimize industrial forming processes. Fraunhofer IPM is conducting research on a new generation of heat pipes and thermal switches and developing application-specific solutions for thermal management.

Overheating is the cause of electronics failures in computers, cars, or airplanes in more than half of all cases. As microelectronic components become ever smaller and more powerful, they produce thermal losses that at times can exceed 100 watts per square centimeter. Cooling these hot spots effectively is essential to ensure that components function faultlessly. Passive cooling designs such as heat pipes (HPs) are especially suitable for these applications, because – unlike active water or air cooling – they have no moving parts and do not require an external power supply. Heat pipes are connected to components and dissipate heat via a condensation and evaporation circuit.

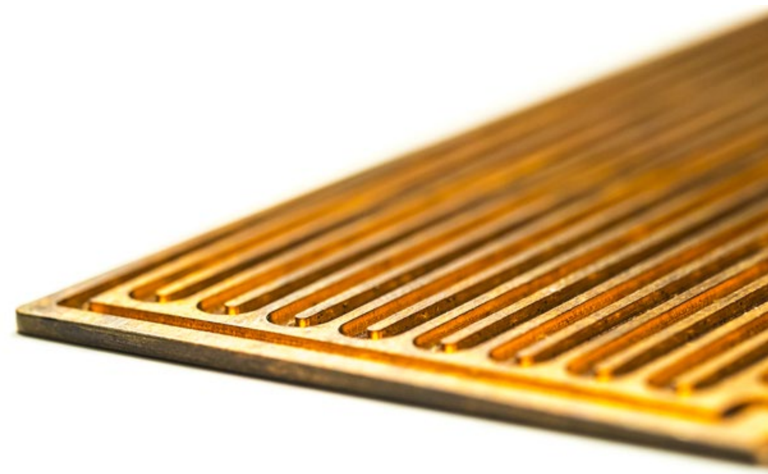
Planar pulsating heat pipes: effective, compact and stable

Fraunhofer IPM develops pulsating heat pipes (PHPs) as an efficient cooling concept for hot spots. In contrast to conventional HPs, PHPs allow for an especially compact, flat, and stable design that simultaneously ensures a high heat transport capacity. This makes them ideal for cooling electronics where the HP height should not exceed 3 mm. In PHPs, heat is transported by both sensible and latent heat. They consist of a capillary structure filled with a working fluid that separates into vapor and fluid segments. Temperature differences between a heat source and a heat sink generate a pulsating movement of these segments, which results in the self-sustaining transport of the fluid through the channels and dramatically improves heat transfer. PHPs can be used as highly effective heat conductors or heat spreaders. As part of various R&D projects, researchers at Fraunhofer IPM have been developing and testing PHPs in a variety of designs using different materials such as copper or glass. In addition, essential techniques were investigated for evacuating, filling, and assembling the pipes, including transient liquid phase (TLP) bonding as well as other soldering and welding techniques. With its prototype of a planar PHP made of copper, Fraunhofer IPM has achieved a thermal conductivity comparable to that of diamond. For the prototype, thin meandering channels were milled into a 1.5 to 2 mm thick copper plate and then partially filled with

< Highly integrated electronic components generate a lot of heat in a small space. Pulsating heat pipes can be used to efficiently dissipate this heat.

THERMAL SWITCHES based on heat pipes can be produced with integrated functional materials. One of the approaches investigated is based on switchable hydrophilic/hydrophobic coatings that make it possible to change the preferred direction of the heat flow (actively switchable thermal diodes). Research is also being conducted on hydrogels, which absorb the working fluid in the heat pipe when the temperature drops below a specified point, thereby "locking it in." When the temperature rises above the set point, the fluid is released again, activating the heat pipe (temperature-sensitive thermal switch).

fluid and evacuated. These planar PHPs could be directly integrated into printed circuit boards. They are far more stable than so-called vapor chambers (planar heat pipes with hollow-chambers) and thus can better withstand the pressure used to laminate printed circuit boards.
Heat pipe-based cooling concepts are an especially attractive option for industry, which is why the team at Fraunhofer IPM is working to find solutions for simulation-based design that would make it possible to model the complex physical relationships in a PHP. The goal is to be able to optimize variables such as size, working fluid, and the connection to the heat sink for each specific application. Intensive research is also underway at the institute on alternative materials and manufacturing processes such as 3D printing or roll bonding, in order to enable flexible, form-specific, and cost-effective manufacturing.



Heat pipes aren't limited to pipe form. They can also be produced as plates just 2 to 3 millimeters thick, making them especially suitable for an integrated cooling of electronic components.

Switching heat on and off
Heat pipes not only dissipate heat, they also make it possible to turn heat flows on and off and regulate them precisely – just as with electric switches. While such thermal switches can be used to enhance, simplify, or even replace active temperature control systems, they have some drawbacks: Their design is complex and they typically only transfer small heat flows. Fraunhofer IPM is collaborating with other Fraunhofer institutes on a new generation of thermal switches based on switchable hydrophilic/hydrophobic coatings and hydrogels. These switches are small and do not require any moving parts. Thanks to their simple design, they are easy to integrate and promise significant improvements in heat transport capacity. The institute has already realized a conceptual study of a heat pipe-based thermal switch featuring a constant hydrophilic coating and including all of the necessary assembly, connection, and filling technology.

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> The SENSOR+TEST measurement fair in Nuremberg is the leading event for Fraunhofer IPM's research topics in the area of gas and process technology.

TRADE FAIRS 2019

4th VDI Technical Conference Vibrations in Machine Tools and Processing Machines
Stuttgart, 3/26–27/2019
Fraunhofer IPM presented the HoloCut system for comprehensive 3D measurement of components in machine tools and gave a lecture on the topic of 3D measurement of precision parts by means of holography.

HANNOVER MESSE
Hannover, 4/1–5/2019
Joint Fraunhofer booth
Fraunhofer IPM presented gas sensors for monitoring industrial processes, leakage detection, and climate control, among them semiconductor gas sensors, IR emitters, colorimetric, and photoacoustic sensors.

Control – International Trade Fair for Quality Assurance
Stuttgart, 5/7–10/2019
Fraunhofer Vision Alliance booth
Several measurement systems for production control were exhibited: "HoloPort" for 3D inline measurement in machine tools, "Track & Trace Fingerprint" for component tracing, "F-360°" for 100 percent surface testing of semi parts in free fall and an inline particle detector for 100 percent cleanliness control the component surface.

AUTOMOTIVE ENGINEERING EXPO
Nuremberg, 6/4–5/2019
AMEPA GmbH booth
Together with AMEPA GmbH, Fraunhofer IPM's Optical Surface Analytics group presented its fluorescence scanner for automated, imaging oil film measurement.

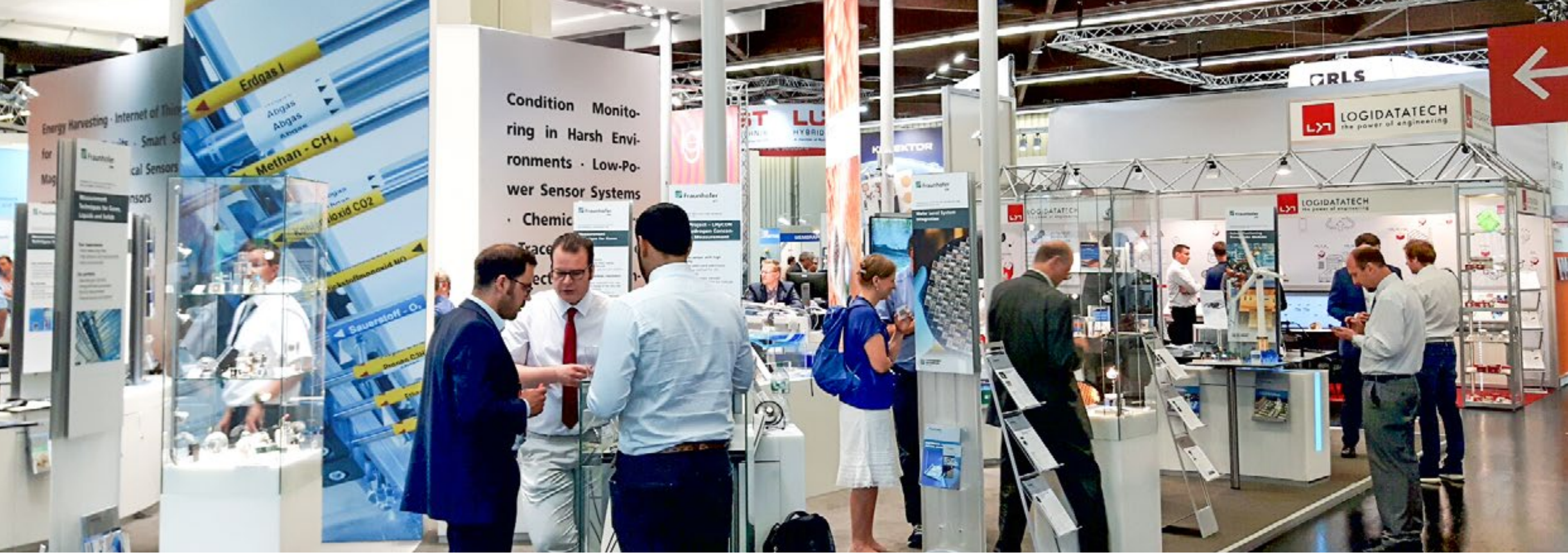
LASER World of PHOTONICS – International Trade Fair for Photonics Components, Systems and Applications
Munich, 6/24–27/2019
Joint Fraunhofer booth
Fraunhofer IPM presented various spectroscopic systems for process analytics. A frequency comb spectrometer for trace gas measurements in the mid infrared was introduced for the first time.

SENSOR+TEST – The Measurement Fair
Nuremberg, 6/25–27/2019
Joint Fraunhofer booth
The institute displayed the entire range of integrated sensor systems, thermal measurement technology and spectroscopy systems for process analytics.

INTERGEO – Conference and Trade Fair for Geodesy, Geoinformation and Land Management
Stuttgart, 9/17 –19/2019
Own booth
The tunnel inspection system TIS was presented for the first time. TIS measures the geometry and moisture of tunnel surfaces simultaneously by using a multispectral laser scanner. AI-based automated analysis of measurement data was another key topic at the fair.

12th Fraunhofer Vision Technology Day
Fürth, 10/23–24/2019
Fraunhofer IPM scientists gave lectures on 100 percent surface testing and inline particle detection. A system for component inspection in free fall was presented as part of the exhibition.

parts2clean – Leading International Trade Fair for Industrial Parts and Surface Cleaning
Stuttgart, 10/22–24/2019
Fraunhofer Cleaning Technology Alliance booth
The Optical Surface Analytics group presented its portfolio of automated surface inspection systems.



TRADE FAIRS SCHEDULED FOR 2020

Due to the corona pandemic, many organizers have cancelled or postponed trade fairs and events, some introduced digital formats.

VDI regio Career
Freiburg, 4/25/2020
(postponed to 2021)

Control
Stuttgart, 5/5–08/2020
(cancelled)

Freiburger Wissenschaftsmarkt
Freiburg, 6/19–20/2020
(postponed to 2021)

Sensor+Test
Nuremberg, 6/23–25/2020
(cancelled)

HANNOVER MESSE
Hannover, 7/13–17/2020
(cancelled)

InnoTrans
Berlin, 9/22–25/2020
(cancelled)

INTERGEO
Berlin, 10/13–15/2020

Chillventa
Nuremberg, 10/13–15/2020

13. Fraunhofer Vision Technologietag
Fürth, 10/21–22/2020

parts2clean
Stuttgart, 10/27–29/2020

EuroBLECH
Hannover, 10/27–30/2020

MEDICA
Düsseldorf, 11/16–19/2020

Oceanology International
London, 12/1–3/2020

WORKSHOPS & EVENTS 2019

Industry Workshop on Thermoelectrics

Fraunhofer IPM, 3/20–21/2019

Some 60 participants attended the Industry Workshop on thermoelectrics, which Fraunhofer IPM organized for the first time in cooperation with the German Thermoelectric Society. The program with twelve lectures focused technological developments in the fields of thermoelectric generators and Peltier cooling technology.

Caloric Systems Workshop

Fraunhofer IPM, 3/27–28/2019

The workshop was held for the second time in cooperation with the German Society of Refrigeration and Air Conditioning as well as Innovationsnetzwerk Magnetokalorik (Magnetocalorics Innovation Network). The program featured ten lectures on caloric materials and magneto-, electro- and elastocaloric systems. The accompanying exhibition displayed no fewer than four operative caloric systems for the first time.

8th Gas Sensor Workshop

Fraunhofer IPM, 10/24/2019

Once again, the gas sensor community met at the institute to discuss technologies and applications in the field of gas sensors. The program included eight lectures and an exhibition. Topics covered environmental measurement technology, gas detection in industrial production processes, and fire gas detection. (Read more on page 19.)

JOINT EVENTS BY FREIBURG'S FRAUNHOFER INSTITUTES

70 years of Fraunhofer: Public event

Freiburg, 9/28/2019

Thousands of people attended the public festival organized by the five Freiburg Fraunhofer institutes in the city center, celebrating the 70th anniversary of the Fraunhofer-Gesellschaft. (Read more on pages 16 to 17.)

Celebrating the 70th anniversary of the Fraunhofer Gesellschaft: Scientists like Dr Kilian Bartholomé from Fraunhofer IPM presented their research activities to the public.

WORKSHOPS 2020 (PREVIEW)

MoLaS – Technology Workshop Mobile Laser Scanning

Originally scheduled for 11/11–12/2020 (postponed)

The fourth MoLaS workshop will be postponed to November 2021 due to the Corona pandemic.

< The escape game for students as part of the big festival of the Freiburg Fraunhofer institutes required cooperation and creativity.

OUR PARTNERS

We are actively involved in groups, specialist organizations and networks, within the Fraunhofer-Gesellschaft, nationwide and worldwide.

Fraunhofer Group for Light & Surfaces

The Fraunhofer Group for Light & Surfaces brings together the Fraunhofer-Gesellschaft's scientific and technical expertise in the areas of laser, optical, measurement and surface technology. With a total of approximately 1800 employees, the six Fraunhofer Institutes in the Group work together to solve complex, application-oriented customer inquiries at the cutting edge of science and technology. But the Fraunhofer Institutes are not only partners in innovation. They also work to produce new generations of scientific and technical experts. In cooperation with the local universities, the young scientists at the Fraunhofer Institutes bring together academic research and industry. Since October 2019, Prof. Karsten Buse has been the Chair of the Group and Dr Heinrich Stülpnagel has been head of central office.
www.light-and-surfaces.fraunhofer.de

Fraunhofer-Gesellschaft

- Fraunhofer-Verbund Light & Surfaces
- Fraunhofer-Allianz Food Chain Management
- Fraunhofer-Allianz Reinigungstechnik
- Fraunhofer-Allianz Verkehr
- Fraunhofer-Allianz Vision

International

- ETS – European Thermoelectric Society
- ITS – International Thermoelectric Society
- MRS – Material Research Society
- OSA – The Optical Society

Germany

- AMA Association for Sensors and Measurement
- Arbeitskreis 4.3.2 Ebenheit der Forschungsgesellschaft für Straßen- und Verkehrswesen e. V. (FGSV)
- Arbeitskreis Prozessanalytik der GDCh und DECHEMA
- Competence Center for Applied Security Technology e. V. (CAST)
- CNA e.V. – Cluster Bahntechnik
- Deutsche Forschungsgesellschaft für Oberflächenbehandlung e.V. (DFO)
- Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V. (DGPF)
- Deutsche Hydrographische Gesellschaft e.V. (DHyG)
- Deutscher Kälte- und Klimatechnischer Verein (DKV) e.V.
- Draht-Welt Südwestfalen – netzwerkdraht e.V.
- Deutsche Thermoelektrik Gesellschaft e.V. (DTG)
- Forum Angewandte Informatik und Mikrosystemtechnik e.V. (FAIM)
- Gesellschaft Deutscher Chemiker e.V. (GDCh)
- Cluster Green City Freiburg
- innoEFF Innovations- und Effizienzcluster
- microTEC Südwest e.V.
- Nano-Zentrum Euregio Bodensee e.V. (NEB)
- Photonics BW e. V. - Innovations-Cluster für Optische Technologien in Baden-Württemberg
- Strategische Partner – Klimaschutz am Oberrhein e.V.
- VDI/VDE-Gesellschaft Mess- und Automatisierungs technik (GMA)
- VDSI - Verband für Sicherheit, Gesundheit und Umweltschutz bei der Arbeit e.V.

PUBLICATIONS 2019

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Technische Sicherheit 9 (10), 36-39 (2019)

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Lyu, X.; Gao, H.; Diehle, P.; Altmann, F.; Tarantik, K.; Schmitt, K.; Wöllenstein, J.

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Optics Express 27, 34559-34581 (2019)

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Comerón, A. [Ed.]: Remote Sensing of Clouds and the Atmosphere XXIV. Proceedings of SPIE 11152, Paper 111520M (2019)

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Bostater, C. R. [Ed.]: Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions. Proceedings of SPIE 11150, Paper 111500M (2019)

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OSA: Digital Holography and Three-Dimensional Imaging. Paper Th3A.7 (2019)

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Experimental evaluation of human kidney stone spectra for intraoperative stone-tissue-instrument analysis using autofluorescence

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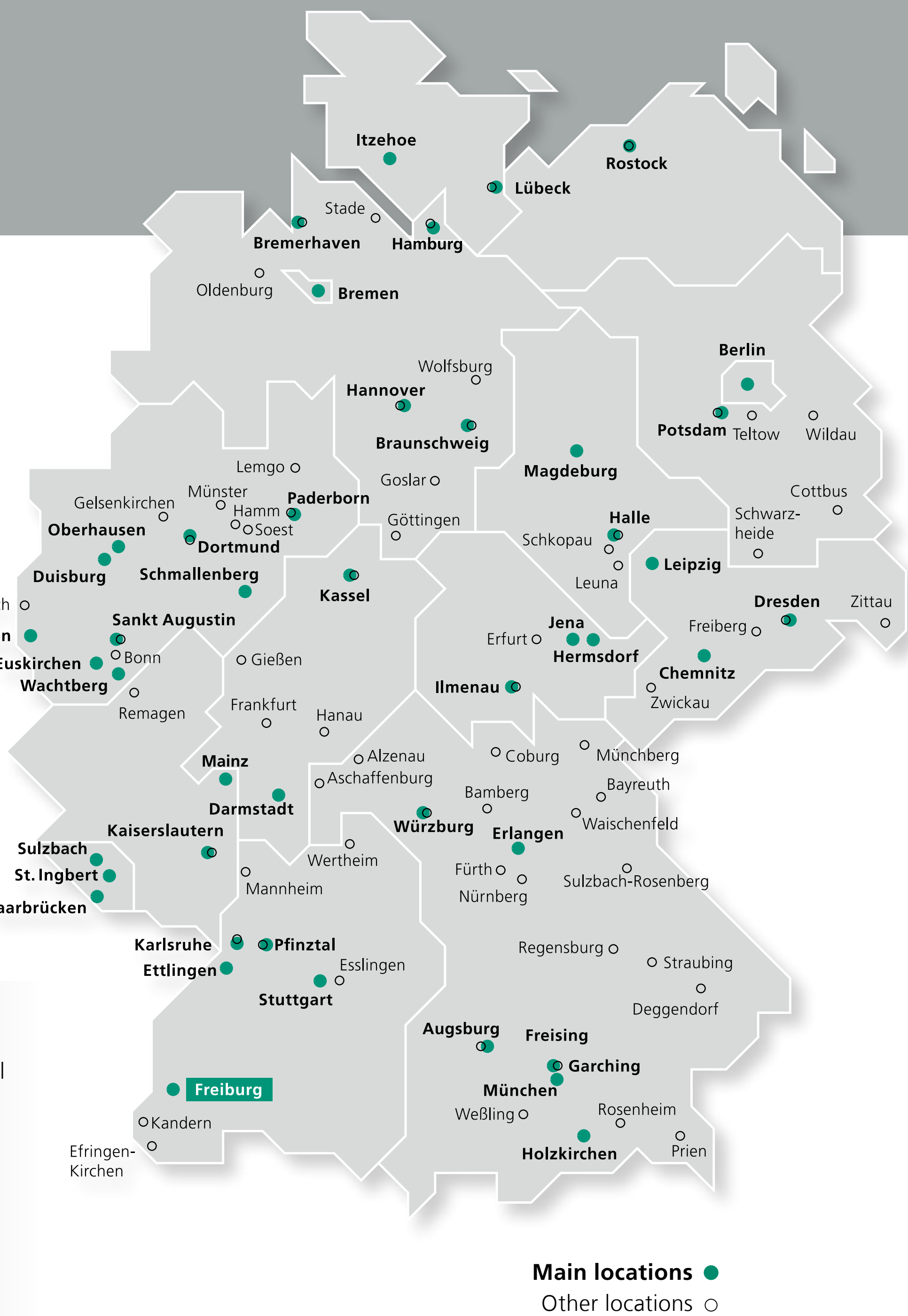

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