FRAUNHOFER INSTITUTE FOR PHYSICAL MEASUREMENT TECHNIQUES IPM

MEASURING · MONITORING · OPTIMIZING

2020/2021

Fraunhofer
IPM

Annual report 2020/2021

Measuring with light: New standards on the horizon!

Measuring • Monitoring • Optimizing

<< Cover *The HoloTop NX optical sensor measures the topography of component surfaces directly in the machine tool, detecting the surface and depth of milling paths over large areas. Due to its compact design, comparable to typical milling tools, it can be integrated into many types of machine tools.*

OUR BUSINESS UNITS

- PRODUCTION CONTROL
- OBJECT AND SHAPE DETECTION
- GAS AND PROCESS TECHNOLOGY
- THERMAL ENERGY CONVERTERS

MEASURING COORDINATES AND DISTANCES WITH LIGHT: NEW STANDARDS ON THE HORIZON!

Dear customers,
dear partners,

Humans have developed increasingly sophisticated tools for measuring lengths, distances and dimensions – from the simple yardstick to micrometer screws and tactile measurement heads. Modern tactile coordinate measuring machines can record the structure of complex 3D components to the nearest thousandth of a millimeter. Optical measurement methods – which in their simplest form involve judging by eye – were long considered mere methods of estimation and were therefore largely excluded from norms and standards.

Light measurements: fast, accurate and contactless

Laser technology – particularly using temporal coherence – and also dramatic advances in cameras and data processing have greatly improved the accuracy of the "photonic yardstick", and are increasingly outstripping tactile processes. Measurements using light are more accurate, considerably faster and also contactless.

Optical coordinate measuring machine

In coordinate measurement technology, we rely on digital holography which offers considerable added value compared with tactile processes. Thanks to its speed, it can achieve 100% inspection at the rate of production. The title image shows a digital holographic sensor for machine tools. In case of tool wear, active adjustment is possible, which allows us to guarantee quality and minimize rejects. In our new building, we operate one of the most precise tactile coordinate measuring machines in Germany. It serves as a point of reference for the optical coordinate measurement machine which we are developing in the project "MIAME – Micrometers to meters: Laser light for submicron 3D measurements on the meter scale" (p. 33).

Highlights: minimized herbicide use, multi-component analysis and record-breaking magnetocalorics

Optical measuring on large length scales with high levels of accuracy and breathtaking speed is steadily replacing traditional measurement techniques in the field of infrastructure surveying and monitoring. Mounted on trains, our cameras record the vegetation in the track bed quickly and accurately so herbicides can be applied exclusively where they are required instead of being poured out indiscriminately (p. 44). We have also been successful in further developing our optical tools for gas and material analysis. Just take a look at broadband spectroscopy with frequency combs, for example (p. 56). We achieved a breakthrough in operating magnetocaloric heat pumps with 10 Hz cycle frequency. Our results were published in the Nature research journal "Communications Physics" (p. 64).

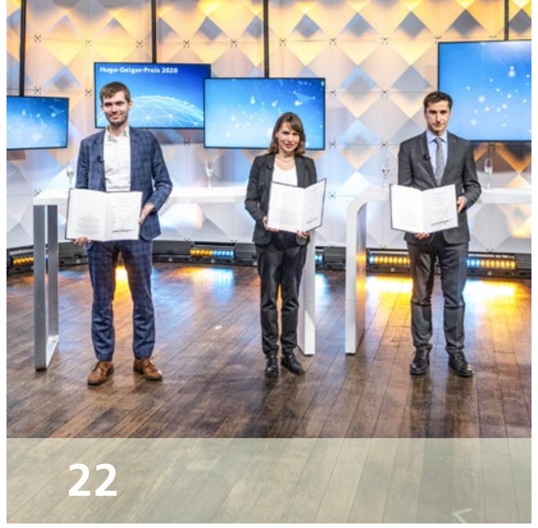
Our innovative strength is a good reason to maintain contact, even during a pandemic. With almost 50 participants, the Online Forum event series got off to a strong start in December, and follow-up events were regularly attended by over 100 interested parties. And we have increased our social media presence to make sure we stay in touch with stakeholders.

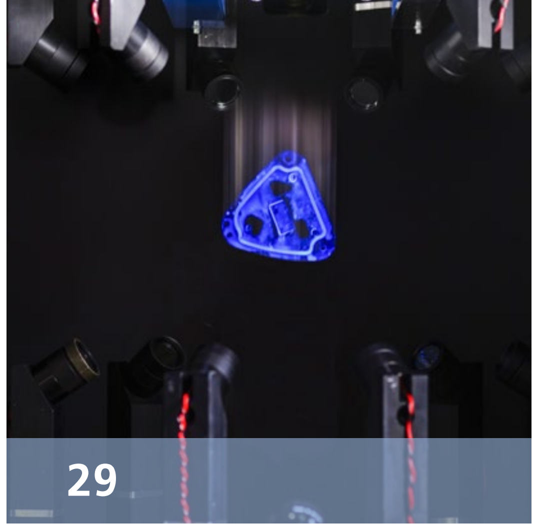
No matter how you prefer to connect with us, take a look inside – we are always happy to hear from you! Enjoy browsing through our annual report and discovering our innovations.

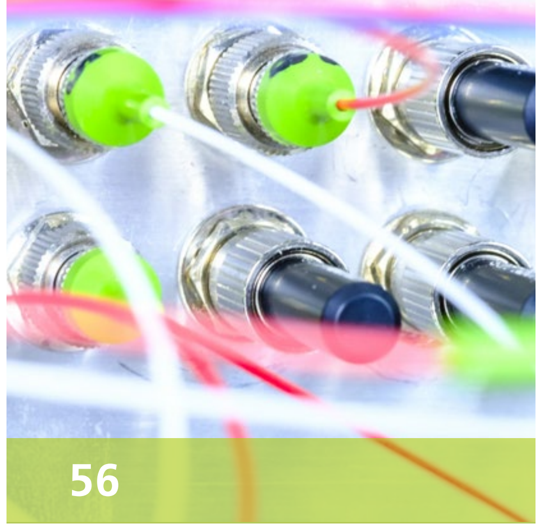
Yours,

Karsten Buse

Prof. Dr. Karsten Buse, Director







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Prof. Dr. Karsten Buse


Deputy Director
Dr. Daniel Carl

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Research
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Organizational Development
Dr. Heinrich Stülpnagel

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Head of Administration
Wolfgang Oesterling


Administration
Sabine Gabele


Information and Communications Technology
Gerd Kühner


Human Resources
Anneliese Zwölfer

TECHNICAL SERVICES


Head of Technical Services
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Mechanics and Construction
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Facility Management
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Thermoelectric Systems
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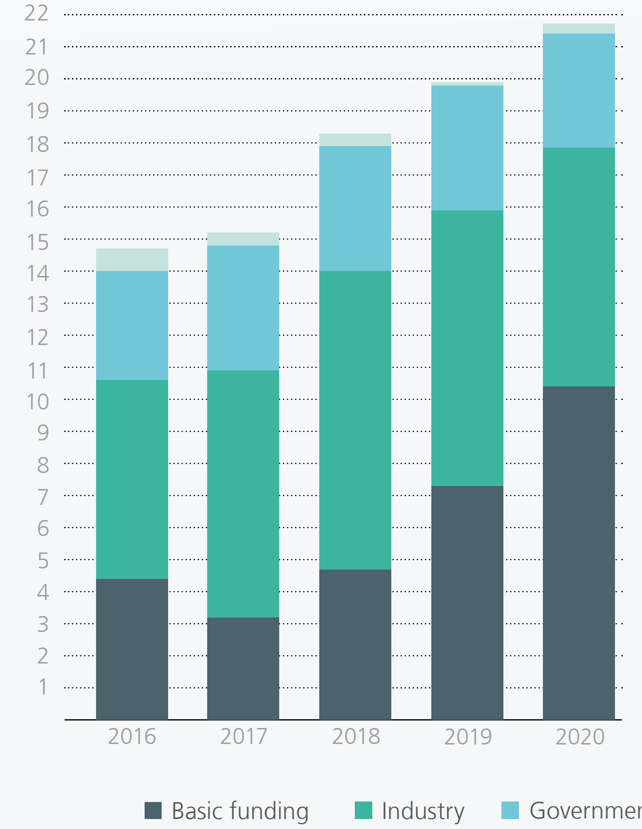
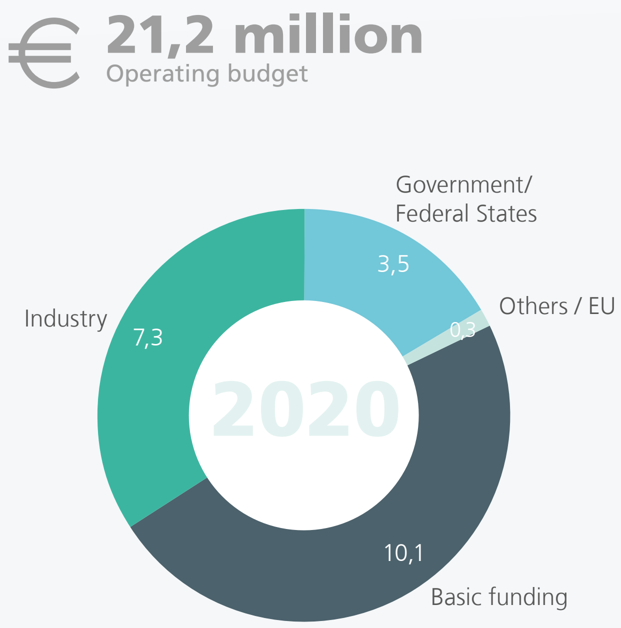




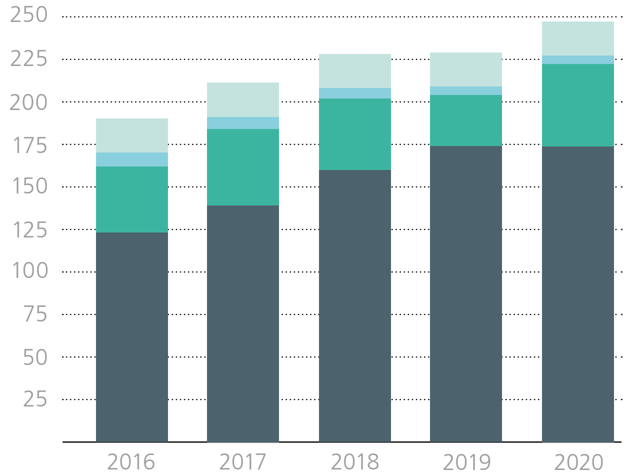
GROWTH DESPITE THE PANDEMIC AND OUR MOVE TO A NEW BUILDING

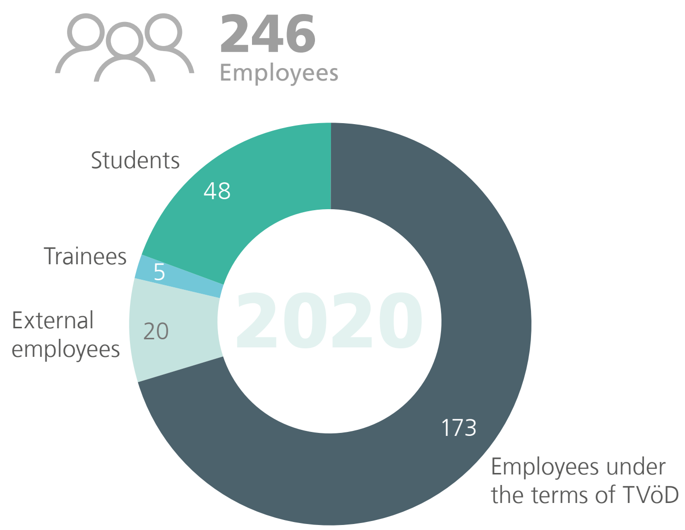
Despite the pandemic, in 2020 we were able to set a successful strategic and organizational course, implement a number of successful research projects and attract research funding. From August to October, notwithstanding the difficult conditions of the Covid crisis, the move into our new building went smoothly.

2020 was an exceptional year. The pandemic caused commercial exhibitions to be canceled and threw industrial partners into difficult situations. At the same time, structural changes affected entire sectors, above all the automotive industry. We were able to meet these challenges by using digital channels and maintaining existing contacts so that the combined yield from contract research hardly changed. The rise in regular base funding is partly due to the move to the new building and partly because the institute was exceptionally successful in the internal Fraunhofer competition awarding research funding for particularly innovative ideas. On the whole, despite the pandemic and despite the complete move of our institute, 2020 saw just over seven percent growth of our operating budget and a positive annual result.

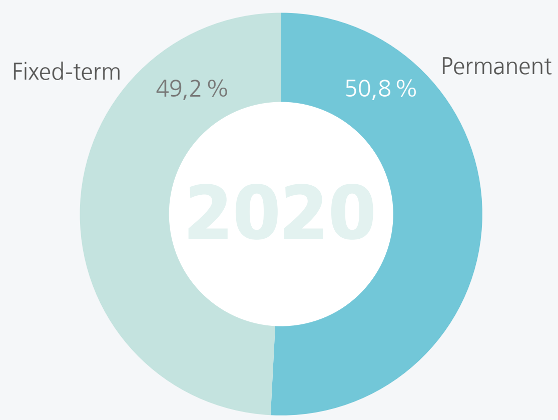
The ever tighter and improved network with the University of Freiburg and Furtwangen University made it easier to attract highly qualified young specialists. The number of students working at the institute, for instance as part of their master's thesis, has grown considerably. This was particularly evident at the end of 2020, once the move was completed and we had properly arrived on the University Campus.

Personnel

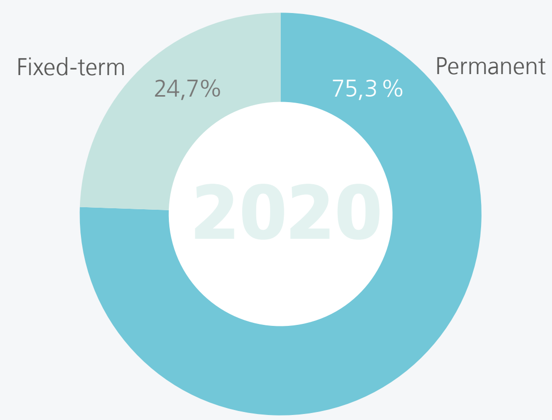




Staff under the terms of the Collective Agreement for the Public Service TVöD: percentages of fixed-term/permanent contracts of employment



Scientifc



Non-scientific

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 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 objects and large structures
- 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

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

“IT and digitalization were major topics of the strategy audit four years ago. It is great to see that these efforts have been successful.”

Prof. Dr. Andreas Nüchter

OUR ADVISORY BOARD

A distinguished and dedicated board of trustees advises and supports us in strategic issues and decisions for the future. In 2020, the advisory board meeting took place online – as did the accompanying lab tours.

Chairman

Dr. Manfred Jagiella
Endress + Hauser Conducta GmbH & Co. KG

Members

Dr. Lutz Aschke
TRUMPF Photonic Components GmbH

Hanna Böhme
Freiburg Economic Tourism and Trade Fair Agency (FWTM)

Stephanie Busse
DB Netz AG

Dr. Mathias Jonas
International Hydrographic Organization

Gerhard Kleinpeter
BMW Group

Prof. Dr. Katharina Klemt-Albert
Leibniz Universität Hannover, Institute for Construction Management and Digital Building

Claus Mayer
Ministry of Economics, Labour and Housing in Baden-Württemberg

Prof. Dr. Andreas Nüchter
Julius-Maximilians-Universität, Würzburg

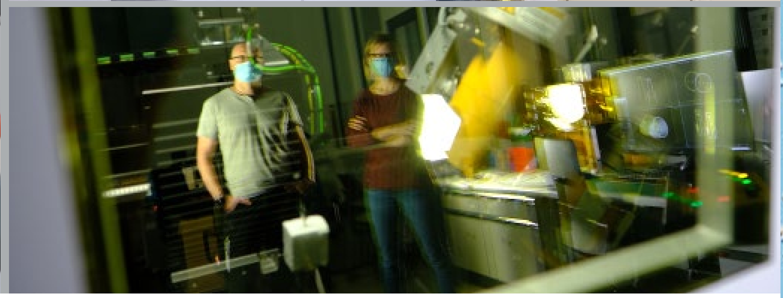
Dr. Volker Nussbaumer
Volkswagen AG, Group Charging GmbH

Dr. Stefan Raible
ScioSense Germany GmbH

Prof. Dr. Michael Totzeck
Carl Zeiss AG

Prof. Dr. Ulrike Wallrabe
University of Freiburg, Department of Microsystems Engineering IMTEK

An x-ray CT scanner of the latest generation allows us to see inside of both small and large samples. This provides us with valuable information for developing our systems.



INVESTMENTS IN TECHNICAL EQUIPMENT

The Institute invested nearly five million euros in new devices and machinery in 2020. Many new purchases had been postponed to the year of our relocation, resulting in a sum that is well above average.

Coordinate measuring machine (Leitz Infinity 12.10.6)
With this new device, Fraunhofer IPM became the owner of one of the most accurate coordinate measuring machines in the world. Among other functions, the tactile system enables reference measurements to be taken for multiwavelength digital holography in measuring surface topographies and is accurate down to E0: 0.3 + L/1000 in a measurement volume of 900 mm × 1200 mm × 700 mm.

3D computer tomograph (Baker Hughes, v|tome|x m 300)
The 3D CT non-destructively analyzes the interiors of both small and large samples. The system is accurate down to the sub-micrometer range and can also penetrate and analyze samples which normal x-rays cannot. It is equipped with the latest-generation high-performing detector. The system reduces scattered radiation to the point that even geometrically complex samples can be depicted clearly. A variance comparison of scanned samples with references is also possible, as is measuring in accordance with VDI 2630 1.3. In-situ measurements (live image) allow for the depiction of fluid dynamics. The system thus provides valuable information for system simulations.

Semi-automatic sputtering system (Dreebit co-sputtering system 145)
The system deposits thin films on both rigid and flexible substrates with diameters of up to 200 mm and heights of up to 10 mm. It enables film thicknesses of up to 2 µm. In addition to depositing precious metals and metal oxides, the system is capable of creating thin metal alloy and metal composite films. This also allows for the stoichiometric deposition of nitrides and oxides.

High precision screen printer (Thieme LAB 1000)
With a print size of 400 mm × 400 mm, the system enables selective coating and functional printing, for example of gas-sensitive materials. Automated screen and substrate alignment ensures printing of single- and multi-layer coatings with a mechanical printing accuracy of ±15 µm. The advantages of screen-printing lie in the material flexibility, the variable and homogeneous coating structure as well as compatibility with many different substrates.

Calligraphic pole construction for micro structuring of lithium niobate crystals (in-house construction)
The calligraphic pole construction enables the structuring of lithium niobate crystals down to the micrometer by using an electrically charged metal needle to serially inscribe individual domains into the material. Polarization patterns of any kind can be created quickly and efficiently, which is not possible with conventional polarization technology. The underlying procedure was developed together with the Laboratory for Optical Systems at the University of Freiburg.

Inspection system for automated texture analysis (in-house construction)
Using pixel-shift technology as a foundation, the "Tex measuring station" enables microscopic resolution in a macroscopic measurement field. The 500 megapixel images are analyzed on the graphic board. Various RGB illumination arrangements ensure realistic lighting conditions. The components are automatically fed into the system by a robot. We use the measuring station when commissioned by clients to analyze the texture of large surfaces and complex objects as well as to provide proof of capability of the inspection systems we have created for use in industrial settings.

OUR MAJOR RESEARCH PROJECTS 2020

A total of fourteen research projects, in which Fraunhofer IPM is involved with more than one million euros each, were carried out by our scientists in 2020. Only projects funded by the public sector or the Fraunhofer-Gesellschaft are listed.

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

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 – 11/30/2021
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)

HochPerForm Highly integrated, fast actuator technology based on shape memory alloys
Project duration: 10/1/2019 – 2/28/2023
Funding: Fraunhofer-Gesellschaft

MIAME Micrometer to meter: Laser light for submicron 3D measurements on the meter scale
Project duration: 4/1/2020 – 3/31/2023
Funding: Fraunhofer-Gesellschaft

FREE FALL: HANDLING-FREE OPTICAL INSPECTION

OBJECTIVE To develop an optical system for 100-percent quality inspection of components using geometry and surface analysis in free fall

BACKGROUND The quality control of mass-produced parts still frequently occurs by means of human visual inspection. Components must be oriented in a specific way for an automated optical inspection. The necessary handling for this, however, is time-consuming and costly. Automated 100-percent production control, particularly for semi-finished products, has therefore rarely proven profitable thus far.

RESULT As part of the "Freifall" (Free fall) project, Fraunhofer IPM worked together with Fraunhofer IGD to map out a solution for automated optical 100-percent production control of mass-produced parts. To achieve this, the team developed a free-fall test system. The components to be tested are fed into an evenly illuminated hollow sphere, in which they are recorded by 24 cameras as they pass through. Three additional position cameras provide information on the components' orientation. Geometric deviations are detected as part of the image analysis. For this purpose, the component's outer contour is identified from many different perspectives and compared with the target contour. Images from six fluorescence cameras provide additional information on the cleanliness and coating of component surfaces with an accuracy of 0.01 g/m².

PROSPECTS Studies and pilot installations will serve to validate the readiness of this technology to be deployed in an industrial environment. The team is also working on increasing measurement frequency and making the programming process more flexible. The "GUmProDig" project, which started in May 2021, will see the linkage of free-fall testing technology with the Track & Trace Fingerprint procedure for component tracing.

TOXIG: SNIFFING OUT TOXIC GASES

OBJECTIVE To detect combustible gases using color-changing sensors

BACKGROUND In the event of a fire, combustion gases occur before smoke forms. Using combustion gas alarms, fires can be detected at an earlier stage and lives can be saved. Small and affordable combustion gas alarms are not currently available on the market.

RESULT In collaboration with Fraunhofer ISC and Fraunhofer EMFT, the team working under Dr. Marie-Luise Bauersfeld has developed an affordable miniaturized gas sensor system which can reliably detect typical combustion gases such as CO, NO_2 and NH_3 at an early stage. The combustion gas detector relies on color-changing sensors which are sensitive down to the ppb range. Readings rely on light-emitting diodes and photodetectors. The sensors were tested in Minimax's and Hekatron's fire test laboratories.

PROSPECTS The demonstration device developed as part of the project used combustion gases to show what potential the color-changing measuring principle has for sensitive gas detection. The goal is now to develop the sensors for long-term stability so they can be integrated into fire alarms as a standard feature. In the future, researchers also hope to utilize the potential of the color-changing principle for detecting more gases in other applications, for instance for determining occupational exposure limit values or indoor air quality.

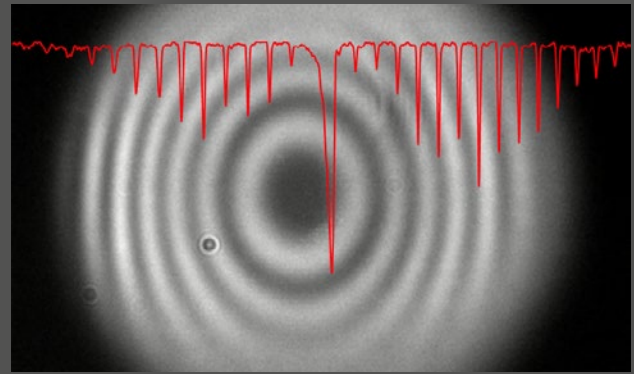
QUILT: INFRARED SPECTROSCOPY WITH VISIBLE PHOTONS

OBJECTIVE Developing application-oriented measurement technologies for imaging and spectroscopy using pairs of entangled photons.

BACKGROUND Using entangled photon pairs, information on the infrared photon can be detected through its visible "partner" photon. This allows infrared spectroscopy and imaging using silicon-based detectors, which are more cost-effective, faster and produce considerably less noise. A total of six Fraunhofer institutes are participating in this project, conducting research in different fields of application and on different key technologies.

CURRENT STATUS The QUILT team at Fraunhofer IPM was able to demonstrate a novel quantum spectrometer which operates in analogy to the measurement principle of a classical Fourier-transform infrared spectrometer. This method translates to sensitive high-resolution spectroscopy. Results have been published in journals and presented at international conferences.

PROSPECTS Next steps for the project involve the development of a mobile, high-performance demonstrator for gas spectroscopy which will be used to explore novel applications.



Using entangled photon pairs, infrared spectra can be measured with visible light.

QMAG: HIGH-PRECISION MEASUREMENT OF WEAK MAGNETIC FIELDS

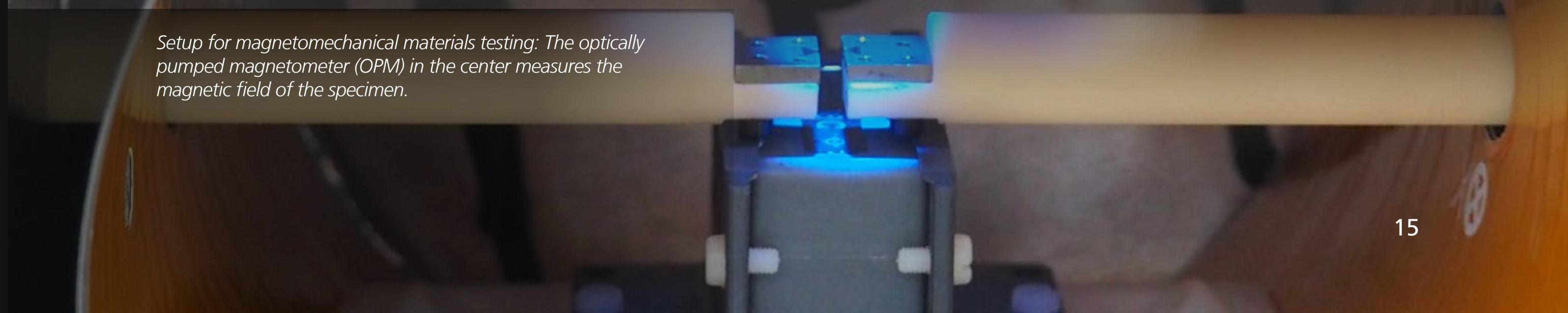
OBJECTIVE Development of new applications for quantum optical magnetic field sensors.

BACKGROUND Optically pumped magnetometers (OPMs) are essentially small laser-based spectrometers which are able to detect extremely weak magnetic fields, like those generated by the weak electric currents in the brain. Since magnetic fields are able to penetrate most materials very well, the QMAG researchers are working towards the application of OPMs in non-destructive material testing and contactless monitoring of flowing liquids inside pipes.

CURRENT STATUS Together with Fraunhofer IWM, we created a novel setup in which steel samples can be subjected to mechanical fatigue while simultaneously measuring their magnetic fields. In proof-of-concept experiments, the magnetic "fingerprints" of materials at different loads could be observed. Flow monitoring is based on nuclear magnetic resonance (NMR) techniques. With the help of OPMs it is possible to pick up signals at very low frequencies which can even pass metal tubes. The project team was able to demonstrate how different liquids can be discriminated based on magnetic signals with a strength of only a few picoTesla (10^{-12} T).

PROSPECTS The second half of the project will be dedicated to translating the successfully demonstrated concepts into measurement techniques while at the same time exploring novel applications. A magnetically shielded room will be installed at Fraunhofer IPM in order to enable basic research on larger samples and components under strictly controlled magnetic ambient conditions. With future industrial application in mind, researchers will collaborate with OPM manufacturers in developing sensors that can be used even without magnetic shielding.

www.qmag.fraunhofer.de



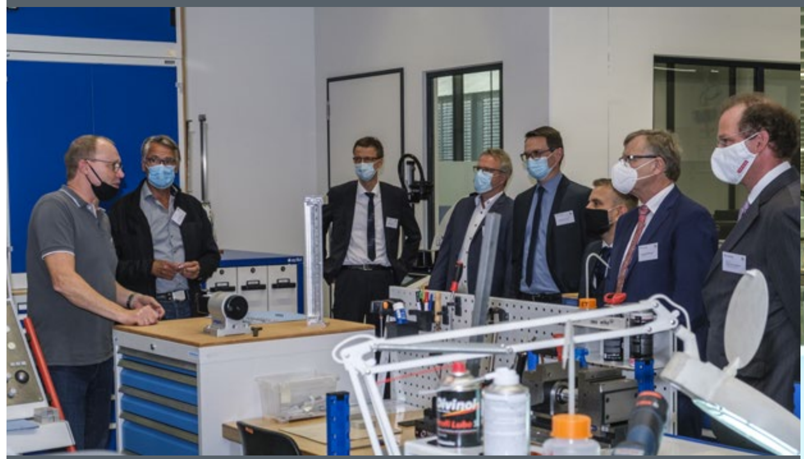
Setup for magnetomechanical materials testing: The optically pumped magnetometer (OPM) in the center measures the magnetic field of the specimen.

From left to right: Dr. Martin Haag, Deputy Mayor and Senior Planning Officer of Freiburg; Dr. Nicole Hoffmeister-Kraut, Minister of Economic Affairs for Baden-Württemberg; Prof. Dr. Karsten Buse, Director of Fraunhofer IPM; Dr. Kerstin Krieglstein, Rector of Freiburg University, and Andreas Meuer, Executive Vice President of the Fraunhofer-Gesellschaft, at the red ribbon-cutting ceremony in the lobby of the new building.

WE'VE ARRIVED! NEW BUILDING INAUGURATED

Meticulous preparations have paid off: Our move to the new location on the campus near the airport took from June to September – just as planned. The new building was officially inaugurated in October. Around 40 high-ranking politicians, scientists and guests from the industrial sector attended the official ceremony celebrating the opening of the new building on October 1, 2020. "A feel-good atmosphere, but high-tech," was how Prof. Dr. Karsten Buse described the new work environment in his welcome address. "The campus by the airport (Campus am Flugplatz) is the environment where knowledge gained from cutting-edge research can be effectively transferred to industry," said Prof. Kerstin Krieglstein, who took part in the ceremony on her first day in office as Rector of the University of Freiburg. In light of the pandemic, a larger celebration could not be held, but research partners, alumni and people involved with the construction of the building have had the chance to view it at separate events.

Even if some of the employees assigned to the new building have had to work from home because of the pandemic, the new offices and laboratories, a large amount of new equipment, plenty of room for meetings and, last but not least, the campus atmosphere of the new location all make for outstanding working conditions. And we plan to really harness the location's full potential when everyone can return to work on-site.



40 guests from politics, science and industry attended the inauguration of the new building.

Dr. Nicole Hoffmeister-Kraut, Minister for Economic Affairs for Baden-Württemberg, emphasized the role of applied research for the innovative strength and competitiveness of SMEs.

"... RIGHT NOW, OVER ME" – PERCENT FOR ART

The artist Tobias Rehberger has installed 65 colorful spherical lighting fixtures of different sizes throughout the entire building. Rehberger was inspired by optics constructions which allow light to pass through various lenses, prisms and mirrors. The spheres are all attached to cords of eight different lengths to which eight different colors are assigned correspondingly. The lights are controlled by switches installed in the hallways. All of the cords join together in the lobby, allowing the colors to intermingle, as motley as the employees at the institute.

The German federal government and the state of Baden-Württemberg have each contributed 25 percent of the new building's total investment volume of 43.1 million euros, with the other 50 percent being funded by the European Regional Development Fund (ERDF). The building is the largest construction project funded by the Ministry of Economics, Employment and Housing of Baden-Württemberg out of the 2014 to 2020 ERDF budget. For the development and basic fixtures and fittings of the institute, the federal and state governments split the costs of special funding, providing an additional 14 million euros in total.

EUROPÄISCHE UNION

EFRE
Investition in Ihre Zukunft.

Baden-Württemberg

Engineering fun: The teens were excited to be involved in the project.

Measurement technology experts from Fraunhofer IPM come together with experts from science and industry in the Online-Forum to discuss applications of the latest measurement technology solutions.

DIY HOLOGRAPHIC MICROSCOPE

As part of a school partnership, we worked together with two extracurricular physics clubs from schools in the Freiburg area to design an affordable 3D microscope which uses a Raspberry Pi single-board computer. A comprehensive report about the project was featured in the 2/2020 issue of Make magazine.

The joint project by researchers at Fraunhofer IPM and pupils from several schools in Freiburg took three years to complete. It resulted in "HolMOS" – a digital holographic microscope available for open science, which can be used to measure transparent biological samples in 3D. The core of the device is a Raspberry Pi with an attached camera. This affordable piece of hardware and the microscope's publicly available, easy-to-use software allow even people without prior knowledge in the field to reconstruct it – starting as a simple microscope and eventually as a complete interferometric microscope.

Thanks to its simple design, the microscope can even be built by amateurs without prior knowledge.

The pupils showed great enthusiasm in working side-by-side with our researchers to develop and test the microscope in practice. Some of the pupils involved continued to work on the project even after graduation. The finished microscope was presented at various schools, at the Maker Faire in Berlin and at the Digital Holography and 3D Imaging conference in Bordeaux.

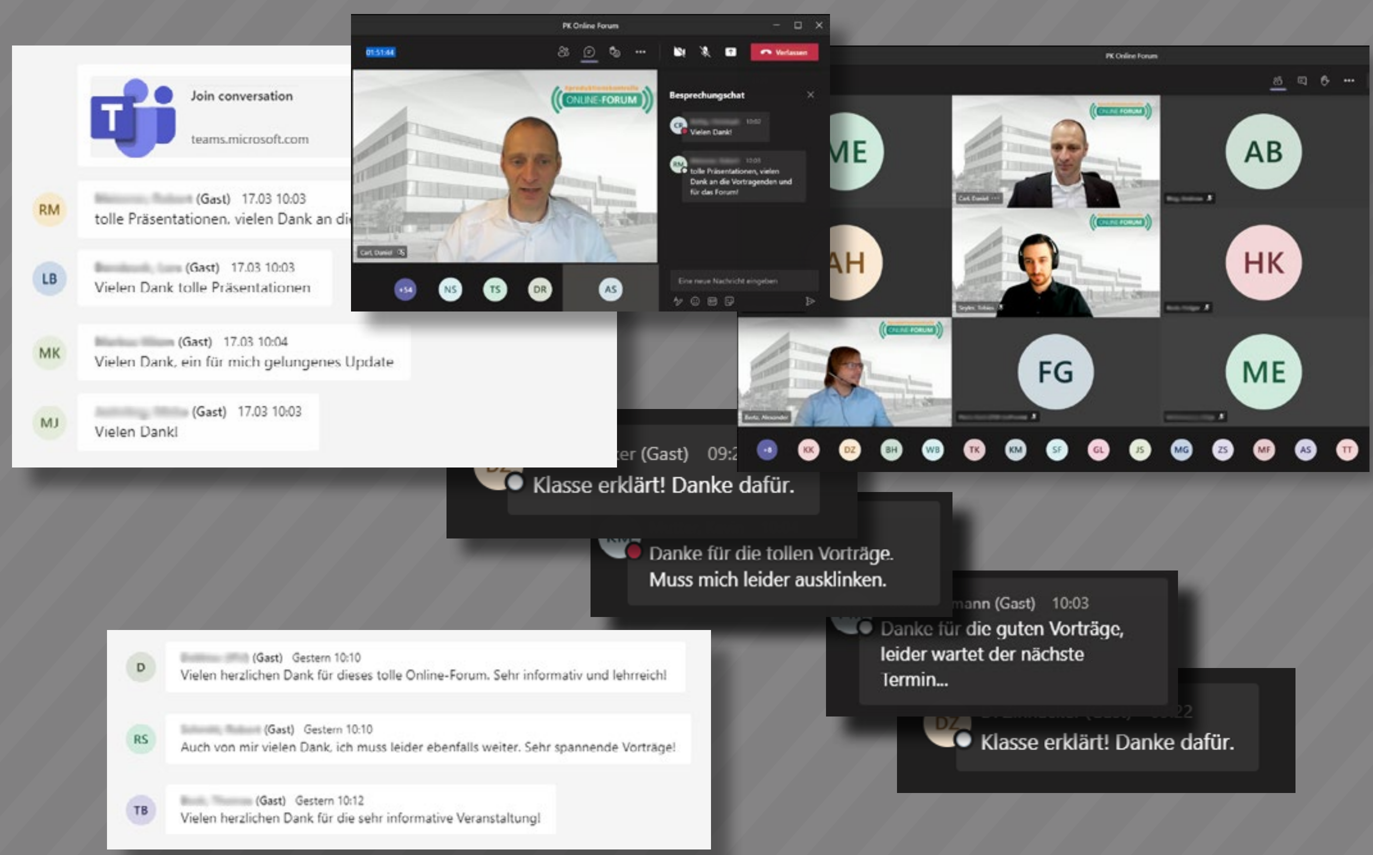
As collaborative partner to the project, the Freiburg Seminar organized the scientific extracurricular clubs for pupils in the final years of their schooling in the Freiburg area. Financial support for the project was provided by the Open Photonics program initiated by the Federal Ministry of Education and Research.

VIRTUAL EXCHANGE

No exhibitions, no workshops, no in-person gatherings – sharing knowledge during the COVID-19 pandemic in 2020 required creativity. Fraunhofer IPM decided to move in a new direction with its Online-Forum virtual event series.

90 minutes, one topic and up to five expert presentations – 2020 marked the start of our new virtual event series "Online-Forum". The event enables the exchange of well-founded expert knowledge via an easy-to-use digital platform. The series was kicked off by the Department of Production Control on the topic of measurement technology for sheet metal forming. And it was a hit – nearly 50 experts from science and industry took part in the virtual discussion.

The event series will be continued in 2021. The dates have already been set and can be found on page 67, and they will be continually updated on our website.



"InnoCool – Konsortialstudie Kalorik" evolved into an expert committee for discussing unanswered questions about the future of caloric cooling technology.

A COLLECTIVE GLIMPSE INTO THE FUTURE OF REFRIGERATION

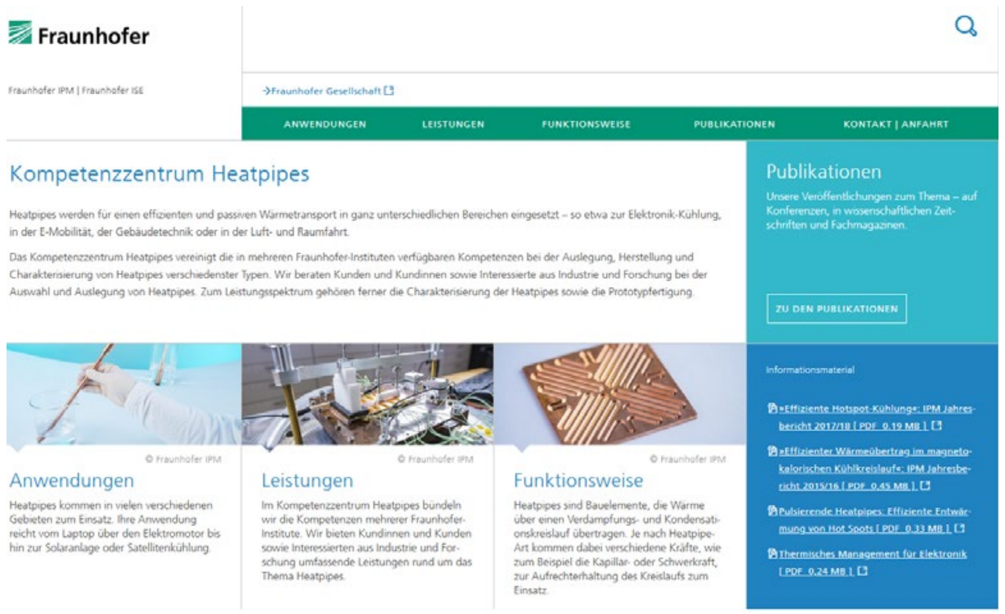
Fraunhofer IPM has been researching caloric systems for heating and refrigeration for several years now. Our joint study on caloric systems "InnoCool – Konsortialstudie Kalorik" brings together manufacturers, technology developers, users and research institutions to gather information about the current state of the art and to work together to identify potential applications.

Caloric air conditioning and refrigeration are currently gaining ground as an alternative to conventional cooling technology. But many questions remain unanswered: Will this new technology be applied in practice? In what fields could it be useful and what would the specific requirements be? Last year, we managed to establish a consortium of nearly 15 companies and research institutions as part of "InnoCool – Konsortialstudie Kalorik". Workshops born from this joint study focus on finding answers to these questions and analyzing potential development scenarios. The goal is to create links along the value chain and set the course for an early market launch of this technology.

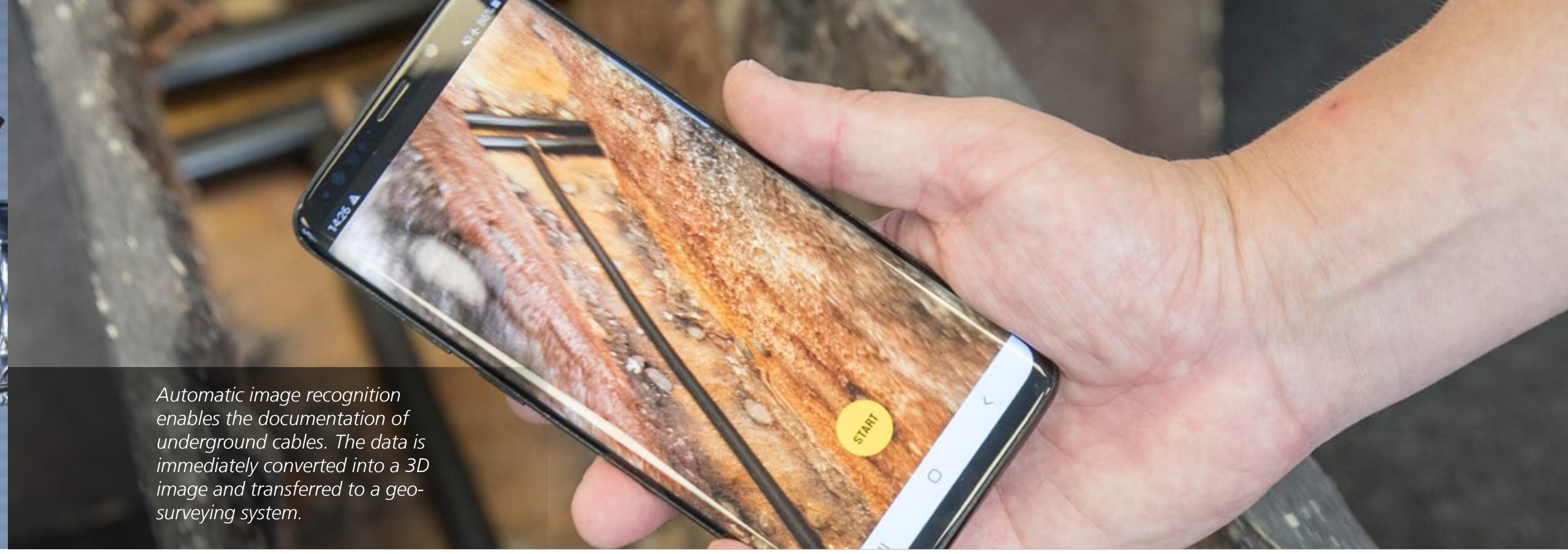
HEAT PIPES CENTER OF EXCELLENCE

Fraunhofer IPM and Fraunhofer ISE pool their expertise in heat pipe research.

Against this backdrop, a website was created for presenting heat pipe technology facts as well as the institutes' research and application updates. Heat pipes are used for efficient and passive heat transfer for various purposes, including for cooling electronics and in the e-mobility, building technology and aerospace sectors. For future applications, Fraunhofer IPM and Fraunhofer ISE are working on new designs for various types of heat pipes, manufacturing processes and heat pipe characterization.



www.heatpipes.fraunhofer.de


Automatic image recognition enables the documentation of underground cables. The data is immediately converted into a 3D image and transferred to a geo-surveying system.

FRAUNHOFER ACQUISITION OF THE MONTH: TRENCHLOG PROJECT

In March 2020, a team from our Object and Shape Detection department received the largest industry assignment across all the Fraunhofer institutes. Bayernwerk Netz GmbH has invested approximately one million euros in the NEXT.TrenchLog digitalization tool, which the project team will be working on until May 2022. Bavaria's largest network operator will use the tool to enable construction companies to document the type, length and position of underground supply lines fully automatically. The trenches are measured using customary tablet PCs equipped with stereo cameras. The camera data are used to automatically generate georeferenced 3D data. Supply lines are then detected via artificial intelligence and transferred into a geo-surveying system. NEXT.TrenchLog will be the world's first AI-supported system that generates georeferenced data for grid expansion.


Prof. Dr. Alexander Reiterer (l.), Simon Stemmler, Dr. Christoph Werner (r.)

TALENTA

Three of our PhD students are currently receiving funding for their research projects through the TALENTA Fraunhofer career program.

Nora Bachmann is conducting research on elastocaloric systems, Laura Engel is developing color-changing sensors and Chiara Lindner's work is dedicated to quantum sensor technology. All three PhD students are receiving funding through the TALENTA start program, which provides support for particularly adept individuals in the early stages of their career. Funding provided through TALENTA is intended to ensure young women the space they need for their doctoral studies and their continued professional development. It also offers opportunities for further qualification and networking. "It is very valuable for me to exchange ideas with colleagues from other institutes and to build up contacts. It helps me assess my own work, motivates me and gives me ideas on how I can tackle things even better," says Nora Bachmann.


Nora Bachmann studied mechanical engineering at TU Darmstadt. As part of her doctoral thesis at Fraunhofer IPM she is developing a new concept for elastocaloric cooling systems.

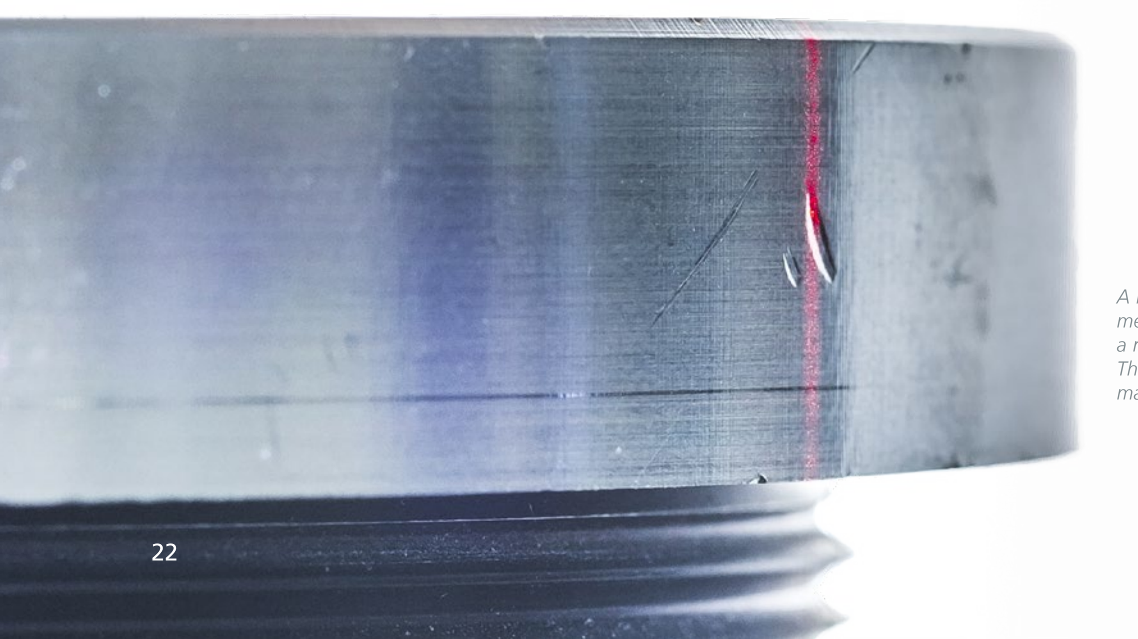
From left to right: Hubert Aiwanger, Bavarian Minister for Economic Affairs, with the winners of the Hugo Geiger Prize – Dr. Simon Fichtner, Dr. Annelie Schiller, Dr. Christian Kalupka. Also pictured are Fraunhofer Executive Board members Andreas Meuer and Prof. Alexander Kurz (r.), who were among those who came to congratulate the prizewinners.

DR. ANNELIE SCHILLER IS AWARDED THE HUGO GEIGER PRIZE

In her doctoral thesis, Schiller proved that digital-holographic measurements are possible, even on moving objects. For this work, she was awarded the Hugo Geiger Prize for outstanding doctoral achievements in the field of applied research.

Digital holography has gained momentum over the past few years. Digital holographic measurements provide extremely exact 3D data on surfaces. Thanks to modern laser technology, excellent cameras and the quick parallel data processing capabilities of graphics cards, it is now possible to capture and process images with 10 million 3D points within 100 milliseconds. This means that the process is fast enough to be integrated directly into production lines. Fraunhofer IPM has been conducting research in this field for years, and has successfully installed HoloTop, the digital-holographic measurement system for conducting quality control at industrial customers' production facilities. Interference images are created by superimposing the reflected or scattered light with light from a reference beam. Until recently, however, even the smallest movement resulted in the 3D information being destroyed. This meant that measurements were only possible for stationary objects. Dr. Schiller solved this problem in her dissertation on measuring the topography of moving objects using digital holography ("Messung der Topographie bewegter Objekte mittels digitaler Holographie"), showing that both linearly moving and rotating objects can be surveyed using digital holography.
Dr. Schiller's solutions for rotating objects are particularly remarkable. She takes advantage of the fact that detuning the reference beam – which is required to compensate for the critical axial velocity vector caused by the rotational motion – does not depend on the radius of the rotating object. Rather, the proportion of critical movement along the velocity vector is linearly dependent on the angular velocity and the position of the sensor.

Dr. Annelie Schiller is a research associate working on digital-holographic measurement techniques.



A novel holographic line sensor measures 3D surface parameters of a rotating metal cylinder in motion. The sensor detects even the tiniest machining traces and defects.

Chiara Lindner started her PhD at Fraunhofer IPM in 2018 in the field of quantum sensing.

CHIARA LINDNER has been conducting research on quantum sensing as part of her PhD at Fraunhofer IPM since 2018. Her work focuses on the question of how entangled photon pairs can be used for infrared spectroscopy.

THREE QUESTIONS FOR ... CHIARA LINDNER

Ms. Lindner, what is so fascinating about quantum sensor technology?
My background is in applied physics, and optics has always been my subject. This has now developed into quantum sensor technology, which is a cutting-edge and ambitious topic at the moment. This new field of research builds on the fundamental principles of photonics. Even though quantum sensing still is a rather young topic at the institute, we have managed to contribute to the state of the art rather quickly.

The advantage of our approach is that we can achieve remarkably good spectroscopic results with extremely small amounts of light. This opens up many exciting fields of application. Biological samples, for example, sometimes react very sensitively to light.

Last year, you achieved a breakthrough in the project: You developed a quantum spectrometer. How does that feel?
It didn't come entirely unexpected, of course; it is something you work towards. It's a bit like knitting a scarf. You put in stitch after stitch, and at some point, you stop and realize: you've already knitted two meters. In everyday life, you don't always take the time to review your own research progress. So when you prepare a conference presentation and look at the whole thing from the outside, you realize how far you've already come. That's a great feeling.

What have been the biggest challenges you have faced during your PhD so far? What were the highlights?
A PhD thesis in itself is, of course, a challenge. For many people, just like for me, it's the start of their career. You have to work more independently than you did during your studies. But that is also one of the most sustainable and valuable skills that you take away from it.

One highlight was certainly my participation at the "Photonics West" conference in San Francisco, shortly before the start of the pandemic. It is truly exciting to be able to present your own research results at such a huge international conference. Also, at the beginning of 2021, my second paper was accepted and was directly chosen as an Editor's Pick. I was very honored by this; I had not expected this at all.

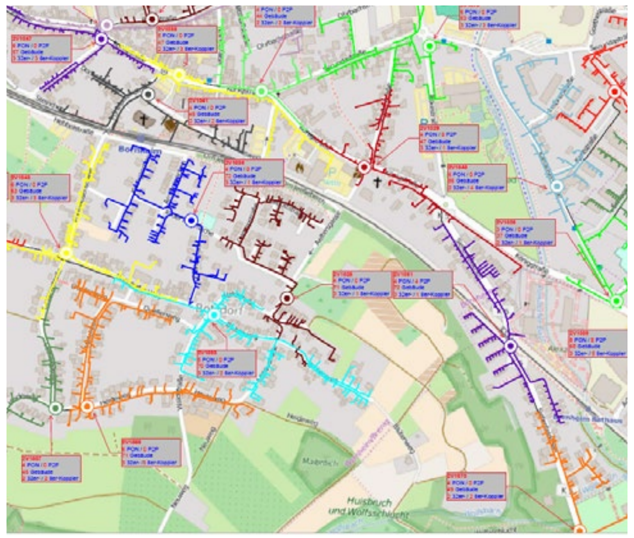
> Fraunhofer IPM has developed special mobile mapping survey vehicles, known as T-Cars, that automatically collect the planning data needed for expanding fiber-optic networks.

>> Niko Gitzen, project leader at Deutsche Telekom Technik GmbH: "With the support of Fraunhofer IPM, we have managed to reduce our planning times for grid expansion works by up to 75 percent."

"We both firmly believed that we would succeed"

"Faster expansion of fiber-optic networks thanks to fully automated route planning" – this is how Niko Gitzen describes the objective of the collaborative project between Deutsche Telekom Technik GmbH and Fraunhofer IPM. To achieve this goal, the project team has not only developed and assembled road assessment vehicles, but also created a revolutionary planning tool. Together, these advancements lay the foundation for automated route planning, something which has not yet been achieved anywhere else in the world. The process is based on highly exact 3D data which are automatically classified using artificial intelligence (AI). Niko Gitzen is responsible for developing mobile mapping activities at Deutsche Telekom Technik GmbH.

How did you come to work with Fraunhofer IPM?
Gitzen: Following a market analysis in 2017, we quickly realized that not many providers on the market are able to carry out automated surface detection – and certainly not at the high level we need for our route planning activities.



"Digital planning maps speed up the route expansion process," says Niko Gitzen. "What used to be a manual process is now automated – all thanks to Fraunhofer IPM."

Why did you not develop the survey vehicles or digital process chain by yourselves?
DT Technik has the skills to build and operate networks and to suppress interference within them. Our outstanding networks ensure the best possible customer experience, regardless of whether connections are wireless or via cables. But at the time, we simply did not have the expertise needed for mobile mapping. This expertise is something we have built up since then over time.

Which role does the technology we have developed play in the success of expanding broadband in Germany?
In the past, our planners generally had to attend to every single issue in person and conduct their inspections on site, clipboard under arm and camera in hand. Now, this is all done by T-Cars and the neural network – both of which will play a key role in the broadband roll-out. This means that planners no longer need to draw up planning maps; instead, they can evaluate and optimize automatically generated ones, which is why the value added has increased substantially.

Deutsche Telekom Technik GmbH (DT Technik) is a subsidiary of Telekom Deutschland GmbH. It is responsible for planning, constructing and operating the fixed-line and mobile telecommunications network infrastructure of Deutsche Telekom within Germany. DT Technik also provides information regarding the location of technical facilities to authorities, civil engineers and utility companies. The company is based in Bonn, Germany.

What were your expectations of the project?
Initially, there was a lot of uncertainty from both sides, but we both firmly believed that we would succeed. The schedule was very ambitious from the outset – and this pressure was intensified by our managers announcing that they wanted to supply fiber-optic connections to up to two million households each year. It was clear that both parties – Fraunhofer IPM and Telekom – needed to get it right. We expected to complete the project by the agreed deadline, with functioning, highly reliable hardware and software. And so we were especially pleased to see everything up and running by the time the project came to a close.

What needs to happen for a development project to succeed?
Regular, open communication is absolutely crucial. We were regularly in touch with one another to discuss even the smallest details and made sure to thoroughly explain to the scientists how our planning processes conventionally work. We could have just said, "This is the contract; all of the details are in there." But that's not how it works. Our goal was always to communicate on a regular basis to ensure we are all on the same page.

Has the investment paid off for Telekom?
High-speed, reliable broadband connections are more important than ever, be they for working from home, homeschooling activities or connecting companies. Demand for connectivity is increasing continuously. By automating our planning processes, we have managed to reduce our planning times for grid expansion works by up to 75 percent. This means that we can work much more quickly, and that saves us money. In addition, we strive to reduce approval times for cities and municipalities through our digital processes. This also results in lower CO_2 emissions, as we are now able to do a lot of our work from our desks.

What technological challenges is telecommunications currently facing?
The telecommunications industry is constantly being reshaped by new technologies – and increasingly by AI. For example, in grid management we use AI algorithms which autonomously recognize when peak loads could occur or technology could fail – before the customer does.

Our joint project has received a number of awards – the 2019 Fraunhofer Prize and the Telekom 2020 Lead-to-Win Award. What does this mean to you and your team?
The Lead-to-Win Award is presented to international project teams in various categories. We won first place in the innovation category, meaning we were the most innovative project across the entirety of Deutsche Telekom! This signals to us that our work is held in very high esteem, but it also increases the pressure we feel to achieve even greater success. But together with partners such as Fraunhofer IPM, we are on the right track.

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 that 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 (marker-free) individual component tracking, optical sensors and measuring systems are often the key to 100 percent real-time control. This assigns them a role as enabling technology for the implementation of modern production strategies 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.

Dr. Daniel Carl
Head of Department
Phone +49 761 8857-549
daniel.carl@ipm.fraunhofer.de

Group **Optical Surface Analytics**

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

Group **Inline Vision Systems**

- Surface inspection shape measurements of semi-parts and components
- Detection of surface defects and straightness of long products
- Marker-free component identification in production and via mobile application

Group **Geometrical Inline Measurement Systems**

- High-precision measurement of functional surfaces at production speed
- Cordless 3D measurement of components directly in the machine tool
- Fast, dynamic deformation measurement

< Inspect 360° inspects the geometry and surface quality of components in free fall. The semi-parts are fed by a conveyor belt and inspected regardless of their spatial orientation.

GROUP **OPTICAL SURFACE ANALYTICS**

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

The research focus of the group is the development of turnkey devices for inspecting surfaces. The systems are used for inspecting the cleanliness and coatings of components and identifying defects. They check rollstock and complex components in production as well as fully scan the surfaces of components of any shape in free fall without the need for further handling. Our systems can be used to test extremely thin coatings – such as barrier layers on plastic materials – for thickness and integrity or monitor the thickness distribution of forming or anti-corrosion oil on components and metal sheets. When monitoring laser machining processes, we use laser technology to perform element analyses of surfaces and coatings. The inline microscopy systems developed by the group characterize the geometry and surfaces of micro-components at the rate of production with outstanding accuracy, for example in medical device production. Drawing on our wealth of experience in the development of optical units, image capturing and image processing as well as specific electronics and mechanics, we are well-equipped to integrate customer-specific measurement and inspection systems into the production line.

Group Manager: Dr. Albrecht Brandenburg

PROBLEM-SPECIFIC IMAGE PROCESSING AND IMAGE ANALYSIS

- Detection of defects which are difficult to identify
- Optimized lighting and customized image capture
- Classification of features according to individual customer criteria

IMAGING FLUORESCENCE

- Detection and localization of organic contamination (< 0.01 g/m²)
- Detection and spatially resolved characterization of coatings
- Layer thickness determination of organic layers down to thicknesses of 20 nm

INFRARED MEASUREMENT TECHNOLOGY

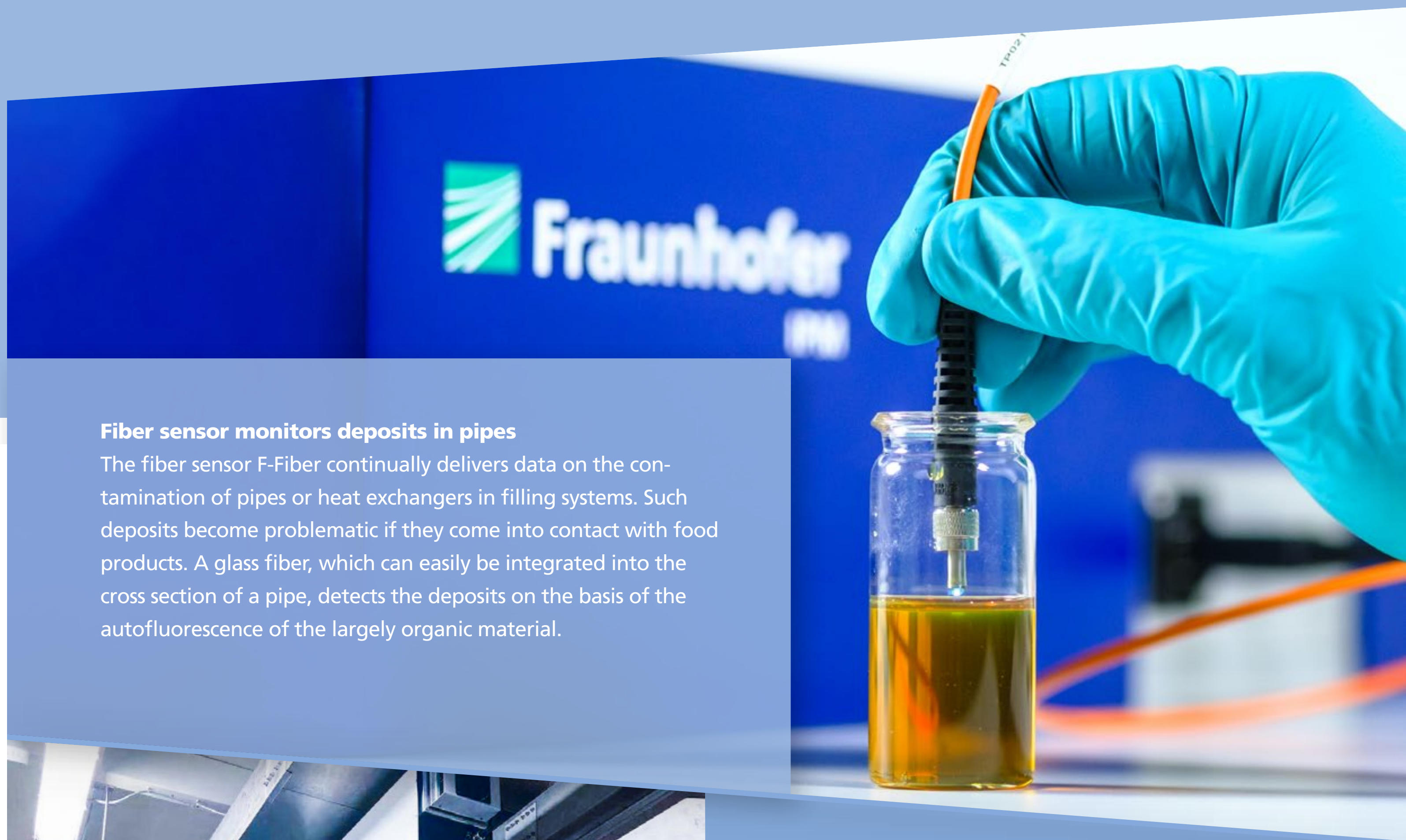
- Detection and thickness measurements of barrier layers from a thickness of 20 nm

LASER-INDUCED BREAKDOWN SPECTROSCOPY

- Contactless surface material analysis
- Thickness measurement of functional coatings
- Detection of coating components down to the ppm range

MICROSCOPY

- Characterization of complex 3D microstructures
- Detection of structural defects, impurities, scratches and incorrect external dimensions
- Repeatability of distance measurement down to the sub-micrometer



Fiber sensor monitors deposits in pipes
The fiber sensor F-Fiber continually delivers data on the contamination of pipes or heat exchangers in filling systems. Such deposits become problematic if they come into contact with food products. A glass fiber, which can easily be integrated into the cross section of a pipe, detects the deposits on the basis of the autofluorescence of the largely organic material.

System for oil coating measurement to be integrated
The team has started work on the integration of four laser scanners for measuring oil coating into the press line of an automotive manufacturer in the USA. The laser scanners carry out spatially resolved measurements on an oil coating as fine as 1 µm which prevents the metal sheets from cracking. The entire surface area of the car body sheets, which can be up to four meters wide, is inspected on both sides by two scanners per side.

Contamination and coating testing in free fall
Components can be fully tested from all sides in free fall – without handling. In a Fraunhofer project concluded in 2020, a fluorescence measurement imaging technique was developed for free fall measurements which detects filmic contamination and organic coatings. In the future, the system will also be able to detect cracks.

GROUP **INLINE VISION SYSTEMS**

Dr. Tobias Schmid-Schirling, Phone +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 the industrial Internet.

Group Manager: Dr. Tobias Schmid-Schirling

100 PERCENT CONTINUOUS MONITORING

- Surface monitoring of wires, cables, and bands as well as pipes, rods, and profiles
- Real-time inspection up to 30 m/s
- Inline detection of microscopic defects
- Automatic defect detection, classification, and documentation

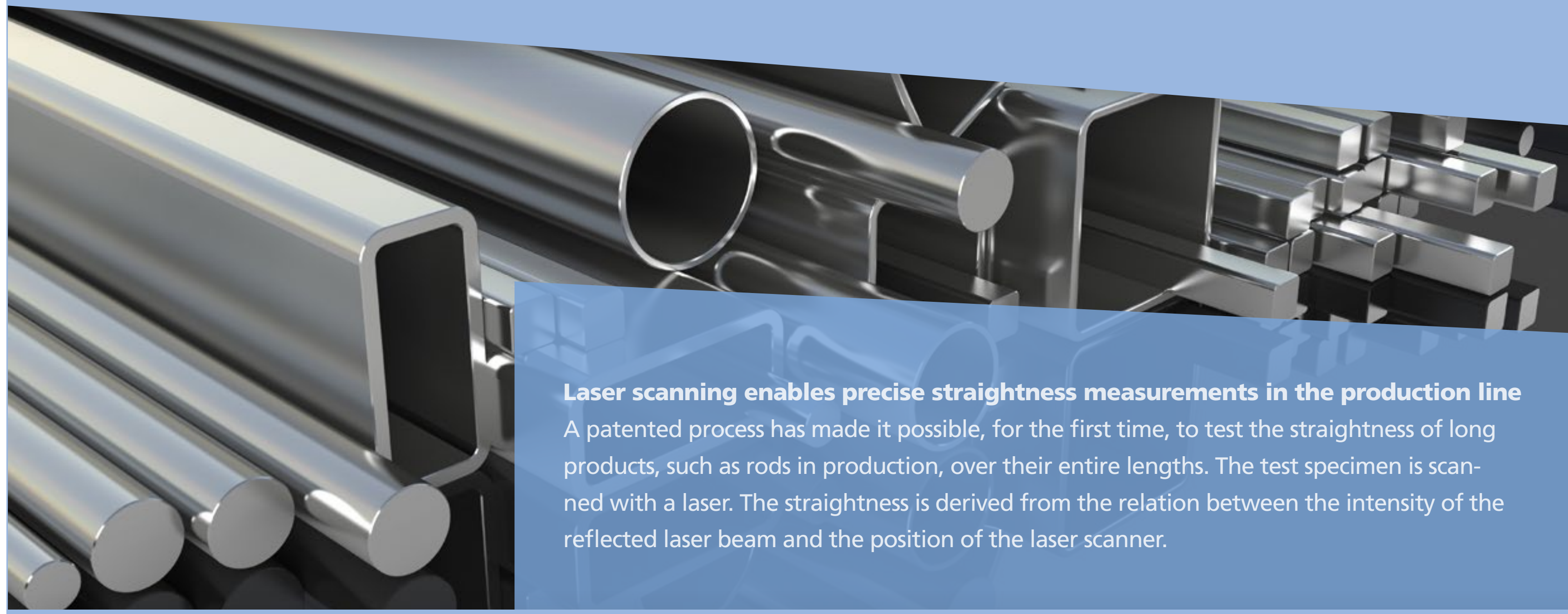
INSPECT 360°: COMPONENT INSPECTION IN FREE FALL

- 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 at 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) for rapid identification at the rate of production
- Stationary vision system or smartphone camera as reading system

Track & Trace Fingerprint via app: Identify components quickly and easily
We have developed a technology which can trace components without markers on the basis of their surface microstructure. The process involves using the high-resolution surface image to generate a numerical identification code and assign an ID. This can now be done with a smartphone. Users take a close-up photograph of the surface and the data matching is performed on a central server.



Laser scanning enables precise straightness measurements in the production line
A patented process has made it possible, for the first time, to test the straightness of long products, such as rods in production, over their entire lengths. The test specimen is scanned with a laser. The straightness is derived from the relation between the intensity of the reflected laser beam and the position of the laser scanner.

Component testing:
Pixel shift camera for expanded object field
Using this camera, surface defects can be identified in high resolution over larger areas than has been possible until now. The camera's 500 megapixels are processed in just a few seconds on a high-performance graphic board and potential defects are classified. A robot positions the components in front of the camera while RGB lighting provides realistic lighting conditions.

GROUP **GEOMETRICAL INLINE MEASUREMENT SYSTEMS**

Dr. Alexander Bertz, Phone +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

- 100% topography control 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

- Comprehensive gear flank control within a few seconds
- 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)

Latest generation of HoloTop sensors progresses into areas of even greater accuracy
Our HoloTop sensor is now capable of measuring a high-precision 20-µm-stepped standard, which was specified by the National Metrology Institute of Germany (PTB) just for us, with a deviation of less than 0.003 µm. The sensor managed to achieve a reproducibility of less than 0.1 µm under industrial conditions when measuring electronics components in acceptance tests.

On the path to an optical coordinate measuring machine
Building an optical coordinate measurement machine is the objective of the "MIAME" project, started in April 2020. The machine should be able to quickly measure the entire surface of meter-large objects with complex shapes down to the sub-micrometer. The core component is a novel light source based on whispering gallery resonators. The project has already attracted great interest in science and industry.

Real-time sensor technology for strain control in materials testing
Cracking propagation can be optically examined marker-free using materials test benches. Our StrainControl system allows us to monitor and control uniaxial and biaxial fatigue tests in real time thanks to GPU-supported evaluation and CoaXPress 2.0 cameras. This allows us to better predict how long the material in highly stressed components such as gas turbines will last.

< For the first time, the Surf-Inspect mobile particle measurement system makes it possible to test for cleanliness in the production line itself simply by placing the wireless measuring head (right) on the surface in question. The sensor head transmits the raw measurement data via Wi-Fi to a base station (left) for automated evaluation.

Mobile particle measurement technology for automated, high-speed imaging

Particle contamination on surfaces is a big problem affecting many production processes. Fraunhofer IPM has developed the Surf-Inspect mobile measurement system for high-speed, on-site particle analysis. The system consists of a small measuring head and a base station. Once the wireless measuring head is placed on a surface, the system automatically detects any particles present and determines their size. An additional patented technology also determines the particle type.

Whether or not a component's surface is sufficiently clean can rarely be adequately checked on a production line. One standard method for analyzing particles involves washing down surfaces and examining the washing fluid afterwards. To enable photo-optical analysis, the particles must be filtered out of the fluid – a very complex operation which is only conducted randomly in practice. To simplify particle analysis so that it can be conducted on the production line directly, a team from Fraunhofer IPM collaborated with the particle measurement technology company PMT Partikel-Messtechnik GmbH to develop the mobile Surf-Inspect system. It is the first system with the ability to test for cleanliness in the production line itself simply by placing the wireless measuring head on the surface in question. The easy-to-handle system reliably determines the particle size down to about 25 µm as well as the type of particle – metallic, non-metallic or fiber. The measurement field is 19 mm × 14 mm large and has a pixel resolution of 5 µm.

Characterization pursuant to VDA 19 – directly on component surfaces

Once the measuring head is placed on the surface and the measurement process is started, Surf-Inspect automatically detects and evaluates the particles found on the surface and determines their size and type pursuant to the VDA 19 testing standard, without making contact with the particles themselves. The results are made available in real time and can be used to help control the process chain. If the critical contamination limit is exceeded, the component can either be rejected or cleaned and fed back through the production line. Moreover, the results can be stored in clients' own quality management systems for documenting quality characteristics. Surf-Inspect thus ensures that surface cleanliness is documented along the entire process chain. The system produces both image data and quantitative measurement values corresponding to particle size, type, position and number. Determining the particle size alone is not nearly sufficient for quality assurance. Particularly metallic particles are critical because even a few individual shavings could result in the entire component group being rejected.

Using **PATENTED IMAGE ANALYSIS**, Fraunhofer IPM is able to classify surface particles based on size and type. This clever digital image analysis system relies on proper lighting to determine whether relevant information for analysis is even present in the image and if it is useful in analyzing the image. The pivotal trick is, simply stated, to light the surface at a very low level from the side and from two positions overhead. This enables the system first to detect and segment particles. In a second step, the system analyzes the amount of light reflected to reliably classify the particles as metallic, non-metallic or fibers, as these types of particle matter all reflect light sufficiently differently.

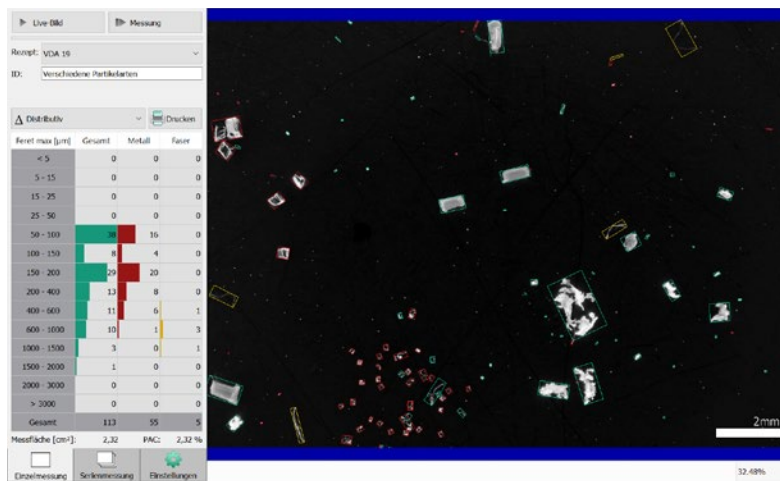
Functional and transferable

The mobile particle measurement system was developed in two stages. First, a functional laboratory prototype was developed with funding from the German Federal Ministry for Economic Affairs and Energy as part of the "MOPA" project (Mobiler Oberflächen-Partikelmesser – mobile surface particle measuring system). This laboratory prototype was equipped with all of the features necessary for detecting and classifying particles. In a second stage, the team collaborated with the company PMT to develop a wireless design for mobile use – the Surf-Inspect system. The measuring head wirelessly transmits the data via Wi-Fi to the base station, where the measurement is automatically evaluated and presented as a final result.

Researchers at Fraunhofer IPM have deftly combined multiple imaging techniques to enable the particles to be classified by type in accordance with the specifications of VDA 19.

Mobile particle measurement technology for the industrial sector

As is standard practice in accordance with VDA 19, the Surf-Inspect system recognizes metallic particles under the right lighting conditions by their gloss. Image processing is used to differentiate harmful metal particles from harmless fibers and non-metallic particle matter. The specially developed and patented image analysis technology was transferred to PMT. The company launched its PartSens 4.0 particle counter at the parts2clean expo in 2020. Since then, PMT has been producing this mobile particle sensor as part of a know-how license agreement with Fraunhofer IPM. The license agreement is ideal for both parties: PMT can continue to produce sensors and Fraunhofer IPM can offer other partners customized particle measurement technology solutions based on this patented technology.



Patented image analysis: Through the combination of various imaging techniques, particles can be detected on the component directly and classified pursuant to VDA 19 according to size and type: metallic (red), non-metallic (green), fiber (yellow).

Dr. Daniel Carl, Phone +49 761 8857-549, daniel.carl@ipm.fraunhofer.de

BUSINESS UNIT

OBJECT AND SHAPE DETECTION

"We cover the entire process chain of 3D data acquisition."

In the "Object and Shape Detection" business unit, we serve the entire process chain for mapping, referencing, interpreting 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, precision 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.

Prof. Dr. Alexander Reiterer
Head of Department
Phone +49 761 8857 - 183
alexander.reiterer@ipm.fraunhofer.de

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 Processing and Visualization**

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

< Our mobile mapping vehicles provide high-resolution images of the road surface and road environment.

GROUP **MOBILE TERRESTRIAL SCANNING**

Dr. Philipp von Olshausen, Phone +49 761 8857-289, philipp.olshausen@ipm.fraunhofer.de

The research focus of the group is the development of time-of-flight-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 and cameras, they can also capture three-dimensional object geometries. For precise position and location detection, we combine the systems with inertial sensors, which allows 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: Dr. Philipp von Olshausen

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, surface images 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

MINIATURIZATION OF MOBILE MAPPING SYSTEMS

- Optimizing the mechanical and electronic setup of complex multi-sensor systems
- Reducing data in real time for fast and efficient data transfer
- Data interpretation in real time
- Adaptable for measuring railway and road environment

Digital model of rail infrastructure
In cooperation with the Institute of Construction Management and Digital Engineering at the Leibniz University Hannover and an industrial partner, we are developing a process which automatically links the latest geometric building information to all existing infrastructure data. The "mdfBIM" project is funded by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) through the mFUND research initiative.

Mobile mapping vehicle delivered
Since the fall of 2020, a survey vehicle built by our team based on our mobile urban mapping system platform has been in operation at Oßwald GmbH. It produces 2D and 3D images of street environments and high-resolution pictures of road surfaces which provide information about longitudinal and transverse evenness. The package also includes customized software for interpreting data.

Shape and material recognition for disinfection robots
As part of the "MobDi" project, 12 Fraunhofer institutes are working together to develop a mobile disinfection robot. To ensure disinfection is both resource-efficient and gentle on materials, we are supplying technology that can identify typical sources of infection. The measurement data are automatically analyzed using deep learning algorithms. #fraunhofervscorona

GROUP **AIRBORNE AND UNDERWATER SCANNING**

Simon Stemmler, Phone +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 Unmanned Aerial Vehicles (UAV) and the adaptation of LiDAR technology for capturing 3D data of large underwater 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 systems will also be able to detect acute damage, for example on bridge piers, caused by natural hazards such as flooding. 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
- Measuremen precision 1 cm, typical 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

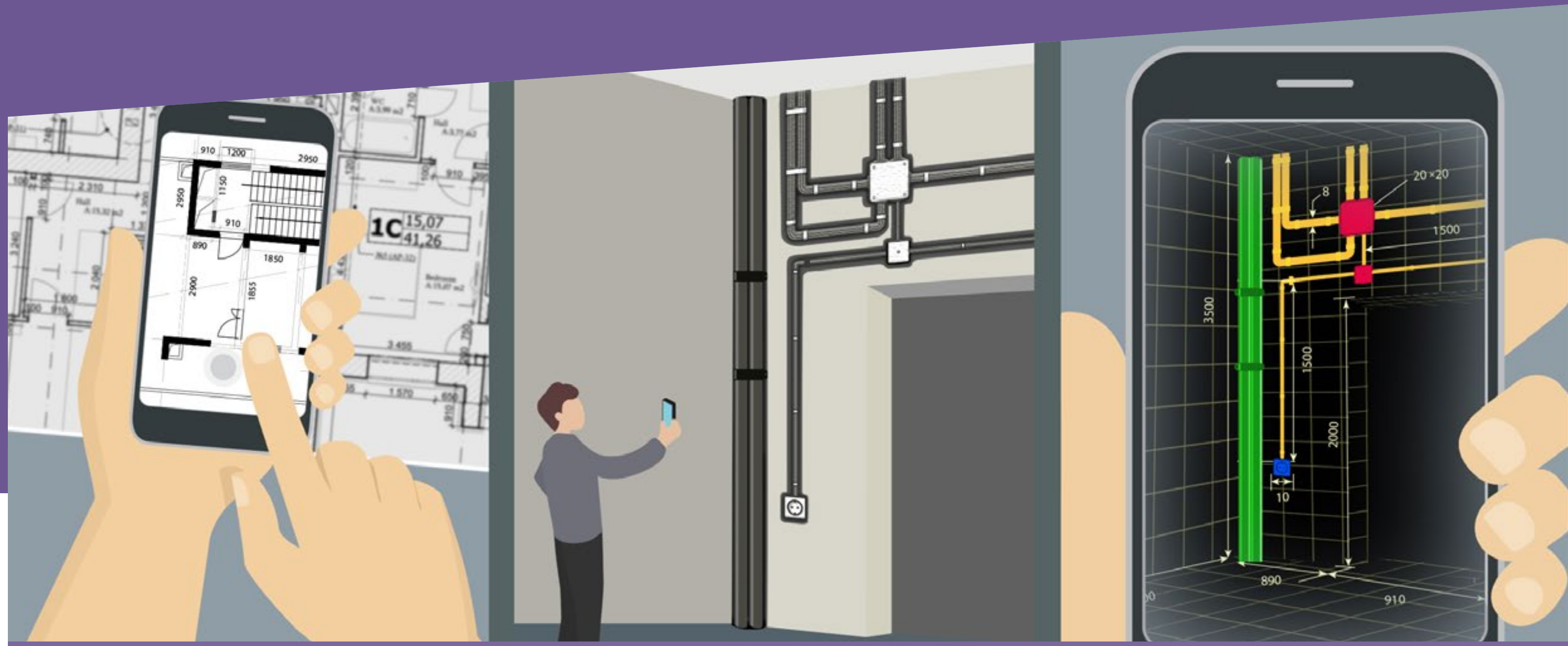
- 3D surveying with subcentimeter resolution, even in turbid water
- Measurements irrespective of light conditions and depth
- Measurement frequency up to 40 kHz, scanning frequency 800 Hz
- Measurement distance up to 40 m (depending on the turbidity of the water)
- Stationary and mobile surveying

SYSTEMS BASED ON CONSUMER ELECTRONIS

- Mobile 3D detection of construction sites and excavation pits
- Using smartphones or tablets for data acquisition
- Georeferencing via GNSS or ground control points
- User interfaces adapted to user scenario

DATA PREPARATION

- Fusion of 3D and 2D data incl. positioning and texturizing
- Derivation of metadata from texturized 3D data
- Automation of surveying tasks



Digitally recording and documenting structural changes
As part of a Fraunhofer project, we are developing a process which links video recordings of building interiors to layout plans. The georeferenced data, collected with a smartphone camera, are integrated in digital inventory plans using algorithms. This allows building refurbishments, such as new cabling, to be digitally captured retrospectively.

Underwater laser scanning: 3D video mode added
For the detection of objects under water, we have supplemented our underwater LiDAR system with a 3D video mode. A new deflection unit was developed which records the objects' surfaces from great distances with unprecedented quality. This makes it possible to monitor structures in turbid waters and detect munitions debris in the sea.

Optical system detects vegetation in the track bed
Equipped with our system for green detection, two spraying trains for automated vegetation maintenance have continuously been travelling at 80 km/h around the German rail system since March 2020. They ensure that herbicides are only applied where unwanted plants actually grow (read more, page 44).

GROUP **SMART DATA PROCESSING AND VISUALIZATION**

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

The group's research foci are the analysis, classification and visualization of spatial measurement data. We use machine learning methods such as deep learning for the fully automated interpretation of 2D and 3D measurement data. This involves training artificial neural networks (ANNs) to recognize and pinpoint objects – for instance from urban infrastructure – in comprehensive mobile measurement system data sets.

Our interactive applications for navigating in measurement data visually support complex analysis and decision-making processes. Depending on the use case, we can also develop visualization variations on appropriate platforms which display the measurement results in real time. This enables recording processes to be readjusted interactively. For real-time visualization on mobile devices with limited processing power, we resort to dedicated visualization components. For AI-based object recognition, we create synthetic training data. In doing so, we are also laying the foundation for the iterative optimization of measurement systems with a view to prospective machine data interpretation.

Group Manager: Prof. Christoph Müller

VISUALIZATION

- Display of massive point clouds
- Real-time rendering at more than 20 frames per second
- Various visualization techniques for intuitive presentation of complex information, e.g. calculation of lighting, color-coding of edges and false-color representation

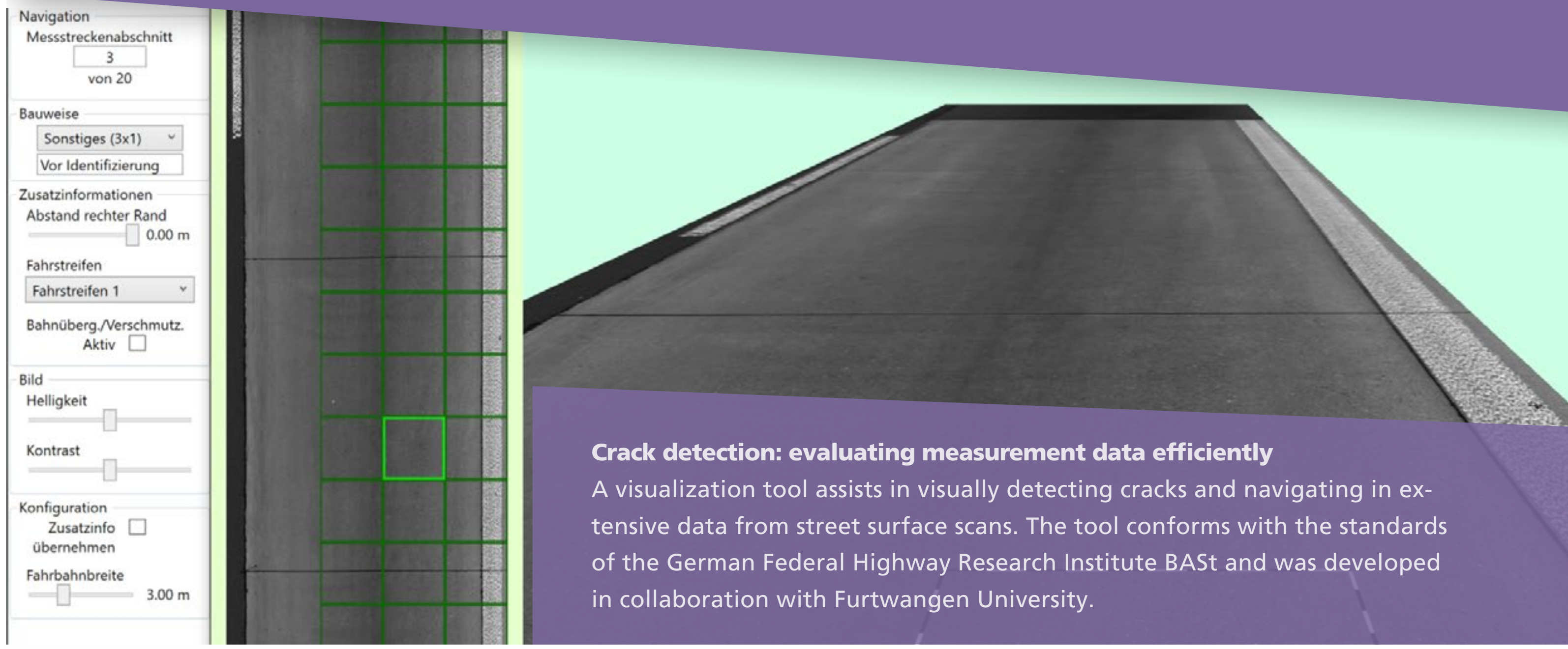
SYNTHETIC TRAINING DATA

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

AUTOMATED DATA INTERPRETATION

- Fully automated interpretation of 2D and 3D measurement data, e.g. by means of deep learning
- Implementation of cloud-based solutions for data processing
- Compilation of comprehensive training datasets for the automated training of algorithms

Purely virtual: Camera data and semantic segmentation using a common 3D model
The team behind the Fraunhofer project "Syntra" created a simulation environment capable of generating synthetic training data for urban environments particularly efficiently. The training data were then evaluated in different grid architectures.



Crack detection: evaluating measurement data efficiently
A visualization tool assists in visually detecting cracks and navigating in extensive data from street surface scans. The tool conforms with the standards of the German Federal Highway Research Institute BASt and was developed in collaboration with Furtwangen University.

Digital documentation of the excavation trench
A visualization component developed by the group enables the exact documentation of underground supply lines, pipes and connections. The measurement data are recorded using a tablet PC equipped with low-cost sensor technology. The software was developed as part of the "NEXT.TrenchLog"project for Bayernwerk Netz GmbH.

< Herbicides such as glyphosate remain the substance of choice for keeping vegetation in the ballast bed in check. To reduce the amount used, an optical system for automated vegetation detection is employed.

Efficient vegetation management with the help of green detection

The railway network of Germany's DB Netz AG covers over 60,000 kilometers. Controlling and clearing the vegetation that grows alongside and on the tracks is extremely cumbersome. Without herbicides, it is impossible to contain the weeds. An optical system for automated green detection enables targeted herbicide application while documenting growth. This makes vegetation management more efficient and more environmentally friendly.

Field horsetail, blackberry bushes, geraniums, brome grasses and evening primrose – these are the most common types of weeds found in and around train tracks, as they can easily take root in the cavities of the crushed stones forming the ballast bed. As a result, rainwater cannot drain quickly enough, the ballast bad fills with mud andcan no longer properly act as a buffer. Vibration and shock from passing trains are no longer sufficiently absorbed, which can lead to changes in the condition of the track. Thus, plants turn into a safety hazard to train operation.

Less herbicide, greater efficiency

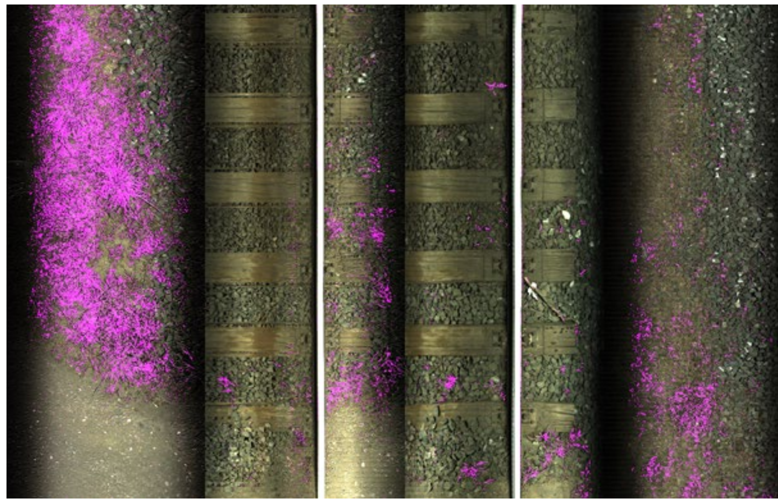
Managing vegetation growth in the ballast is a never-ending challenge. Railway system operators commission specialist service providers such as Certis Europe B.V. with controlling growth by using crop protection products, in particular glyphosate. The broadleaf herbicide effectively and reliably eradicates the growth, but its use is controversial because of its negative ecological effects. This is why Deutsche Bahn announced a decrease in the use of glyphosate by half, starting from 2020. Fraunhofer IPM has developed a camera-based system to help Certis achieve this goal. Thanks to the system's automated vegetation detection capabilities, herbicides are only applied in areas where plant growth actually poses a risk. As an added feature, plant development over the years is now documented based on the camera images as well as information on location and growth coverage. Since spring 2020, two spraying trains equipped with the system have been dispatched across the Germain railway network for vegetation management.

Previously, vegetation detection had been a manual and visual process. Up to three people had to monitor a specific area of track from aboard the spraying train, manually triggering a spraying command whenever they spotted vegetation. The maximum speed at which this was effective was 40 km/h. The new camera-based vegetation detection system, however, automatically and precisely triggers the spraying mechanism. It works reliably, accurately and fault-free over long periods of time – because it doesn't get tired. And what's more, cameras and processors react more quickly than humans. At a speed of 80 km/h, the spraying train travels twice as quickly as it could when carrying the manual system – a substantial increase in efficiency. In the medium term, the goal is to achieve even greater travel speeds. The amount of herbicide sprayed is also set to be significantly reduced from the previous 6 liters per hectare.

THE SPECTRAL FINGERPRINTS OF PLANTS – THE "GREEN GAP": Green vegetation has its own characteristic spectral fingerprint. This means that light is reflected in the wavelength range of 490 nm to 620 nm – the green gap – and from 780 nm upwards in the near-infrared (NIR) spectrum, while light in the wavelength ranges of 400 nm to 490 nm (blue spectral range) and 620 nm to 780 nm (red spectral range) is absorbed. We use this specific absorption and reflection behavior in the automated detection of living plants.

Multispectral system spots green

A total of eight cameras are built into a weatherproof housing to detect vegetation. Two pairs of cameras – each comprising one RGB and one NIR camera – record the left and right sides of the tracks; an additional two pairs of the same types of camera are mounted underneath the train to observe the middle of the tracks. The cameras have a ground resolution of 1.5 mm. The ballast bed is evenly lit by 500 high-performance LEDs, enabling vegetation detection even in poor lighting conditions and at night.



The survey image shows the vegetation in detail (depicted in purple). The optical RGB and NIR camera system uses the specific absorption and reflection behavior of certain light spectra for the automated detection of living plants.

The recorded track areas are subdivided into quadrants. If the degree of ground coverage by plants in a given quadrant exceeds the permitted threshold value, this triggers a sensor signal, which then activates the required number out of a total of eight moveable spray nozzles. Both the size of these quadrants and the threshold value for the degree of ground coverage can be adjusted individually. In addition to the degree of ground coverage, GNSS information is recorded to pinpoint the exact location. The results can be output as a chart or as a table.

Image analysis and signal processing within a second

When developing the system, achieving the required speed of image processing and signal evaluation as well as of relaying signals to the existing onboard spray nozzle technology posed a particular challenge. The possible distance between the camera system and the spray nozzles is limited to approximately 30 to 50 m by the length of the train and the order of the individual cars in the given direction of travel. A travel speed of 80 km/h equates to 22.2 m which the spraying train can cover every second. Due to technical and physical inertia, the spraying mechanism works with a certain delay. However, the maximum permissible time between image capture and the triggering of the spraying command is one second in total. The camera images are processed line by line and analyzed using a field-programmable gate array (FPGA).

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

BUSINESS UNIT
GAS AND PROCESS TECHNOLOGY

"We develop tailor-made measuring systems for gas and process monitoring."

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 and tailor-made light sources and detectors as well as energy-efficient sensor systems and 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
Head of Department
Phone +49 761 8857-134
juergen.woellenstein@ipm.fraunhofer.de

Group **Integrated Sensor Systems**
- Gas sensitive materials
- Micro-optical infrared 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
- New spectroscopic measuring methods
- Quantum sensing

< The industry needs robust and precise measuring systems. Our tailor made systems facilitate safe gas and process monitoring.

GROUP **INTEGRATED SENSOR SYSTEMS**

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

The group's research focuses on developing gas-sensitive materials, micro-optic infrared components and compact gas sensor systems. Drawing on our expertise in microsystems engineering, we design miniaturized system components and sensor systems as MEMS (micro-electro-mechanical systems) and MOEMS (micro-opto-electro-mechanical systems). Ensuring the robustness, reliability and energy efficiency of the modular gas sensor systems is of the utmost importance. The areas of application range from environmental measurement technology to personal protection, and detection is possible from just a few ppm to several percent. The customized gas sensors developed by Fraunhofer IPM help, for example, to guarantee optimal air quality or detect toxic gases at an early stage.

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 for trace gas detection
- Colorimetric gas sensors: complex compounds such as an Rh complex for selective CO detection and porphyrins for NO_2 detection

MICRO-OPTIC INFRARED COMPONENTS

- Micro-optic components for wavelengths ranging from 3 to 20 µm
- Infrared emitter: e.g. modulated up to a frequency of 10 Hz (up to 750 °C)
- IR detectors: e.g. PbSe photodiodes for wavelengths ranging from 3 to 5 µm
- Diffractive optics: e.g. Fresnel lenses for the mid-infrared range

MINIATURIZED GAS SENSOR SYSTEMS

- Integration of gas-sensitive materials and/or optical components in energy-efficient gas sensor systems
- Modular structure with application-specific sensors, evaluation electronics and control electronics
- Photoacoustic systems: e.g. miniaturized for selective CO_2 detection or UV-based for SO_2 detection
- Filter photometer: e.g. for ethylene detection

Sensor for monitoring patients in intensive care

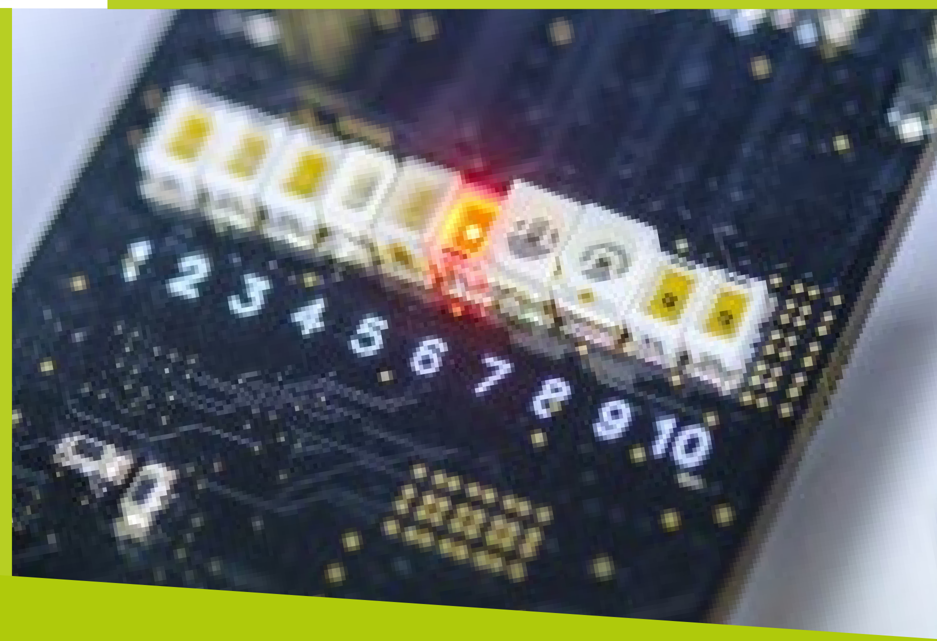
As part of the "Fraunhofer vs. Corona" action plan, we are developing a non-invasive transcutaneous sensor for monitoring the arterial CO_2 levels of critically ill patients in real time. The sensor is applied to the skin and has the size and weight of an in-ear headphone. The concentration is determined on the basis of the photoacoustic effect.

Excellent NO_2 detectors for integration into measurement systems

We have achieved excellent results in resonant low-cost photoacoustics. We have built detector modules for gases such as NO_2 which are characterized by a detection limit in the low ppb range, a high degree of selectivity and long-term stability combined with impressive cost efficiency. As a result, the technology outperforms many existing measurement techniques.

Early and reliable detection of combustion gases

We have succeeded in developing new gas sensor systems which can reliably detect typical combustion gases such as CO, NO_2 and NH_3 at an early stage. The materials used react with a specific color change when combustion gases are detected (down to the ppb range). Readings rely on light-emitting diodes and photodetectors. When combined with the corresponding electronics, the resulting systems are both cost-effective and robust.



GROUP **SPECTROSCOPY AND PROCESS ANALYTICS**

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

The group's research focus lies on developing spectroscopy systems for the detection and analysis of liquids and gases. Our primary method is laser spectroscopy, but we also use methods like Raman, FTIR and ATR 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

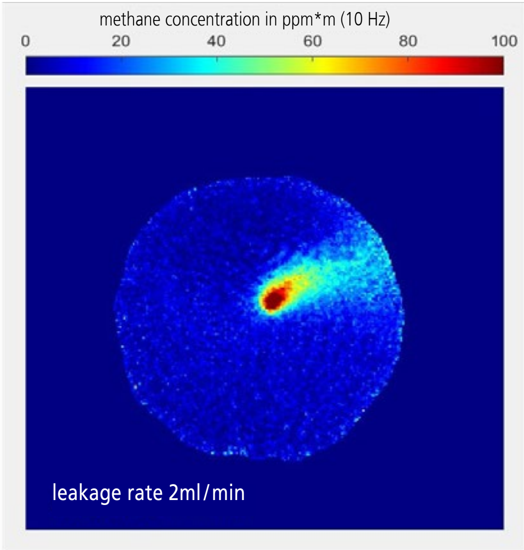
OPTICAL SYSTEMS

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

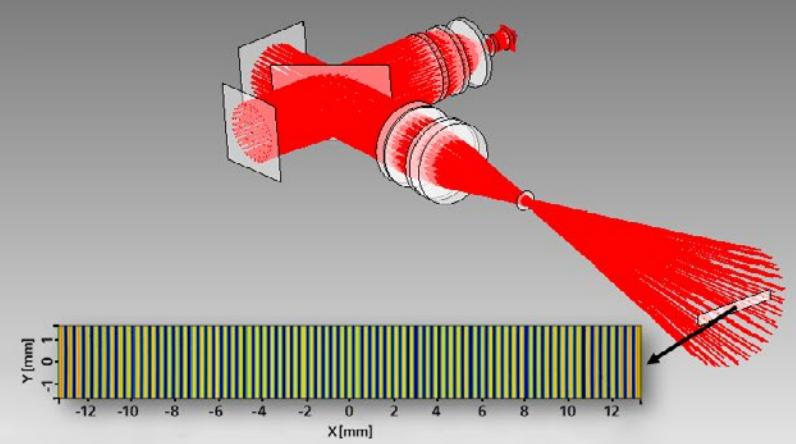
EVALUATION METHODS

- 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

Measurement system for the calorific value of natural gas
RMA Measuring and Control Technology commissioned the development of an infrared spectroscopic gas analyzer, which was then tested at a Power-to-Gas feed-in point over a period of eight months. With accuracy down to the 100-ppm range, the system recognizes the composition of natural gas and the proportion of hydrogen it contains.



Imaging method detects minimal leakage
We have succeeded in optimizing imaging laser spectroscopy for the sensitive remote gas detection of leaks. A high-speed infrared gas camera makes gas leaks visible, and adaptive evaluation enables a high-contrast representation of leakage flows under 1 ml/min. A stored model for direct absorption spectroscopy allows us to quantify concentrations in ppm*m.



Wave optics model expands simulation possibilities
In developing optical measurement systems, we now conduct both geometric and wave-optical simulations of beam paths. Outside influence on the detector signal can thus be more realistically simulated and spectrally analyzed. The image shows laser light being integrated into a Michelson interferometer with a diffraction grating, producing a spatial interferogram.

GROUP **THERMAL MEASUREMENT TECHNIQUES AND SYSTEMS**

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

The group's expertise comprises microsystems engineering, sensor technology, measurement system development and multiphysics simulation. We have many years of experience developing MEMS-based cleanroom production technologies for manufacturing sensors and thermoelectric modules. We develop customized microstructures and microsystems for the temperature-dependent determination of material parameters (such as thermopiles), designed exactly for specific applications. The group's work includes modeling, layout and process development as well as material, component and system characterization. We are constantly expanding our expertise by using new methods, materials and measurement technologies.

Group Manager: Martin Jägle

CUSTOM-MADE MICROSTRUCTURES

- Electrical and thermal measurement of analytes or functional materials
- Characterization of liquid substances (e.g. oils, refrigerants)
- Detection of deposits (e.g. calcification, fouling or scaling)
- Inspection of solids
- Sensors for combustible gases

THERMAL MEASUREMENT SYSTEMS

- Measurement systems for temperature-dependent materials characterization in broad temperature ranges (-200 to +1000 °C), e.g. measurement of Seebeck or Hall coefficients, or of thermal and electrical heat conductivity (incl. service and maintenance)
- Durable electronic systems for harsh environments

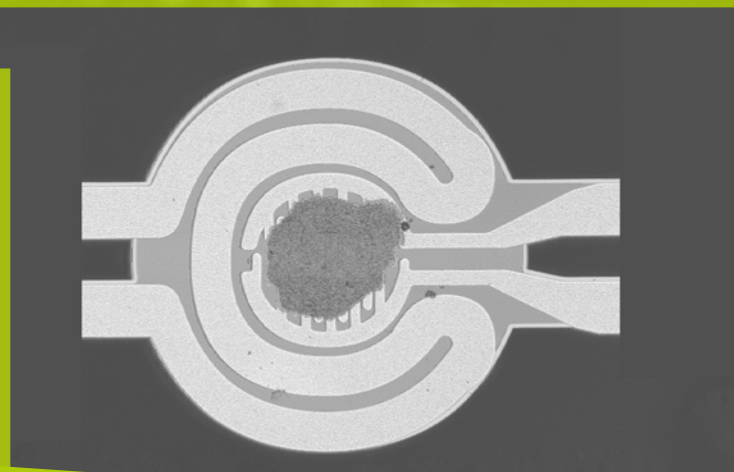
SIMULATION OF PHYSICAL PROCESSES

- Multiphysics simulations for coupled electrical, thermal, mechanical and fluid effects, from microsystems to kilometer-large energy storage devices

New pressure test bench taken into operation
A newly installed pressure test bench allows us to test and measure components up to one meter in length with a diameter of 10 cm at pressures of up to 2000 bar and temperatures up to 200 °C. Measurement systems can be operated on the pressure test bench via electric access points leading into the sample chamber, and additional sensors can be integrated.

USB drive measures hydrogen content in the environment
A compact H_2 sensor, displayed here in the form of a USB drive, measures the ambient hydrogen content and provides a warning when concentrations become dangerously high. With the rise of hydrogen as an alternative to fossil fuels, sensors such as these are becoming more and more important for preventing explosions.

MEMS pellistors for safe fuel gas measurement
The group has developed MEMS pellistors with novel, printable catalysts that operate at a temperature of up to 100 °C less than before. The sensors' low operating temperature and small size enable the safe and economical measurement of combustible gases.



GROUP **NONLINEAR OPTICS AND QUANTUM SENSING**

Dr. Frank Kühnemann, Phone +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

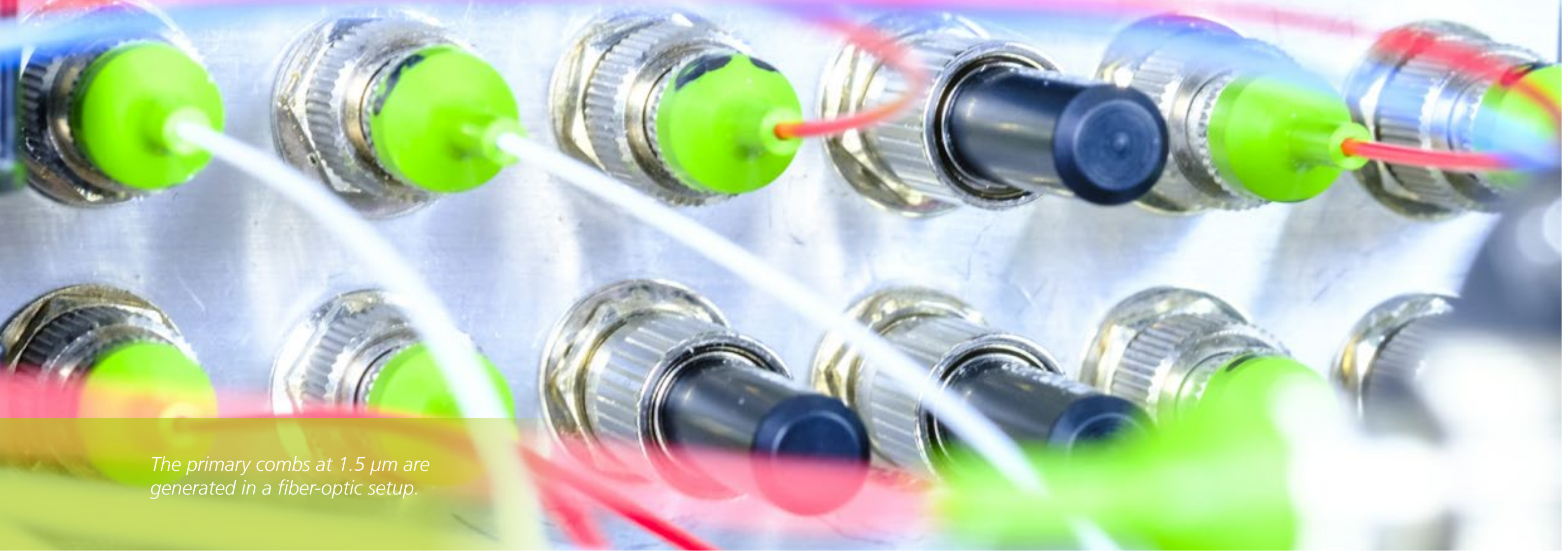
- Spectroscopy with entangled photon pairs – quantum Fourier transform infrared spectrometer
- Magnetic field sensors with optically pumped magnetometers – NMR at ultra-low magnetic fields

New generation of the C-WAVE optical parametric oscillator
In the fall, Hübner Photonics launched the C-WAVE GTR optical parametric oscillator, developed together with Fraunhofer IPM. With new wavelengths and an improved design, the light source is now suitable for even more applications in research and industry.

NMR measurement techniques at low magnetic field strengths
The group has opened a new laboratory for quantum sensor technology where new measurement techniques for nuclear magnetic resonance (NMR) at particularly low magnetic field strengths will be developed. This will be achieved by using optically pumped magnetometers as highly sensitive sensors.

Record numbers attend "Sensing with Quantum Light"
Now in its third year, the annual event "Sensing with Quantum Light", co-organized by the group, demonstrated its global significance as an important gathering for experts in quantum imaging and spectroscopy. There was a three-fold increase in the number of participants attending the hybrid event. We presented the first gas measurements performed with the Quantum Fourier Transform Infrared Spectrometer we developed.

SQL 20



The primary combs at 1.5 µm are generated in a fiber-optic setup.

Trace gas analysis with frequency combs – broadband and sensitive

Fraunhofer IPM has developed a new measuring device for trace gas analysis based on dual-frequency comb spectroscopy. Using this method, researchers can examine broad mid-infrared wavelength ranges quickly, highly sensitively and at a very high spectral resolution. This novel tool closes the gap between broadband FTIR spectroscopy and QCL/ICL-based spectroscopy. It is particularly suited for the analysis of gas mixtures with complex spectra.

Mid-infrared molecular spectroscopy is a sensitive analysis tool used in gas sensor technology and for materials characterization. Modern systems rely on quantum or interband cascade lasers (QCL/ICL) for highly sensitive detection, while Fourier transform infrared (FTIR) spectrometers excel in spectral bandwidth. Fraunhofer IPM has now developed a spectrometer which uses frequency combs to detect trace gases, closing the gap between conventional FTIR and QCL / ICL-based spectrometers by combining their advantages.

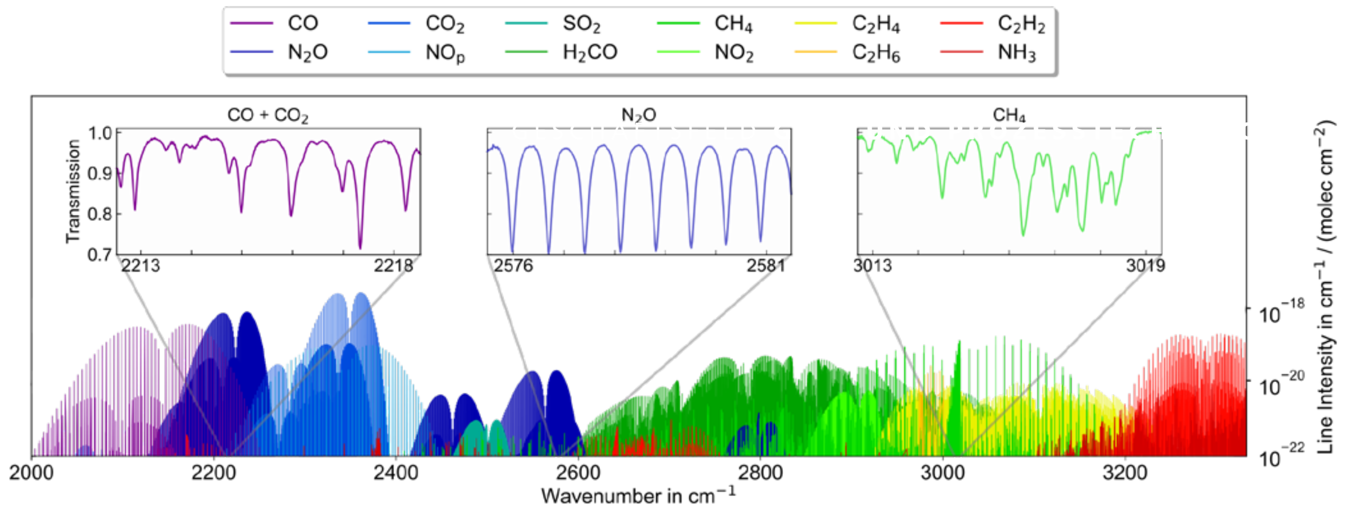
The principle of dual-frequency comb spectroscopy

Frequency combs are lasers which emit a large number of coherent and equally spaced modes simultaneously. In the frequency domain, this phenomenon looks like the teeth of a comb, giving rise to the name frequency comb. To be able to detect the spectral information of all of the comb's modes at the same time, a second, synchronized frequency comb with slightly wider spacing between these modes is used. By superimposing both signals on a detector, all of the optical information scanned by the combs can be coded into a single, easy-to-record radio frequency signal.

Frequency combs are already commercially available, particularly in the near-infrared (NIR) spectral range. In the particularly interesting mid-wave infrared spectral region (MIR), where most molecules display substantial vibration bands. Frequency combs that are particularly suited to highly sensitive trace gas detection are still lacking. A straightforward approach to tapping into this mid-infrared region is to transfer an NIR comb to the MIR region using nonlinear frequency conversion, a technique which Fraunhofer IPM has been using for many years to develop laser light sources such as optical parametric oscillators (OPOs).

Flexible in the mid-infrared region

Pursuant to this concept, Fraunhofer IPM's dual-frequency comb spectrometer consists of two modules: the dual-frequency comb generator and the MIR converter. To generate a frequency comb, a laser beam with a wavelength of 1.55 µm is split into two rays, in which the two combs with slightly differently spaced frequencies are generated via electro-optic modulation (EOM) and subsequently broadened to the final bandwidth with several hundred to two thousand comb teeth – a tried-and-tested procedure. Since they stem from the same original laser, both combs are intrinsically coherent and the electro-optic modulation allows the spacing of the comb teeth to be adapted to the structure of the spectra being examined. This procedure is decidedly less complex than conventional dual comb systems, and using fiber-optic standard components makes this setup robust.



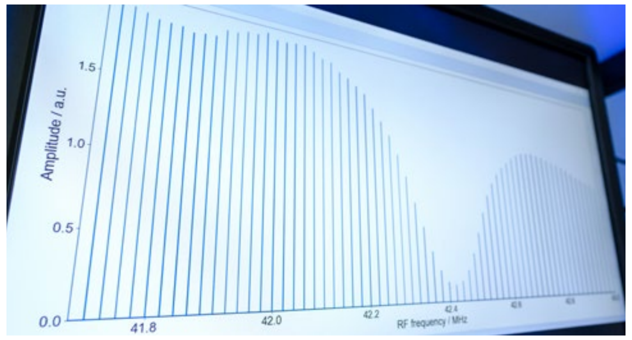
Typical gases found in exhaust gas or in the air have characteristic bands in the mid-infrared spectrum (seen here in a simulation). Fraunhofer IPM's dual-frequency comb spectrometer covers the entire relevant range of frequencies and is capable of taking broadband measurements.

A **FREQUENCY COMB** comb (FC) is a laser light source that emits light using a large number of adjacent spectral lines with equal and well-defined frequency spacing, hence the name frequency comb. If the frequency comb covers a frequency range of at least an octave, the frequencies of the individual comb teeth can be determined with extreme accuracy. This phenomenon is therefore also known as an "optical ruler." Researchers began developing frequency combs more than 20 years ago. Their work was considered revolutionary. Prof. Theodor Hänsch of the Max Planck Institute for Quantum Physics and his colleague from the USA, John Hall, received the 2005 Nobel Prize in Physics for their work designing and developing optical frequency combs to be used in precision spectroscopy.

The available number of comb teeth (and thus the spectral coverage) is smaller than with other comb types, but EOM-based combs provide a much higher signal-to-noise ratio on the individual comb modes. This is essential for conducting highly sensitive trace gas measurements.
In a second step, the NIR dual-comb is transferred to the MIR region by way of difference-frequency mixing, a procedure where Fraunhofer IPM demonstrates its strengths in the field of nonlinear optical frequency conversion. Using an optical-parametric oscillator (OPO) developed in-house, which is currently marketed under the name C-WAVE GTR (s. p. 55), the pump wavelength can be varied between 1.0 and 1.3 µm. This enables the MIR comb's central wavelength to be flexibly tuned to any desired spectral range from 3 to 5 µm depending on the exact spectral region being examined for trace gas detection.

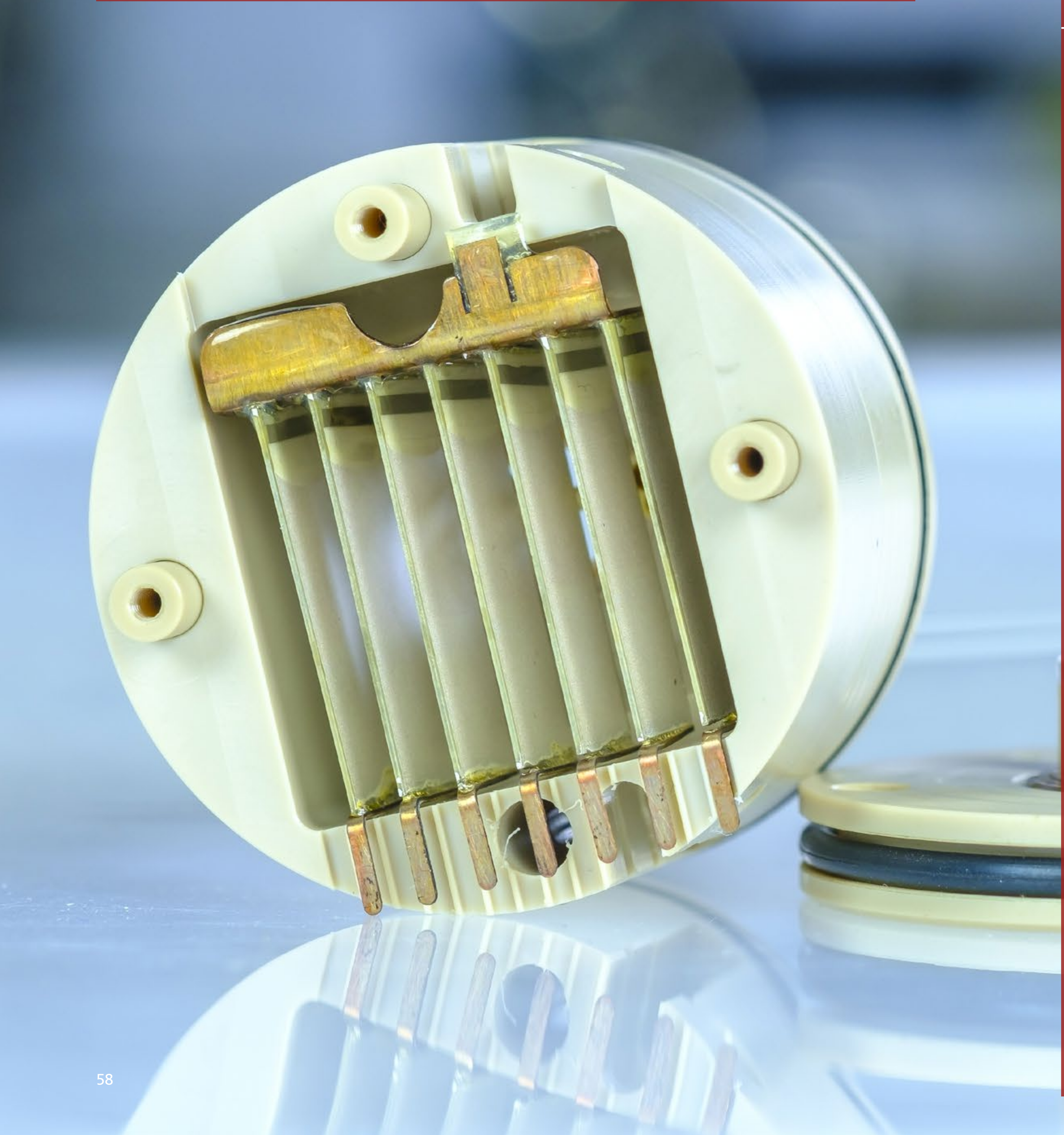
Multi-purpose demonstration unit for various applications

The system is rounded out with operating software for collecting and processing data as well as system control. This provides for continuous measuring, efficient data compression and real-time analysis. Full control over measuring parameters means that customized adjustments can be made according to the requirements of the measuring task at hand – quick spectral scanning at up to 20 kHz, instant spectral coverage up to 20 cm^{-1} and spectral resolutions of up to 250 MHz (< 0.01 cm^{-1}) for detection in low gas pressure ranges.
This technology can be used for many applications spanning many fields, from quick combustion analysis and finely tuned process control to gas mixture certification to exhaust gas analysis (N_2O and CO_2, see Fig. above) or determining stable carbon isotope ratios (^{12}C and ^{13}C) in the greenhouse gases CO_2 and CH_4. Other potential applications include multi-component atmospheric monitoring (CH_4, CO_2, N_2O, ...) and the characterization and quantification of contamination in hydrogen (H_2), which can lead to catalyst deactivation e.g. in fuel cells.



The absorption band of a gas is scanned by many closely spaced adjacent laser lines at the same time.

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



BUSINESS UNIT
THERMAL ENERGY CONVERTERS

"We develop systems for cooling as well as switching, pumping, converting and conducting heat."

The Thermal Energy Converters Business Unit concentrates research activities on pumping, converting, conducting and switching heat. Our work draws on more than 20 years of experience and far-reaching expertise in special measurement techniques, simulation, material development and system integration.

Our skills include the development, conception and assembly of efficient caloric heat pumps and cooling systems based on magnetocaloric, electrocaloric or elastocaloric materials, as well as the development of thermoelectric modules and systems. Moreover, we are conducting research on novel designs for efficient heat transfer based on heat pipes and heat pipe-based thermal switches for precisely regulating heat flows.

Dr. Olaf Schäfer-Welsen
Head of Department
Phone +49 761 8857 - 173
olaf.schaefer-welsen@
ipm.fraunhofer.de

Group **Thermoelectric Systems**

- Development of thermoelectric modules and systems
- Conversion of waste heat into electricity in the milliwatt to kilowatt range
- Direct use of waste heat from furnaces for the grid-independent operation of consumers
- Innovative Peltier cooling
- Structural, thermal and electrical analytics of components and materials

Group **Caloric Systems**

- Heating and cooling without harmful refrigerants
- Development of magnetocaloric, elastocaloric and electrocaloric systems
- Development and characterization of heat pipes for thermal management

< Components of an electrocaloric segment equipped with several ceramic components connected in parallel. A check valve specially developed for the caloric heat pipe is shown next to the segment. The electrocaloric material was provided by Fraunhofer IKTS.

GROUP **THERMOELECTRIC SYSTEMS**

Dr. Olaf Schäfer-Welsen, Phone +49 761 8857-173, olaf.schaefer-welsen@ipm.fraunhofer.de

The group's research focuses on thermoelectric modules and systems, also for high temperature processes. Our activities range 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 many years of experience in materials and module development, measurement technology, simulation processes, system construction and material analysis.

One of the group's core areas of expertise is the semi-automatic production of thermoelectric modules. These modules are used as thermoelectric generators for waste heat conversion, e.g. in small combustion plants. In addition, they 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

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

ANALYTICS FOR COMPONENTS AND MATERIALS
- Non-destructive structural, thermal and electrical analytics of components and materials
- Innovative 3D computer tomography: Analytics chains, failure analysis, live and in-situ examinations (also of fluids within components)

Self-powered exhaust gas treatment for small furnaces
We have managed to develop a demonstration system as a retrofit solution for wood-powered furnaces: The air-cooled thermoelectric generator with heat pipe-based heat transfer converts a portion of the heat from the exhaust gas flow, generating 20 W of electrical power from 12 kW of heating power. Depending on the operating point, the output could cover the electricity consumption of an additional consumer for exhaust gas treatment (e.g. an electrostatic particle separator).

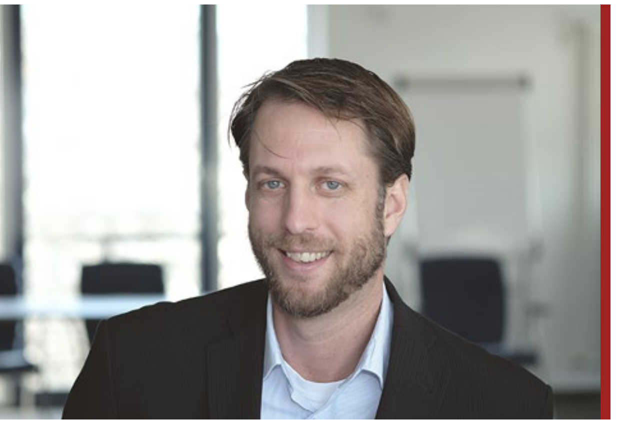
Highly precise, quick heating of pipes
The "HochPerForm" project involved the development of a ring-shaped Peltier module for heating a hollow cylinder. The pipe can be heated up homogeneously with a heating rate of 18 K/s and cooled with a cooling rate of 10 K/s using 10 thermoelectric strips. This allows the quick and precise setting of the pipe temperature within the range of 0–120 °C.

GROUP **CALORIC SYSTEMS**

Dr. Kilian Bartholomé, Phone +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 (PHP) represent another field of work for the group. PHP transfer heat considerably more efficiently than copper, for example, and they offer several advantages over conventional heat pipes. The PHP 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

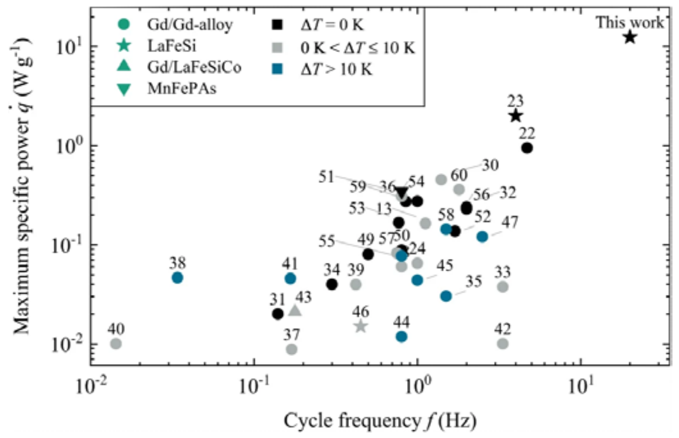
- Reduced energy needs thanks to efficient technology
- Heating and cooling without harmful refrigerants
- Low-noise and low-maintenance systems

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

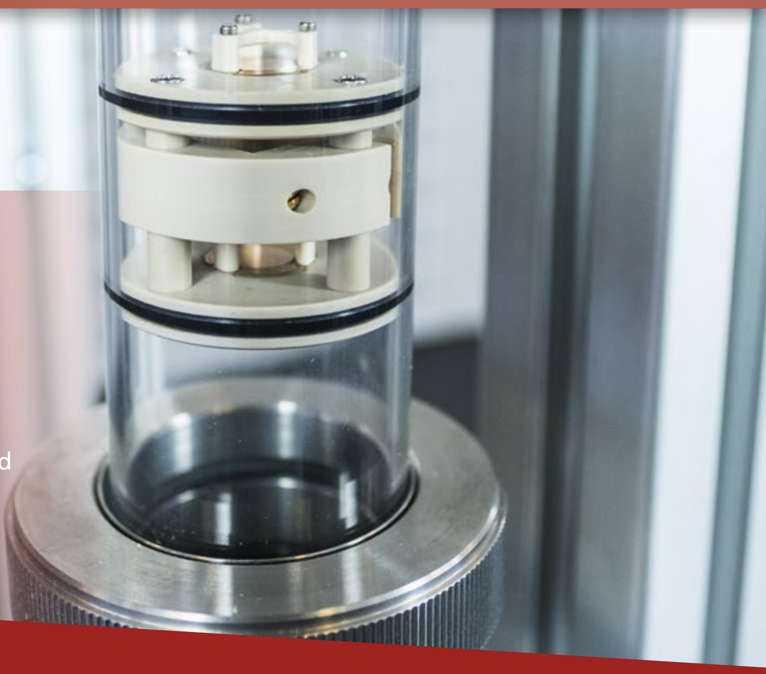
HIGH EFFICIENCY HEAT TRANSFER WITH LATENT HEAT

- Heat transfer via evaporation and condensation
- Heat transfer coefficient of higher than 10^5 W/(m²·K)
- Extremely fast and efficient heat transfer for system frequencies up to 20 Hz

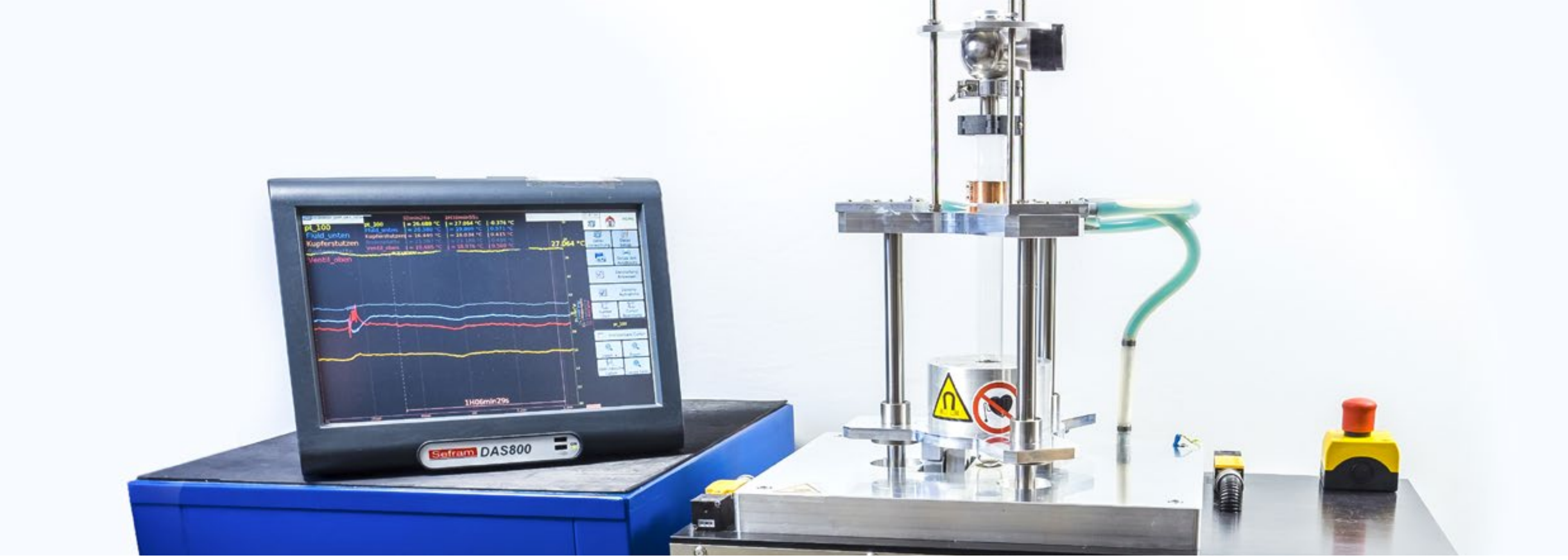


Milestone in the development of caloric cooling systems
The group has succeeded in developing the first caloric cooling system to achieve a specific power that is an order of magnitude higher than all previously developed systems. Active magnetocaloric heat pipes are at the heart of the system. The group published this breakthrough in the Nature research journal "Communications Physics".

Research into heat pipes with functional materials
The group has opened up a new field of activity. By integrating functional materials into heat pipes, it will become possible to develop thermal switches that shift at a programmed temperature. Above a certain temperature, heat transportation improves by a factor of 20 compared with below this switching temperature.



Proof of concept for electrocaloric heat pumps
In the "ElKaWe" project, we have demonstrated that it is possible to integrate electrocaloric materials into heat pipes for heat transportation. This lays the foundation for the development of electrocaloric heat pumps for heating and cooling as part of the Fraunhofer lighthouse project. Six Fraunhofer institutes are involved in the project.



< In active magnetocaloric heat pipes, all system components are characterized and optimized in a two-phase region (liquid-vapor). The vaporization and condensation of a fluid in the two-phase region is also used in conventional heat pipes, hence the term "active magnetocaloric heat pipe."

Magnetocaloric heat pipes: refrigeration reimagined

Alternative forms of cooling and heating are a topic of discussion all around the globe. But the requirements for sustainable refrigeration and HVAC technology are complex. Systems must be highly cost-effective and energy-efficient to stand a chance of competing with conventional technology. For several years now, Fraunhofer IPM has been researching the development of magnetocaloric cooling systems which run free of harmful refrigerants. A novel approach promises to significantly outperform previous magnetocaloric systems with regard to cooling performance, price and efficiency. Active magnetocaloric heat pipes are at the heart of the system.

Refrigerators, air conditioning units, heat pumps – for over one hundred years, compressor technology has been dominating the field of refrigeration. But compressors are loud, comparatively inefficient and often use potentially harmful refrigerants, some of which are combustible or toxic, while others are harmful to the environment and are therefore closely regulated. Magnetocaloric cooling systems do not require any liquid refrigerants, as the cooling effect is achieved by the magnetocaloric material directly. A system developed by our research group has surpassed previous caloric systems in cooling power density by one entire order of magnitude, holding the potential to permanently change refrigeration as we know it.

Use of latent heat through active magnetocaloric heat pipes

Previous research on magnetocaloric systems was based on the principle of active magnetocaloric regeneration (AMR systems). This involves pumping a fluid carrying the thermal energy of the magnetocaloric materials into the heat exchangers. Such systems allow for high cooling performance and broad temperature ranges, but the friction can result in significant losses. This leads to poor efficiency and power density.

Researchers at Fraunhofer IPM have therefore turned to a different mechanism: active magnetocaloric heat pipes. These use a magnetocaloric material enclosed in multiple chambers arranged in a circle. A rotating magnet in the center of said circle causes the material to heat up (magnetization) and cool down (demagnetization) in an alternating pattern. The heat transfer occurs exclusively via the vaporization and condensation of the fluid (e.g. methanol), and check valves serve as thermal diodes. This enables the use of latent heat and minimizes friction-induced heat loss.

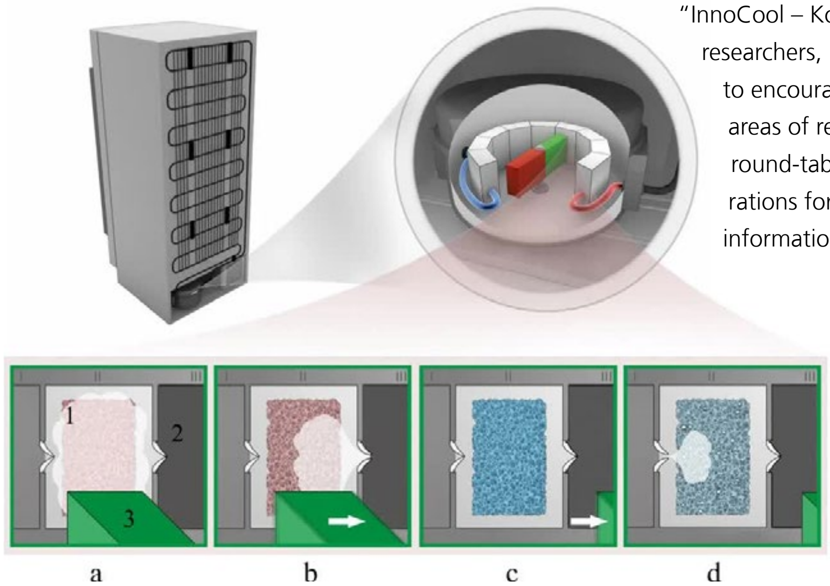
Now for the first time, this system's superiority can be demonstrated in numbers. The cooling power density is one order of magnitude greater than in all previous systems. This increased cooling power density is achieved through a high cycle frequency, which enables high cooling power with minimal material usage – a decisive factor for making a system cost-effective. The results were published in the nature journal "Communications Physics" in 2020. Initial simulations show a substantial increase in efficiency as well. At a cycle frequency of 20 Hz and a temperature in the medium range, approximately 60% of the Carnot cycle – the theoretical upper limit of efficiency – can be achieved.

The **MAGNETOCALORIC EFFECT** was discovered in 1917. It describes how magnetocaloric materials heat up in the presence of a magnetic field. By alternating magnetization and demagnetization, a cooling cycle can be created. It wasn't until the 1990s that scientists succeeded in developing alloys which show a significant change in temperature even at room temperature. Since then, caloric cooling systems research has moved further into the limelight worldwide. The group works with lanthanum-iron-silicon compounds on account of their favorable magnetocaloric properties, high environmental compatibility, excellent availability and low price.

Taking the leap to application

Magnetocaloric cooling systems are becoming much more competitive thanks to the principle developed at Fraunhofer IPM. The new technology has the potential to compete with the over-one-century-old compressor technology in applications such as the cooling of switching cabinets, industrial deep freezing systems and other applications, which previously used large amounts of liquid refrigerants that regularly had to be changed.

In the laboratory, the team is now working on optimizing the system's design to enable the experimental measurement of the increased efficiency and to increase the temperature range even further. The group also established the "InnoCool – Konsortialstudie Kalorik" expert committee of researchers, users and manufacturers of cooling systems to encourage early knowledge transfer between the areas of research and application. Workshops and round-table discussions promote early-stage preparations for launching the new technology. Further information on the study can be found on page 20.



(a) Magnetization causes the magnetocaloric material (MCM) to heat up, and the condensed liquid to vaporize. (b) This vaporization causes a rise in pressure, the right-hand valve then opens and the gaseous fluid transports the heat to the next segment. (c) Then, through the magnet's rotation, the MCM is demagnetized. The MCM cools down to below its initial temperature. The gaseous fluid condenses on the MCM and the pressure drops. (d) The left-hand valve opens and the gaseous fluid enters from the left-hand segment. Heat is transferred.

Dr. Olaf Schäfer-Welsen, Phone +49 761 8857-173, olaf.schaefer-welsen@ipm.fraunhofer.de

TRADE FAIRS | EVENTS 2020

Due to the COVID-19 pandemic, almost all trade fairs in 2020 were canceled or postponed.
Some trade fairs went online.

EVENTS ORGANZIED BY FRAUNHOFER IPM

Online-Forum #produktionskontrolle
Digital event, December 16, 2020
"Measurement technology for metal shaping" the first event in our new Online Forum series in December 2020, was attended by 50 guests from research and industry. The monthly event shines the spotlight on production control topics and provides the opportunity for scientists and users to have expert discussions in an informal setting.

TRADE FAIR PARTICIPATION

SQL20 – Sensing with Quantum Light, International Workshop
Berlin, September 6–9, 2020, hybrid event
The Institute presented the latest results from the development of its quantum Fourier transform infrared spectrometer (Q-FTIR). The Q-FTIR will be used as part of the new infrared spectroscopy process for gas analytics.

Chillventa eSpecial
Digital event, October 15, 2020
In his presentation on "Caloric Materials for Thermal Compression", Dr. Kilian Bartholomé explained how thermal compression using caloric materials can ensure the high performance of caloric cooling systems.

Fraunhofer Solution Days 2020
Digital event, October 26, 2020
At the Fraunhofer Solution Days 2020, the Fraunhofer-Gesellschaft presented innovations from healthcare, digital economy, plant and machine engineering as well as mobility. As a member of the Vision Business Unit, Fraunhofer IPM took part in the event under the headline of "Inline Quality Inspection Checkup". Digital presentations covered particle detection and precise 3D measurements of large functional areas in combination with marker-free component tracing.

Parts2clean
Digital event, October 27, 2020
Fraunhofer IPM presented optical measurement systems for the automated 100-percent control of surfaces. Based on various imaging processes such as imaging fluorescence analysis, these systems detect and quantify both particulate and film contaminations.

EuroBLECH Digital Innovation Summit
Digital event, October 27–30, 2020
At the International Sheet Metal Working Technology Exhibition, Fraunhofer IPM presented the F-Scanner for large-area inline inspection of oiling quantity and distribution on large metal sheets.

TRADE FAIRS | EVENTS SCHEDULED FOR 2021

While uncertainty still prevails for 2021, our planning activity continues: where possible and appropriate, we will participate in digital trade fairs or expositions.

EVENTS SCHEDULED AT FRAUNHOFER IPM

9. Gassensor Workshop (German)
Online event, March 18, 2021

Girls' Day (German)
Online event, April 22, 2021

Online forum #production control (German)
Digital event series
- "Measurement Technology for precision surfaces", January 27, 2021
- "Measurement Technology for materials and component testing", February 24, 2021
- "Marker-free tracking and tracing", March, 17, 2021
- "Component testing in free fall", April 21, 2021
- "Particle measuring technology", May 12, 2021
- "Detecting and quantifying filmic impurities", June 23, 2021
- "Remote tracking and tracing via Fingerprint", July 21, 2021

Online forum #LiDAR and #MobileMapping (German)
Digital event series
- "Data acquisition", October 14, 2021
- "Data interpretation", November 4, 2021
- "Applications", November 25, 2021

Further events are planned:
www.ipm.fraunhofer.de/online-forum

SCHEDULED PARTICIPATION IN TRADE FAIRS

Sensor+Test
Online event, May 4–6, 2021

Freiburg Science Fair
Online event, June 7–26, 2021

World of Photonics Congress
Online event, June 20–24, 2021

VDI regio Career
Freiburg, October 9, 2021

parts2clean
Hybrid: Stuttgart/online, October 5–7, 2021

13. Fraunhofer Business Unit Vision Technology Day
Fürth, date t.b.d

Blechexpo
Stuttgart, October 26–29, 2021

MEDICA
Düsseldorf, November 15–18, 2021

Laser World of Photonics (originally planned for 2021)
Munich, April 26–29, 2022

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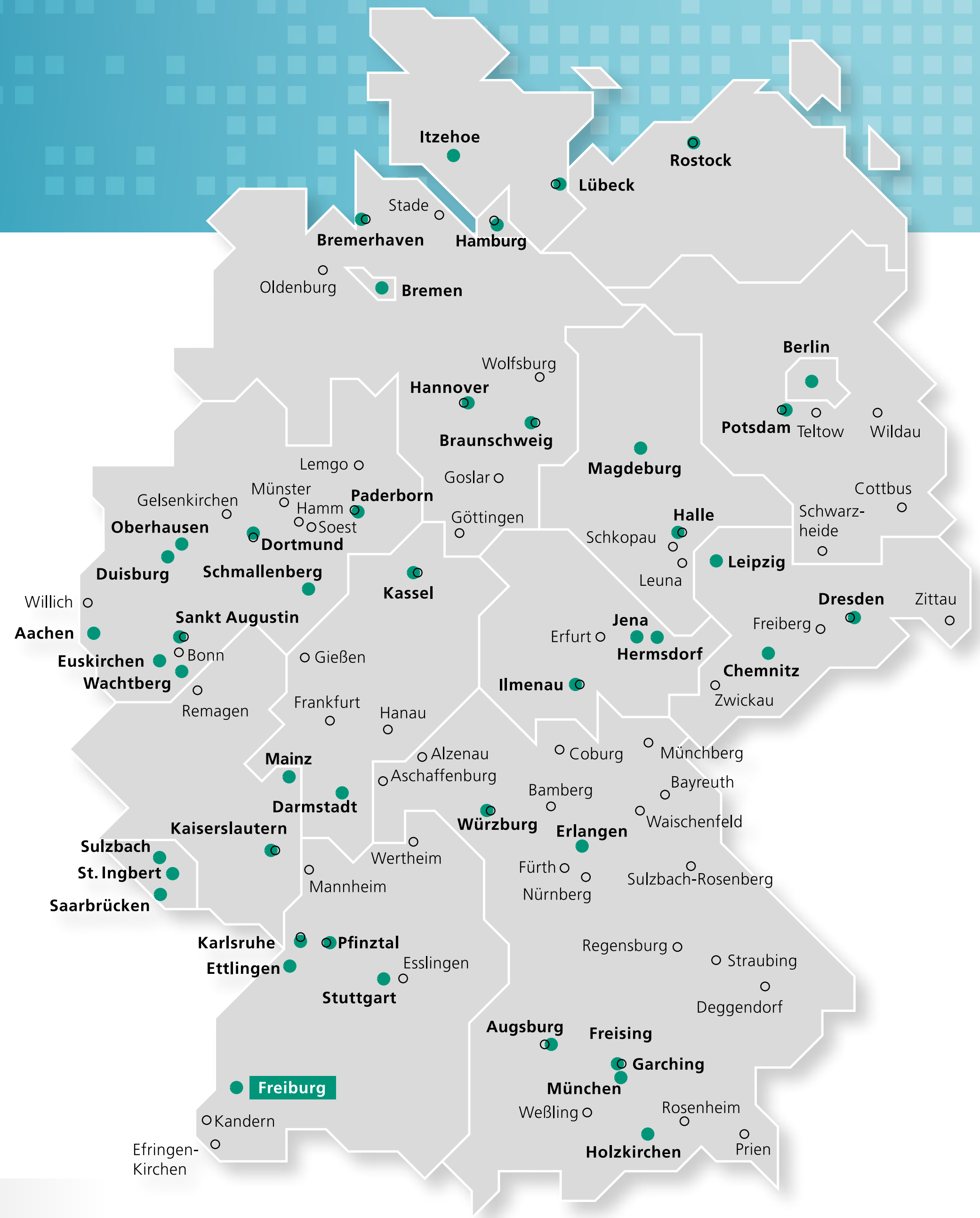

Main locations ●
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Fraunhofer IPM
Fraunhofer Institute for Physical Measurement Techniques IPM
Georges-Köhler-Allee 301
79110 Freiburg, Germany

Phone +49 761 8857-0
Fax +49 761 8857-224
info@ipm.fraunhofer.de

www.ipm.fraunhofer.de/en

Editorial Address
Fraunhofer Institute for
Physical Measurement Techniques IPM
Communications and Media
Georges-Köhler-Allee 301
79110 Freiburg, Germany

Phone + 49 761 8857 - 0
Fax + 49 761 8857 - 224
info@ipm.fraunhofer.de

Responsible editor
Holger Kock (holger.kock@ipm.fraunhofer.de)

Editorial Team
Mirja Eschermann, Holger Kock, Anja Strobel

Design
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