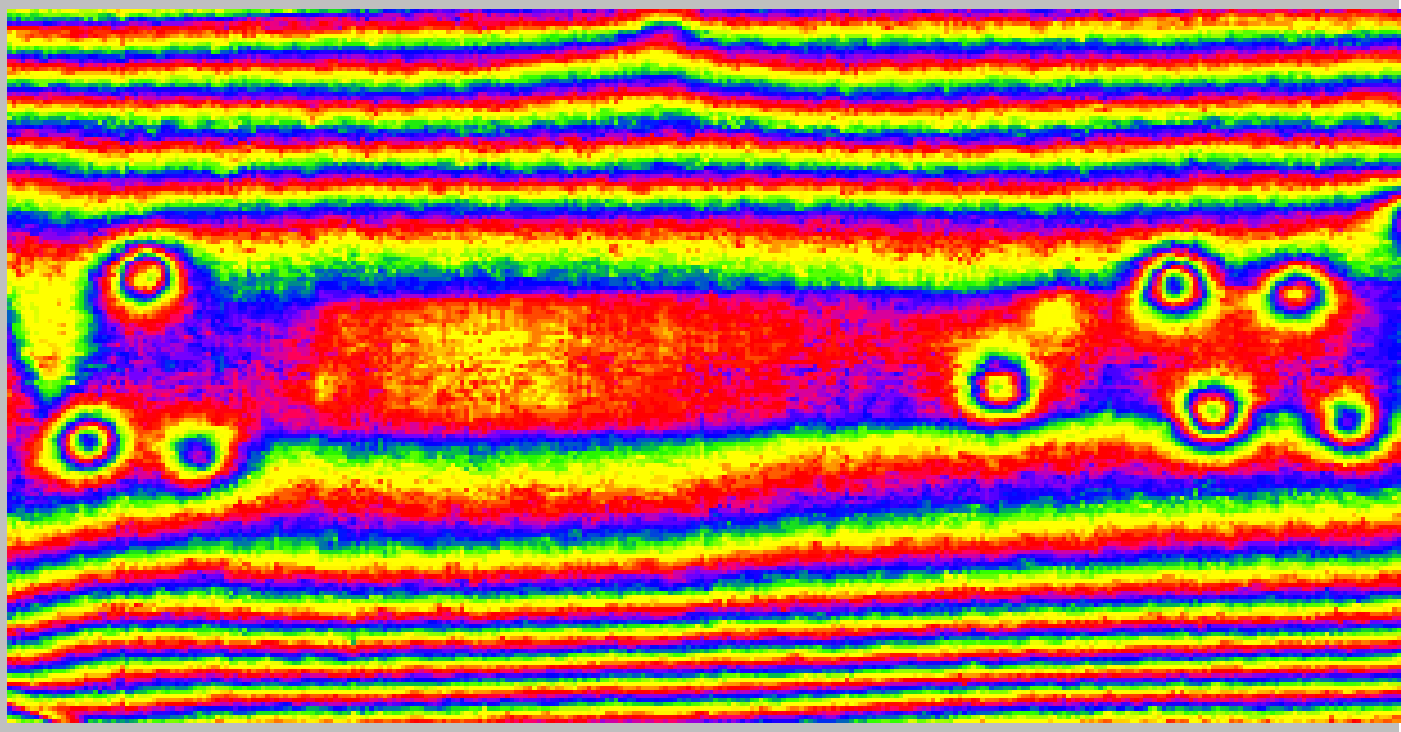
Annual Report

2023/2024



Contrast-enhanced thermographic visualization of sub-surface defects
in a composite material

BIMAQ

Bremer Institut für
Messtechnik, Automatisierung
und Qualitätswissenschaft

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Preface

Dear friends and partners of the institute!

In 2023/24, the Bremen Institute for Metrology, Automation and Quality Science (BIMAQ) initiated leading science projects, contributed to an innovative study program in production engineering, and continued in its strong support of young academics' careers.

To discover new paths in measurement science, a research priority program from the Deutsche Forschungsgemeinschaft (DFG) was successfully applied for and will be coordinated by us. In the SPP2433, nineteen projects from all over Germany will jointly work on introducing new measurement techniques on flying platforms. As a central research task, the capabilities and thus the measurement uncertainty budget for drone-based measurements will be clarified. It is expected that the research work will provide new measurement solutions for industry and society, such as the strongly automatized inspection of wind turbines, the localization of potential leakages in widespread pipeline structures, and the monitoring of volcano gas emissions.

In addition, Smile – a laboratory for sensitive machining of biological materials is funded by the Volkswagen Stiftung. In agreement with the purpose of the Momentum funding initiative, the goal is to open up opportunities to advance the content and strategic development of the professorship. Here, the research focusses on the holistic fusion of data and knowledge for the improved machining of biological materials in surgical treatments as well as of inhomogeneous materials of the future in production.

And it is also a great honor, that I was elected as head of the association of professors of measurement techniques (AHMT e.V.) for the period 2024/2025 – to support the discipline of measurement techniques at the universities, which includes the support of young academics' careers.

There is so much more to explore in the present annual report about our past and ongoing activities, e.g., the advance of our ERC project on indirect optical geometry measurements. Before you start to read, let me express my special thanks to the continuing support of the Deutsche WindGuard GmbH, who donated for the 7th time a student award for young talents. My congratulations to the awardee in 2023. I also thank our seminar guests Dr. Seefeld (BIAS) and Dr. Ahmerkamp (MPI for Marine Microbiology) for their inspiring talks, and of course all BIMAQ students, colleagues as well as research and industrial partners for their continuous support.

Bremen, June 2024

Prof. Dr.-Ing. habil. Andreas Fischer

BIMAQ - the institute

Vision, topics and infrastructure

The research focus of the Bremen Institute for Metrology, Automation and Quality Science (BIMAQ) is the holistic investigation of optical measurement systems, which includes the design, realization, characterization and, finally, the application of novel measurement techniques. By applying a rigorous system-based analysis of the measurement systems, the limits of measurability and the respective uncertainty principles are investigated in order to determine and to surpass the limits of state-of-the-art approaches. Beyond pure measurement tasks, automation aspects and the application of quality controls are investigated as well. However, the core competence of BIMAQ is measurement system engineering, which is a key discipline for solving technical and overall social challenges.

A key challenge is to obtain information in situ or in-process from highly unsteady or complex technical processes. For this purpose, model-based, dynamic measurement systems are a key topic of the BIMAQ research, which includes interdisciplinary fundamental and application-oriented research on the measurement methods and their applications. Current research topics cover tasks from production engineering, materials science, wind energy systems and fluid mechanics.

In addition to methodical innovations for instance based on multi-sensor-system approaches, one highlight at the BIMAQ is a unique laboratory for large gear metrology with a coordinate measurement device for gears up to a few meters. This illustrates the unique BIMAQ expertise regarding the metrology of large gears and geometrical measurements with a high dynamical range.

Further laboratories and equipment exist in the BIMAQ main building and the BIMAQ-Technikum, for instance for the analysis of the surface topography and strain down to the nanometre scale, for thermographic flow analyses from long distances of several hundred meters and for laser-based flow measurements.

BIMAQ

Bremen Institute for Metrology, Automation and Quality Science

Research
Teaching
Knowledge

Metrology

Automation | Quality control

University of Bremen

Methods

Measurement system theory
- Modeling and simulation
- Uncertainty relations
- Limits of measurability

Measurement system technique
- Optical high-speed systems
- Multi-sensor-systems
- Large volume metrology

➔ **model-based, dynamic measurement systems**

Applications

Production engineering & Material science
- Geometry and roughness metrology
- Thermography, Boundary layer analysis
- Optical in-process metrology & control

Wind energy systems & Flow processes
- Gear-wheel metrology
- Gear metrology
- Flow metrology

BIMAQ competences

BIMAQ - the institute

Staff

Director

Prof. Dr.-Ing. habil. Andreas ***Fischer***

Emeritus

Prof. Dr.-Ing. Gert ***Goch***

Administration

Eva ***Schultze***
Swenja ***Robinius*** (since 11/2023)

Research Scientists

Dr.-Ing. Gert ***Behrends*** (until 09/2023)
Dr.Eng. Adriano ***Boaron*** (since 03/2024)
Dipl.-Ing. Jakob ***Dieckmann***
M. Sc. Caroline ***Dorszewski***
M. Sc. Björn ***Feld***
Dr.-Ing. Axel von ***Freyberg***
M. Sc. Friederike ***Jensen***
M. Sc. Claudia ***Niehaves***
M. Sc. Tajim ***Rahman***
M. Sc. Aage ***Rehfeldt*** (02/24-05/2024)
Dr.-Ing. Yannik ***Schädler*** (since 08/2023)
Dr.-Ing. León ***Schweickhardt*** (until 03/2024)
Dipl.-Ing. Michael ***Sorg***
Dr.-Ing. Dirk ***Stöbener***
M. Sc. Misri ***Talati*** (11/23-05/2024)
Dr.-Ing. Andreas ***Tausendfreund***
M. Sc. Marina ***Terlau***
M. Sc. Philipp ***Thomaneck***
M. Sc. Jiuzhou ***Xiang*** (since 02/2024)

Student Research Assistant

Nowshin ***Ahmad***
Simon ***Arndt***
Shadman Kabir ***Aninda***
Julian ***Gebken***
Daniel ***Luft***
Henrik ***Mahnke***
Femi ***Martin***
Hasnain ***Moavia***
Alexander ***Müller***
Debojit ***Mukhopadhyay***
Kathri Achchige ***Ravindu Pradeepa***
Aage ***Rehfeldt***
Simon ***Richter***
Arthur ***Süß***
Misri ***Talati***
Kannamkulam ***Veetil***

Technical Assistants

Dipl.-Ing. Werner ***Behrendt***
Dipl.-Ing. Frank ***Horn***
Uwe ***Reinhard***

Alumni

Dr.-Ing. Merlin ***Mikulewitsch*** (06/2023)
M. Sc. Ann-Marie ***Parrey*** (06/2023)
Dipl.-Ing. Paula ***Helming*** (04/2023)
Dr.-Ing. Felix ***Oehme*** (04/2023)
Dr.-Ing. Marc ***Pillarz*** (02/2023)
Dr.-Ing. Christoph ***Vanselow*** (01/2023)
Dr.-Ing. Daniel ***Gleichauf*** (12/2022)
Dr.-Ing. Jan ***Osmers*** (08/2020)
Dipl.-Phys. Gabriela ***Alexe*** (06/2020)
Dr.-Ing. Christoph ***Dollinger*** (04/2020)
Dr.-Ing. Gerald ***Ströbel*** (04/2020)
M. Sc. Volker ***Renken*** (04/2020)
M. Sc. Matthias ***Auerswald*** (12/2018)
Dr.-Ing. Stefan ***Patzelt*** (02/2018)
Dipl.-Ing. Jan ***Westerkamp*** (02/2018)
M. Sc. Johannes ***Stempin*** (05/2017)
Dr.-Ing. Helmut ***Prekel*** (01/2017)
Dr.-Ing Peiran ***Zhang*** (12/2016***)***
Dipl.-Ing. Thomas ***Behrmann*** (07/2016)
M. Sc. Martina ***Fuhrmann*** (07/2016)
Dr.-Ing. Marc ***Lemmel*** (03/2016)
Dr.-Ing. Philipp ***Thiemann*** (03/2014)
Dr.-Ing. Karsten ***Lübke*** (09/2013)
Dr.-Ing. Dennis ***Kruse*** (01/2013)

Participation in scientific committees and associations

Member	Short Name	Scientific Committee / Association
BIMAQ	AUKOM	AUKOM Ausbildung Koordinatenmesstechnik e. V.
Andreas **Fischer**	CIRP	International Academy for Production Engineering
Andreas **Fischer**	DGaO	Deutsche Gesellschaft für angewandte Optik
Andreas **Fischer**	AHMT	Arbeitskreis der Hochschullehrer für Messtechnik e. V.
Andreas **Fischer**	ForWind	ForWind – Zentrum für Windenergieforschung
Andreas **Fischer**	MAPEX	Center for Materials and Processes
Andreas **Fischer**	BEST	Bremen Research Centre for Energy Systems
Andreas **Fischer**	SPIE	The International Society for Optics and Photonic
Andreas **Fischer**	EOS	European Optical Society
Andreas **Fischer**	Optica	The Optical Society
Andreas **Fischer**	IEEE	Institute of Electrical and Electronics Engineers
Andreas **Fischer**	VDI	Verein Deutscher Ingenieure & VDI Kuratorium Bremen
Andreas **Fischer**	GALA	Deutsche Gesellschaft für Laser-Anemometrie
Andreas **Fischer**		Regelungstechnisches Kolloquium in Boppard
Andreas **Fischer**	WGP	Wissenschaftliche Gesellschaft für Produktionstechnik
Gert **Goch**	WGP	Wissenschaftliche Gesellschaft für Produktionstechnik
Michael **Sorg**	DFMRS	Deutsche Forschungsvereinigung für Meß-, Regelungs- und Systemtechnik e. V., Geschäftsführer
Michael **Sorg**		BMWi-Forschungsnetzwerke Energie: Systemanalyse, Stromnetze, Erneuerbare Energien
Dirk **Stöbener**	MAPEX	Center for Materials and Processes
Dirk **Stöbener**	VDI	Verein Deutscher Ingenieure
Axel **von Freyberg**	FVA	Forschungsvereinigung Antriebstechnik e. V., Arbeitskreis Messtechnik
Axel **von Freyberg**	DFMRS	Deutsche Forschungsvereinigung für Meß-, Regelungs- und Systemtechnik e. V., Vorsitzender des Wissenschaftlichen Kuratoriums

LAB

Laboratory for dimensional metrology

BIMAQ's infrastructure features a variety of modern high-precision measurement systems. The equipment ranges from tactile coordinate, gearing and roughness measuring devices to optical systems like stripe pattern projection laser triangulation and terrestrial laser scanners as well as thermal, magnetic and acoustic probing systems and sensors for non-destructive analyses. The equipment is used for the calibration and validation of newly developed measurement and sensor systems, but it is also the basis for measurements within research projects and for the regional industry.

BIMAQ conducts form, size and location tests on very small to very large components, i. e. dimensions of a few millimetres up to 200 meters.

We offer standardized measurement and evaluation procedures as well as customer-specific solutions, such as the evaluation of advanced features or the digitization of a component or measurements on wind turbines during operation.

Services

- development of measurement and evaluation strategies
- acquisition and analysis of dimensional deviations - tactile and optical measurements
- characterization of the surface quality - tactile and optical measurements
- gear inspection
- surface integrity analysis - non-destructive and non-contact
- order/reference measurements

Contact: a.freyberg@bimaq.de

Tactile measurement of a 5-axis milled gear segment

Laboratories

LAB

Laboratory for large gears (in BIMAQ-Technikum)

To calibrate large gears, only a few appropriate standards exist, that allow the traceability of the test processes to the SI unit 'meter' with sufficient accuracy. In close cooperation with the National Metrology Institute of Germany (PTB), BIMAQ was involved in developing large gear standards with a diameter of 2000 mm and more.

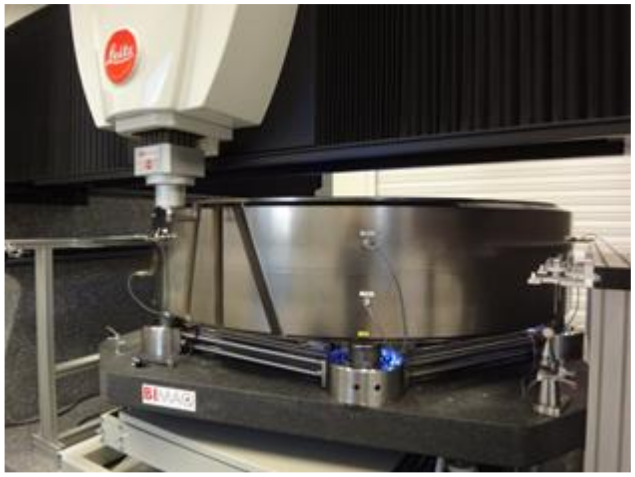
Furthermore, BIMAQ analyses the cause-effect relationships between gear manufacturing, geometric deviations and occurring gearbox damages. Also, special test rigs for lightweight gears were established. In the field of quality inspection of gears, algorithms are developed in order to evaluate dimensional measurement data.

Technical specifications

Portal coordinate measuring machine Leitz PMM-F 30.20.7:

- measuring volume:
  3.0 x 2.0 x 0.7 m^3

Tactile measurement of large cylindrical gearing



Measurement on a 2 m gear standard with BIMAQ's large CMM

- measuring uncertainty:
  $MPE_E = (1.3 + (L \text{ in mm})/400)\ \mu m$
- workpiece mass:
  max. 6,000 kg
- rotary table:
  for rotation-symmetric components up to 3.0 m diameter
- air conditioning:
  maximum temperature gradients 0.4 K/h, 0.8 K/d, 0.2 K/m

Services

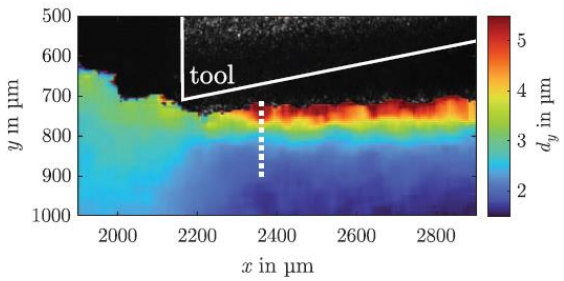
- order/reference measurements
- analysis and evaluation of geometric deviations
- development of measurement and evaluation strategies
- calibration of inside sensor systems
- software development

Contact: a.freyberg@bimaq.de

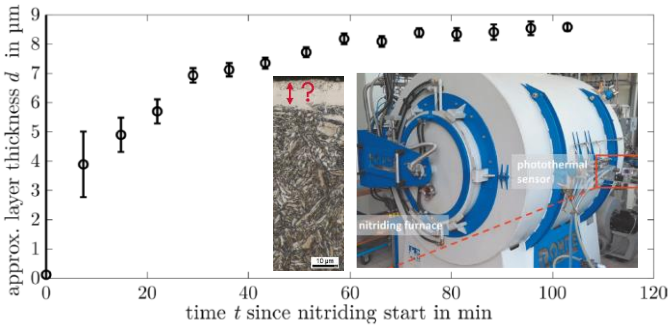
LAB Laboratory for optical metrology

The laboratory for optical metrology focuses on creating, characterizing and applying near-process measurement systems for manufacturing and process engineering. The measurement methods for geometry-related measurement quantities are investigated with simulative and experimental approaches to understand and surpass current limits of measurability as well as to open up new application fields. Here, the limits due to challenging environmental measurement conditions (in-line, in-situ, in-process), the required high measurement speed, the moving measurement objects, as well as due to fundamental, natural sources of uncertainty (photon statistics, random surface structures) are clarified.

The processes that have been considered yet include forming processes, subtractive machining, additive machining, and material treatment.



Example 1: In-process workpiece deformation measurement with laser speckles during milling with high spatiotemporal resolution, and analyzing the error due to high gradients. [L. Schweickhardt et al.: Digital speckle photography in the presence of displacement gradients. Journal of the European Optical Society-Rapid Publications 19(1):16 (10 pp.), 2023]



Example 2: In-process layer thickness measurement during gas nitriding at >500°C with sub-micrometer uncertainty. [M. Mikulewitsch et al.: Influences on quantitative nitriding layer thickness measurements using model-based photothermal radiometry. HTM Journal of Heat Treatment and Materials 77(5):357-373, 2022]

Furthermore the scatterometric quality assessment of micro- and nanostructures on surfaces, i.e. even below the diffraction limit of light, is studied by solving the Maxwell's equation for nanostructured surfaces, which means a rigorous light scattering analysis.

Services

- basic research for new measurement methods
- feasibility studies on the near-process application of measurement principles, particularly in manufacturing and heat treatment processes
- development of measuring methods for industrial applications
- simulation and measurement of light scattering on micro- and nano-structured workpieces to assess the structural quality
- non-destructive surface integrity/topography checking and material characterization

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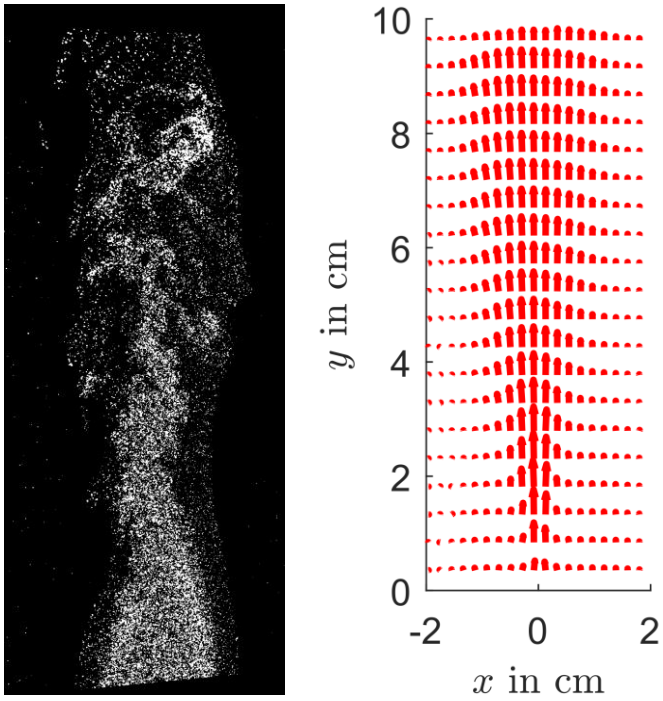
Laboratories

LAB

Laboratory for flow metrology

The three velocity components of a flow field can be determined in a measurement plane with a stereoscopic particle image velocimetry (PIV) system, which is the centerpiece of the laboratory for laser-based flow metrology. The particle-based measurement technique is applied in challenging conditions, e. g., hot jet flows, flame flows or two-phase flows. The main research topic is to quantify the measurement uncertainty caused by the influence of inhomogeneous refractive index fields. These fields lead to varying image distortions and, thus, measurement deviations of the particle position. The uncertainty budget for the determined velocity fields are obtained from model-based error propagations of the simulative and experimentally investigated refractive index field. The analysis of the measurement uncertainty budget is a key topic to identify and finally overcome fundamental limits of measurability.

Stereoscopic PIV system



PIV raw image (left) and mean velocity field (right) of a flame flow

Technical data

Dual-head PIV-Laser (Quantel Evergreen):

- pulse energy: 2 × 200 mJ
- wavelength: 532 nm
- pulse rate: 15 Hz
- pulse length: <10 ns
- light guide arm: 2.1 m

2 × sCMOS cameras (Andor Zyla):

- resolution: 5.5 Mpixel
- pixel width: 6.5 µm
- dynamic: 16 bit

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LAB

Laboratory for thermography

Boundary layer flow visualization on wind turbine rotor blades in operation

The boundary layer flow influences the temperature distribution on the surface of a rotor blade, which can be detected by a high speed thermographic imaging system. BIMAQ offers thermographic measurements of rotor blades on wind turbines in operation. Measurements are conducted in cooperation with the Deutsche WindGuard Engineering GmbH in Bremerhaven. Measurements can be performed from a distance between 60 m and 500 m.

Technical data

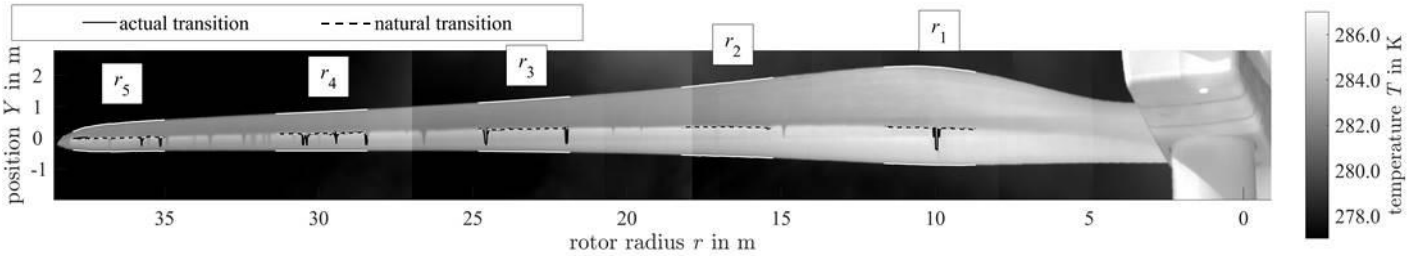
ImageIR thermographic imaging systems:

- high speed IR imaging system
- thermal resolution (NETD): < 0.025 K
- spectral ranges: 2 – 5 µm & 7.7 – 10.2 µm
- detector format: 640 x 512 pixel
- focal length incl. telephoto lens: 13 - 200 mm
- integration times between 1 µs and 1600 µs

ImageIR thermographic imaging system

Services

- determination of the laminar/turbulent transition location
- detection of early laminar-turbulent transition due to leading edge contamination, erosion, manufacturing irregularities or the effects of leading edge protection
- analysis of impact of leading edge protection on the boundary layer flow
- inspection of vortex generators, zig-zag tapes and other flow control devices
- investigation of the feasibility of anti-icing and de-icing systems



Evaluated thermographic image of the rotor blade of an 1.5 MW wind turbine with a 77 m rotor diameter

BIMAQ - the institute

Laboratories

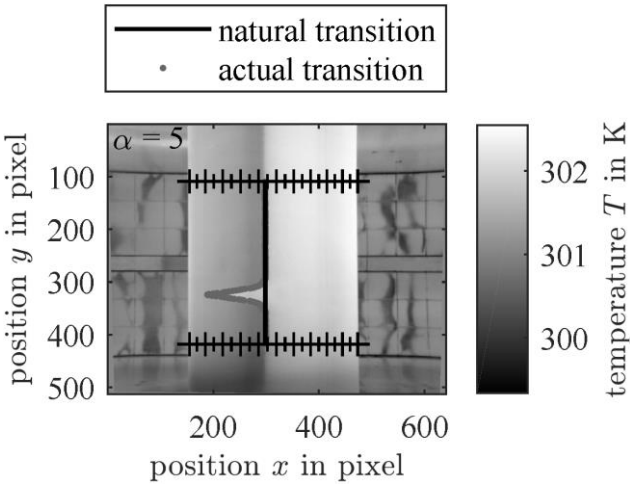
Boundary layer flow visualization in wind tunnel experiments

In order to investigate the boundary layer flow phenomena on airfoils, thermographic measurement approaches are developed and applied. The research focus are new image evaluation techniques based on the flow dynamics. The flow experiments with two different IR imaging systems are performed at the Deutsche WindGuard's aeroacoustic wind tunnel in Bremerhaven, where laminar air flows at speeds of up to 360 km/h and chord-Reynolds numbers of up to 6 million can be generated.

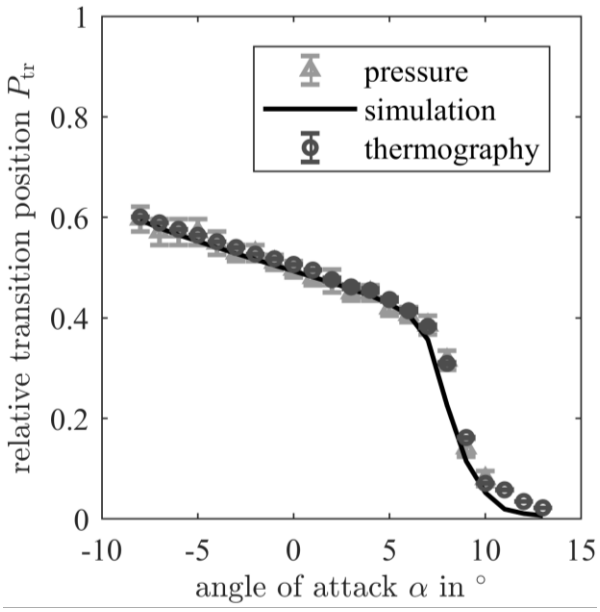
Technical data

VarioCam hr:

- detector format: 640 x 480 pixel
- thermal resolution: 0.030 K
- spectral range: 7.5 - 14 µm
- focal lengths: 12.5 mm and 30 mm



Thermographic flow visualization on an airfoil in the wind tunnel



Relative position P_{tr} of the laminar-turbulent transition on the chord as a function of the angle of attack α

ImageIR:

- detector format: 640 x 512 pixel
- thermal resolution: 0.025 K
- spectral range: 2 - 5 µm
- focal lengths: 12 mm, 25 mm, 100 mm and 200 mm

Services

- localization of the laminar-turbulent transition with a measurement uncertainty < 0.5 % chord length
- visualization of flow separations
- automated evaluation of wind tunnel campaigns
- comparison with reference measurements and simulation data

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LAB

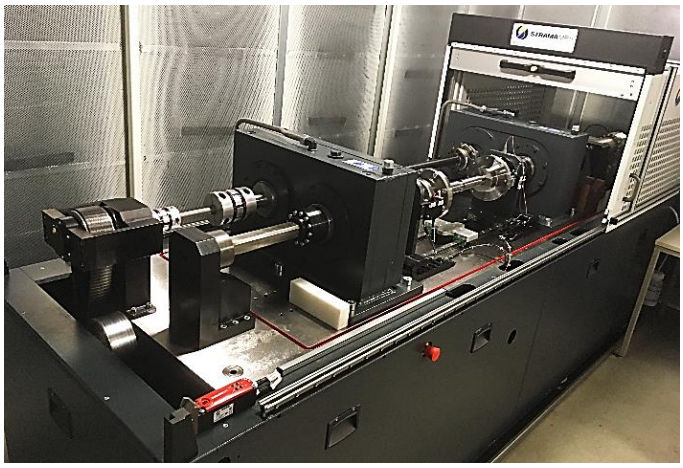
Laboratory for wind turbine sensors (in BIMAQ-Technikum)

Wind turbine generators (WTG) are dynamically highly stressed, which can lead to bearing and gear damages. For targeted improvements in design, production and choice of material meaningful metrics are missing. The individual trans-mission components (gears, bearings, shafts) are metrologically not accessible during operation, so far. A few states can be observed from the outside, e. g., temperature changes on the housing or

Drivetrain inside the hub of a wind energy system

noises or vibrations. But, the causes of problems are mostly inside the gear housing. These include mechanical stresses which may lead to undue distortion of the individual teeth and subsequently to wear of the tooth flanks.

For testing new sensor concepts for WTG drivelines, the dynamic behaviour of WTG drivelines can be simulated experimentally in the BIMAQ-Technikum using a torque test rig. In addition, a WTG drive train and a 3.4 MW research WTG are available for sensor tests.



Torque test rig

Technical test rig specifications

- torque: ± 1,000 Nm
- speed: ± 3,000 min^{-1}
- axial force: 0 – 10,000 N

Services

- development of sensing prototypes
- order and reference measurement
- development of new measurement and evaluation strategies
- algorithm development

Wind turbine drive train for sensor tests

Contact: a.freyberg@bimaq.de

BIMAQ - the institute

Laboratories

LAB

BIMAQ-Technikum and mechanical workshop

BIMAQ maintains a 400 m² Technikum to support the research work.

The Technikum contains / houses:

- laboratory for large gears
- torque test rig
- experimental field
- mechanical workshop

For the production of test rigs, test stands and prototypes, the mechanical workshop is equipped, for example, with a

- CNC milling machine
  Travel distance:
  400 mm x 400 mm x 400 mm
- 3D printer
  Building space:
  203 mm x 203 mm x 152 mm
- milling drill plotter
  maximum material size:
  229 mm x 305 mm x 35 mm

Mechanical workshop

In addition, the Technikum houses a measuring drone, which has the following specifications:

- hexacopter
- load capacity: 10 kg
- diameter: > 2 m

BIMAQ measuring drone (top) in comparison with a DJI Phantom 3 (bottom)

Services

- item and small-batch production
- additive and cutting machining

Contact: a.freyberg@bimaq.de

Smile

Laboratory for Sensitive machining of biological materials

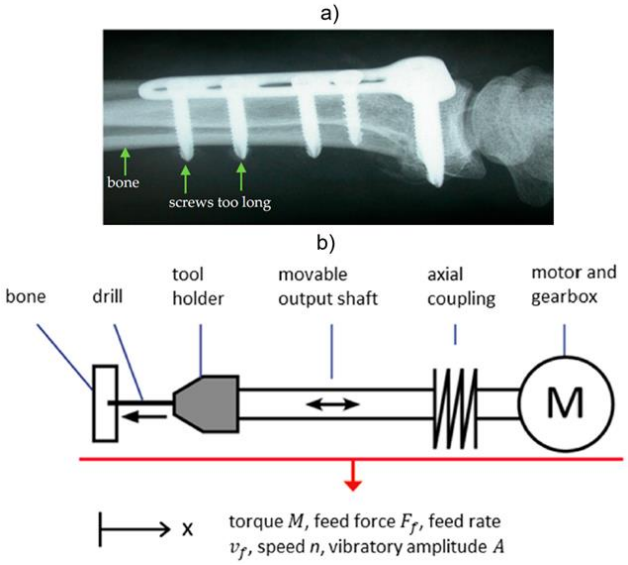
Funding organization: VolkswagenStiftung
Funding ID: Momentum 9C189
Duration: 15 Mar 2024 – 14 Mar 2028
Project scientist: Adriano Boaron

The sensitive machining of inhomogeneous biological materials plays an important role in the field of surgery, e.g. during boring of bones. An experienced doctor is required to indirectly assess the machining result during the treatment. For this assessment, the doctor has to perform a data fusion of multiple indirect sensing results, including his expert knowledge about the machined material and the machining process. To increase the treatment success rate, the aim is to create a superior technical solution without the need of an expert person.

For this reason, a *laboratory for the sensitive machining of biological materials* is created to investigate in-process multisensory measurement systems, and to develop and test methods for the fusion of sensor data and knowledge.

Focusing on a bone drilling experiment in the first phase, the sensor data from multiple sensors will be fused by means of machine learning approaches to indirectly measure material parameters such as hardness, thicknesses of material layers and the drilling depth as machining result. In the second phase, new ground is broken by starting the transfer of the sensitive machining approach to other machining processes and materials.

The scientific goal and novelty are to use machine learning to model the inverse relation between the multi-sensor data and the unknown material and machining parameters. The long-term goal is controlling the machining of complex materials and, in addition, providing an in-process estimation of the actual material conditions. This enables the targeted adjustment of material parameters in addition to the geometrical machining aim. Thus, sensitive machining will improve the accuracy and precision in machining unknown inhomogeneous materials in manufacturing and surgery.



(a) Screw protrusion due to an incorrect dermination of the drill channel length.
(b) Principle of the multi-sensory drive train.

[1] M. Sorg, J. Osmers: Methodical approach for determining the length of drill channels in osteosynthesis. Sensors 19:1-10, 2019.

PROTA

Near-process characterization of temperature field and material ablation changes during laser chemical machining

Funding organization: DFG
Funding ID: 451385285
Duration: 1 May 2021 – 30 Apr 2024
Project scientists: Merlin Mikulewitsch,
Claudia Niehaves

Compared to other micromachining processes like micro milling, laser chemical machining (LCM) can achieve a higher removal quality with respect to shape accuracy at acute edge angles and small edge radii. However, the production speed of LCM is lower, in particular because the removal rate is limited to avoid obstructive boiling bubbles, see Fig. 1.

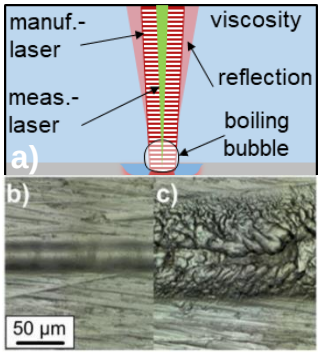


Fig. 1: a) LCM process, and the different manufacturing results for b) slow machining without boiling bubbles and c) fast machining with disturbances due to boiling bubbles caused by an increased surface temperature.

The research project *Prota* aimed to increase the process understanding of LCM in order to minimize the influence of boiling bubbles on the removal quality. To this end, an in-situ measurement system was realized for the first time that can access the surface geometry of the machined workpiece and the near-surface temperature in the process fluid by means of a confocal fluorescence microscopy setup.

As a result, measurements of the machined microstructures were enabled, see Fig. 2, by employing a model-based signal processing. This was combined with a temperature measurement by determining the temperature-dependent fluorescence lifetime τ with ns-precision, see Fig. 3.

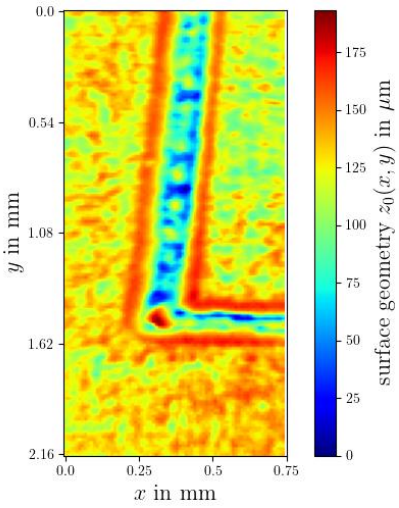


Fig. 2: In-situ geometry measurement of a LCM structure.

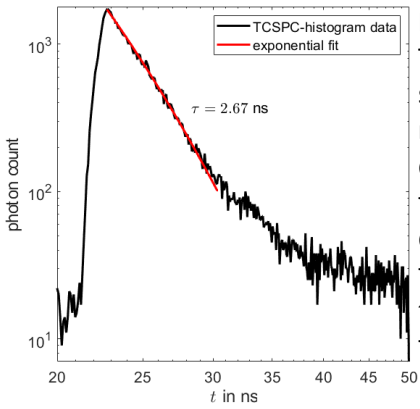


Fig. 3: Time-correlated single-photon measurement to determine the temperature-dependent fluorescence lifetime τ of the LCM process fluid.

[1] D. Stöbener, M. Mikulewitsch, A. Fischer: Fluorescence-based measurements of material removal and process temperature during laser chemical machining. 23th International Conference & Exhibition of the European Society for Precision Engineering and Nanotechnology, Copenhagen, Denmark, 12.-16.6.2023, pp. 389-390.

StreuCompress

Design method for in-process testing of nanostructured surfaces based on scattered light measurements and machine learning

Funding organization: DFG

Funding ID: 497286574

Duration: 1 Dec 2022 – 30 Nov 2025

Project scientist: Tajim Md Hasibur Rahman

Precisely engineered nanostructured surfaces increase the quality and functionality of electrical and mechanical systems. Since the fabrication of nano-surfaces inherently includes process uncertainties, a surface quality inspection is required.

The inspection of nano-surfaces must be non-invasive as well as fast and robust enough to be a part of the mass-production line. Among optical non-tactile measurement approaches, Angle-Resolved Scatterometry (ARS) is promising and fulfils the requirements. In ARS the angle of incidence of a coherent light source is varied and scattered light is detected for different angles [1]. However, the image processing for detecting defective nano-surfaces always needs an adaptation according to the type of nanostructure. Therefore, the project *StreuCompress* aims to develop a universally applicable method to design an ARS-based surface inspection that is suitable for any nanostructured surfaces.

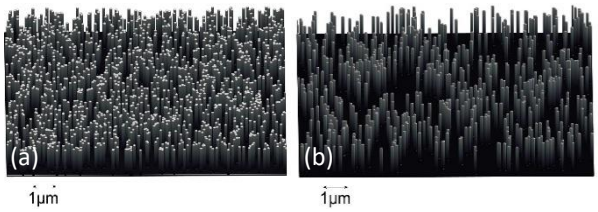


Fig. 1: (a) Defect-free nano-surface.
(b) Defective nano-surface.

The solution approach is a virtual experimentation setup, which consists of a digital surface modelling (see Fig. 1) and a rigorous scattered light simulation using the Discrete Dipole Approximation algorithm. As first result, the created virtual setup demonstrated the capability of a mean-intensity-based signal processing to distinguish nanorod-surfaces with different grades of vacancy (see Fig. 2), and to determine the measurement uncertainty due to the surface randomness, which for the example is <6 %.

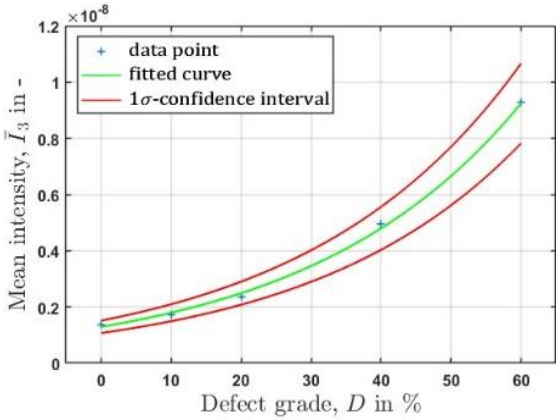


Fig. 2: Mean intensity plotted against different defect grades of surfaces with nanorods.

As next steps, the virtual setup will be used for other nano-surface types and/or defect types to check its universal applicability, followed by experimental validation. In addition, compressive sensing approaches are investigated to speed up the measurement and to minimize the number of required sensor positions.

[1] G. Alexe, A. Tausendfreund, D. Stöbener, A. Fischer: Maschinelles Lernen für Abdeckungsmessungen von Oberflächen mit abgeschiedenen Au-Nanosphären mittels Lichtstreuung. tm - Technisches Messen 86(S1):S47-S51, 2019.

MoVeHo

Model-based in-process tool wear determination in high-performance turning

Funding organization: DFG

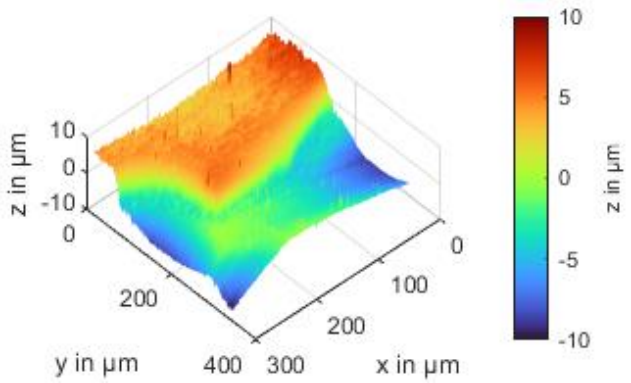
Funding ID: 521384759

Duration: 1 Feb 2024 – 33 Jan 2027

Project scientist: Jiuzhou Xiang

Tools are of central importance for productivity and manufacturing costs in metal-cutting production. The maximization of tool life is therefore the focus of tool development, especially in high-performance machining. Here, the main focus is on the use of coatings to optimize the tool wear properties. Despite the variety of tool coatings used, there are still considerable deficits in the understanding of the underlying wear mechanisms. To reduce these deficits, a novel greybox wear model is developed for high-performance turning.

Wear on the edges of a tipped turning tool.



WLI topography measurement of tipped turning tool with multi-layered surface.

The model combines complementary methods for tool wear determination (knowledge- and data-based models) and uses data sources from in-process measurements for the wear investigation that have not been considered so far.

For the training of the data-based neural network, the wear parameters of the cutting tool in the workspace of a machining process must be determined. This requires in-situ measurement methods for the tool geometry and layer thickness. In the project *MoVeHo*, optical measurement methods are studied, which do not affect the cutting process, allow good accessibility without spatial restriction of the process and offer high spatial and temporal resolutions.

A previous study showed that photothermal radiometry is suitable for quantitative thickness measurements of the nitride layer under in-process conditions in an industrial nitriding furnace [1]. In *MoVeHo*, the signal model will be enhanced from single-layer to multi-layer systems. In addition, a laser line triangulation sensor is used to measure the tool geometry. Both sensor systems will then be mounted on a 6-axis industrial robot in the turning machine, to collect an extensive data basis during numerous tool wear experiments for the training of the blackbox model component as part of the greybox model.

[1] M. Mikulewitsch, J. Dong, A. Fischer: Influences on quantitative nitriding layer thickness measurements using model-based photothermal radiometry. HTM J. of Heat Treatment and Materials 77(5):357-373, 2022.

BrewFlex

Potentials of making energy loads flexible and efficiency increase – How brewerys can optimally use their potentials of a flexible loads to support and manage the energy transition

Funding organization: AiF

Funding ID: 22949 N

Duration: 1 May 2023 – 31 Oct 2024

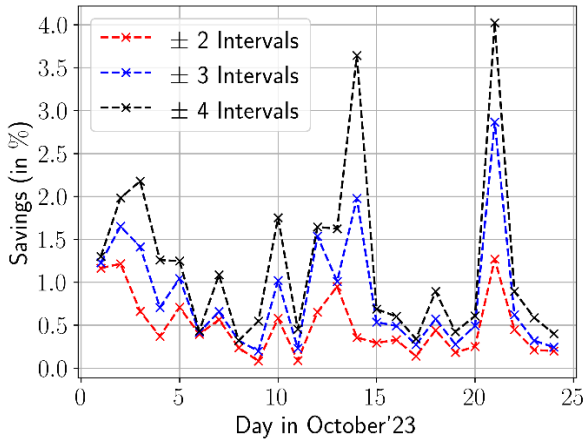
Project scientist: Yannik Schädler

In order to defossilize the energy system, the identification and exploitation of operational potentials for load flexibility and energy efficiency increase is inevitable. Indeed, the use of renewable energies requires a significantly increased flexibility of the entire system, both on the supply and on the demand side, due to their fluctuating character.

Since in many cases smaller companies lack a systematic overview of the business potentials, the project *BrewFlex* aims to identify and quantify the potentials for load flexibilization and energy efficiency improvement from a technical and business perspective for small and medium-sized enterprises (SMEs) in the brewing industry.

The potentials are recorded and evaluated on the basis of essential process data, which are obtained from the real processes. At the same time, the costs and revenues for operational adjustments to utilize the potentials are collected in order to evaluate their impact. The aim of the project is to produce an industry guide that transparently presents a survey of the potentials as well as the evaluation methods developed in the project.

The BIMAQ is contributing to the method development by developing a web-based data collection tool that can be used to collect real load characteristics in breweries and consolidate them in a database. Standardized analysis algorithms are developed for the collected data, which enable comprehensive data visualizations to understand data correlations and sought-after potentials. The analysis and visualization tools can then be used to derive possible measures for load flexibility and energy efficiency improvement and to assess their energy efficiency and economic consequences.



Estimated potential of load flexibilization: Energy savings over one day, based on the load data from October 2023 and for different numbers of permitted 15-min intervals time-shifting flexibility of the load.

[1] Y. Schädler, M. Sorg, A. Fischer: Measurement data-driven investigation of the actual power grid resilience with increasing renewable energy feed-in. Energy Science & Engineering 10(1):145-154, 2022.

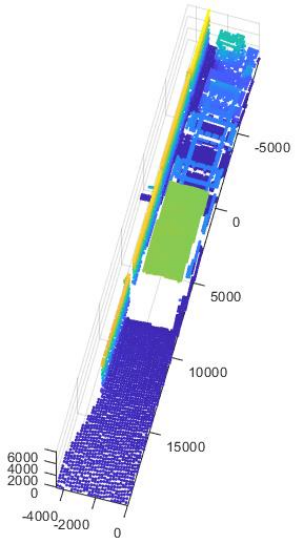
[2] Y. Schädler, M. Sorg, A. Fischer: Data-based energy coverage measurements to discover the potentials of regional energy storage. tm - Technisches Messen 89(5):301-309, 2022.

3D-Safety

Certified system for person safety

Funding organization: BAB
Funding ID: FUE0653B
Duration: 15 Nov 2022 – 31 Oct 2024
Project scientists: Aage Rehfeldt,
Philipp Thomaneck

In view of increasing competition, port operators are faced with the challenge of operating their ports and terminals efficiently and thus with increasing automation. In order to ensure personal safety in the port area, a new class of so-called 3D multilayer scanners is to be used. In order to achieve certification status, it is not only necessary to evaluate the data sufficiently quickly, but it must also be ensured that person recognition is carried out redundantly, i. e. via several sensors and two independently operating algorithms.



3D measuring data of a scene within a container terminal showing a container (green) on a truck (light blue).

The goal of the project *3D-Safety* is the development of an evaluation system, which guarantees a certified person safety in the port area based on 3D multilayer scanners. In addition to the redundantly operating algorithms, the system demands a >128-fold increased data processing, a frame rate of 10 Hz and a measurement range of 100 m.

After a preparatory data processing, the data evaluation is being developed, tested and evaluated via 4 different methodological approaches: The application of statistical algorithms, the use of a principal component analysis [1], the 2D image recognition via trained neural networks and the object recognition in the 3D point cloud via a trained AI. Finally, the four developed algorithms are to be linked via ensemble learning in order to increase the uncertainty of the evaluation system on the one hand and to ensure the required redundancy on the other hand.

Due to the systems and functions to be developed, the safety of the logistics of goods weighing tons in a time-critical man-machine network can be significantly improved. In the future, the developed technology can also be transferred to other applications with necessary personal safety, e. g. driverless transport systems.

[1] D. Gleichauf, F. Oehme, M. Sorg, A. Fischer: Laminar-turbulent transition localization in thermographic flow visualization by means of principal component analysis. Applied Sciences 11(12):5471 (22 pp.), 2021.

FlexGear

Establishment of lightweight design concepts for gearboxes of wind turbines

Funding organization: BMWK

Funding ID: 03LB1000A

Duration: 1 Dez 2020 – 31 May 2024

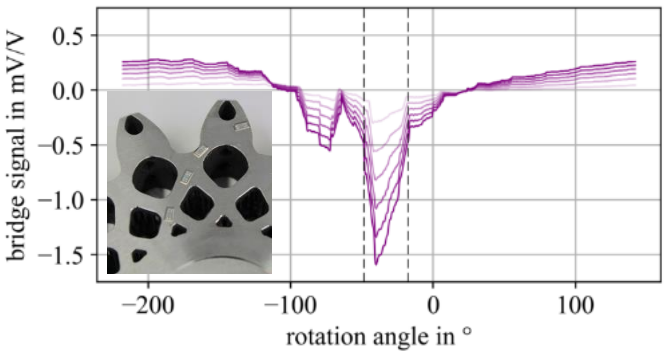
Project scientists: Philipp Thomaneck

In order to meet climate protection targets, there is a trend in industry towards conserving resources and saving energy through lightweight construction. Coupled with the objective of expanding the wind energy sector and installing larger wind turbines with a power ≥ 5 MW, lightweight construction is also becoming important for gear technology.

In order to save resources and energy, the material consumption in the design and manufacturing of gearboxes must be reduced by lightweight construction. Previous lightweight construction concepts only considered the structural optimization of the gearwheel body, but not the gear rim. This shows potential for new, holistic lightweight design concepts.

The joint project *FlexGear* aimed to develop design guidelines for holistic lightweight gears with an integrated load monitoring, which is of interest for instance for wind turbine gearboxes.

The additively manufactured lightweight demonstrator with a weight reduction of 58 % compared to a conventional gear was experimentally tested under static and dynamic loads as part of the project. As a result, the design concept was validated for the nominal load range by static load tests. In addition, experimental investigations were carried out in a dynamic gear test rig, where the inside sensor system was used for the first time. For this purpose, strain sensors were mounted at highly stressed positions of the gear, with which precise measurement signals from the tooth flank, tooth root and lightweight structure could be recorded and evaluated [1]. At the end of the project, high-speed digital speckle photography was additionally tested to enable areal, non-contact in-process measurements of the dynamic gear loads.



Manufactured bio-inspired lightweight gear with 4 strain sensors to perform in-process measurements, and the output signal of one sensor during tooth meshing, studying different applied torques.

[1] M.Terlau, M. Pillarz, A. von Freyberg, A. Fischer: Validation of an inside sensor system for deformation measurements on bionic lightweight gears. Sensor and Measurement Science International (SMSI 2023), Nürnberg, 8.-11. Mai 2023, No. P22, pp. 322-323.

PreciWind

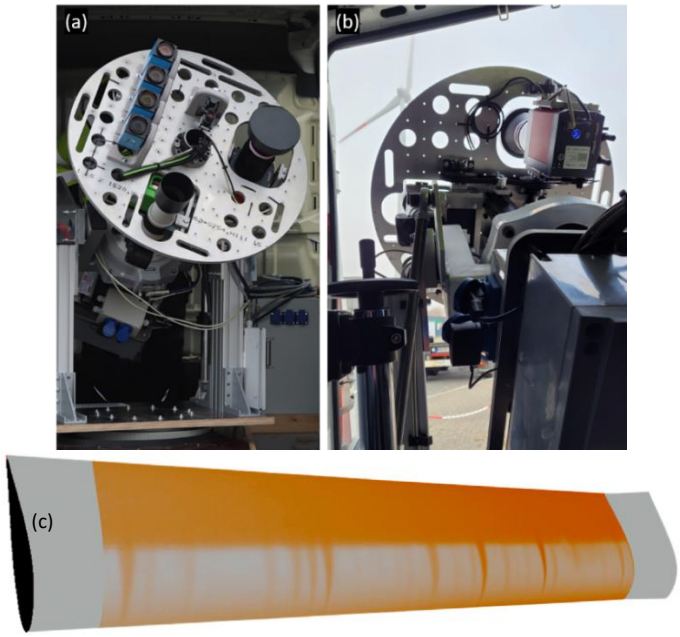
Precise measuring system for non-contact acquisition and analysis of the dynamic flow behaviour of wind turbine rotor blades

Funding organization: BMWK
Funding ID: 03EE3013D
Duration: 1 Jan 2020 – 31 Oct 2023
Project scientists: Daniel Gleichauf,
Paula Helming,
Ann-Marie Parrey

The boundary layer flow of aerodynamic profiles on wind turbine rotor blades is unsteady, since the wind speed, the turbulence level and the angle of attack vary, even during one revolution of the rotor. This dynamic behaviour influences, among others, the efficiency of the energy production of the entire wind turbine.

The state-of-the-art approach for a non-invasive measurement of the boundary layer flow on rotor blades of wind turbines in operation is thermographic flow visualization. It enables a contactless differentiation between different flow regimes by evaluating the different surface temperatures as a result of the flow-dependent heat transfer coefficient. So far, the measurement system only visualizes static flow phenomena by taking single snap-shots of the rotor blade during operation, and dynamic deformations are not considered.

Within *PreciWind*, laser-based blade deformation measurements were realized [1], and the geometry information was merged with thermographic images to yield a 3D thermographic flow visualization [2]. Furthermore, a co-rotating measurement platform has been developed and realized, so that a radial section of the rotor blade is continuously observable during the rotor revolutions. As a result, the dynamic behaviour of wind turbines is now accessible with so far unmatched resolution.



(a) Front view of the co-rotating measurement system. (b) Back view of co-rotating measurement system while performing measurements on a wind turbine. (c) Thermographic data combined with blade geometry [2].

[1] P. Helming, A. Intemann, K.-P. Webersinke, A. von Freyberg, M. Sorg, A. Fischer: Assessing the rotor blade deformation and tower-blade tip clearance of a 3.4 MW wind turbine with terrestrial laser scanning. Wind Energy Science 8:421-431, 2023.

[2] A. Fischer, A.-M. Parrey, N. Balaresque, A. von Freyberg: Flow visualization by means of 3D thermography on yawing wind turbines. Frontiers in Energy Research 11:1240183 (12 pp.), 2023.

AutoFlow

Thermographic flow condition detection on rotor blades of offshore wind turbines during operation using an automated and disturbance robust flight system

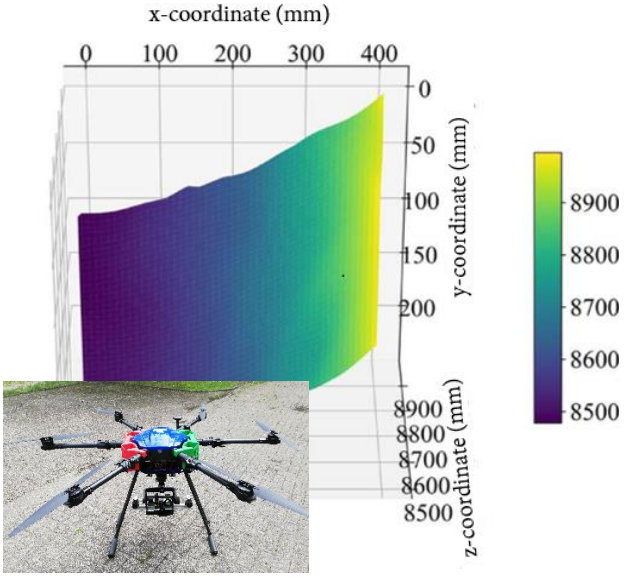
Funding organization: BMWK
Funding ID: 03EE3064A
Duration: 1 Aug 2022 – 31 Jul 2025
Project scientist: Friederike Jensen

Currently, the wind turbines are shut down for a condition analysis, which leads to high downtime costs for maintenance. The research project *AutoFlow* focuses on recording and evaluating the blade condition during operation. An automated multi-sensor equipped flight system is being deployed, which can perform thermographic as well as geometric measurements. The results gained in this project should not only lead to significant savings in maintenance costs for system operators, but also increase the operational safety by enabling the detection and repair of potential damage at an early stage.

A main focus of the project is the thermographic flow visualization as a tool for the analysis of the boundary layer flow condition of a rotor blade. Previous research shows that even small modifications of the aerodynamic airfoil such as contamination or erosion have a negative influence on the boundary layer flow [1].

To compare thermographic data of different rotor blade sections, a geometric mapping of the thermograms to the rotor blade geometry is required. However, the rotor blade geometry is rarely available, so that the geometry must be ideally determined during the thermographic measurement.

For this purpose, a photogrammetric camera system based on the triangulation principle was developed. A point pattern is projected onto the rotor blade using a laser and recorded by cameras in a stereo arrangement. The different viewing angles of the cameras allow the calculation of the 3D coordinates for each laser point on the rotor blade section. A surface geometry is created by interpolating the point cloud.



Drone-based laser triangulation system and measured 3D surface of a rotor blade segment (interpolated) from a measuring distance of d = 8.7 m.

[1] F. Jensen, M. Sorg, A. von Freyberg, N. Balaresque, A. Fischer: Detection of erosion damage on airfoils by means of thermographic flow visualization. European Journal of Mechanics - B/Fluids 104:123-135, 2023.

µRoboForm

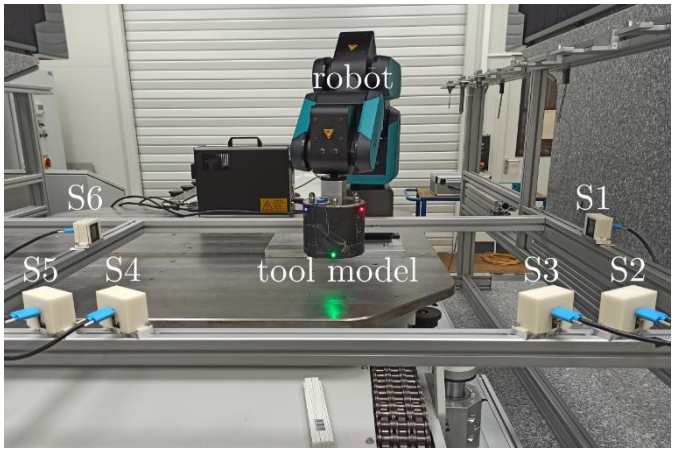
High-precision formed parts through measurement-based real-time control of the volumetric compensation of robot-assisted forming processes

Founding organization: BMWK
Funding ID: 22860 BG
Duration: 1 Mar 2023 – 28 Feb 2025
Project scientist: Marina Terlau

The flexible production of customized sheet metal parts is a challenge in industrial production. Forming processes in particular require expensive tools adapted to the target geometry. Industrial robots offer a suitable alternative for forming sheet metal parts because of their flexibility and low cost for a comparatively large machining volume. However, the deformation and the positioning uncertainty of the robot result in larger geometric deviations of the formed parts.

The aim of the project *µRoboForm* is therefore to reduce the geometric deviations by means of a measurement-based compensation of the position and orientation deviations of the tool center point (TCP) in robotic forming processes. A system of multiple novel optical sensors, which are installed independently of the robot kinematics, is used for a precise detection of the position and orientation of the TCP.

Based on previous work showing that the developed optical sensors are suitable for measuring the three-dimensional TCP position in ISF [1, 2], the sensor system was now extended to measure not only the TCP position but also the TCP orientation. The concept was validated using a minimal configuration of six sensors measuring the positions of three LEDs on the tool simultaneously.



Minimal setup for measuring the TCP position and orientation. LEDs at the TCP highlight the points to be measured.

The next challenge will be the integration of the measuring system in the robot cell followed by the active TCP position and orientation correction based on the measurements. In the final phase of the project, the controlled forming process will be demonstrated and the reduction of geometric deviations of the formed workpieces will be validated.

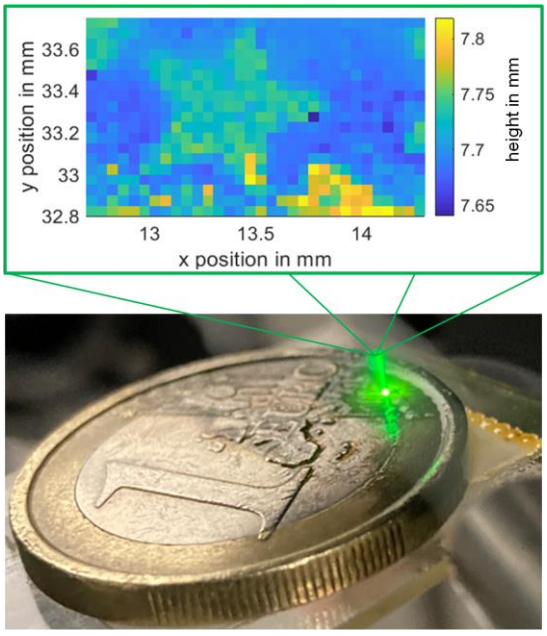
[1] M. Terlau, A. von Freyberg, D. Stöbener, A. Fischer: Shadow-imaging-based triangulation approach for tool deflection measurement. Sensors 23(20):8593 (20 pp.), 2023.

[2] A. von Freyberg, M. Terlau, D. Stöbener, A. Fischer: Optische Messung der Werkzeugablenkung in der inkrementellen Blechumformung. tm – Technisches Messen, 2023.

Indirect optical geometry measurement

Funding organization: ERC
Funding ID: 1010440456 - InOGeM
Duration: 1 Sept 2022 – 31 Aug 2027
Project scientists: Andreas Tausendfreund,
Björn Feld,
Claudia Niehaves

Optical metrology is driving our society forward and has strong impacts on manufacturing, mobility, medicine and fundamental science. Optical techniques allow fast and precise geometry measurements, but only if sufficient light energy is reflected from the object's surface to the photo detection unit. For this reason, specific measurement approaches for each surface type had to be developed such as deflectometry for highly reflective surfaces. To provide one single measurement approach applicable to any surface and with the potential of sub-micrometre resolution, *InOGeM* will initiate a paradigm shift: instead of measuring the object's surface, the geometry of the surrounding atmosphere is measured.



3D geometry of the star of a 1 € coin using indirect optical measurement of the surrounding fluorescent atmosphere.

In the very first stage of the project, the feasibility of the InOGeM approach has been successfully determined. For this purpose, a solution of Pyrromethene 567 in Di-Ethyl-Hexyl-sebacate was used to seed the measurement atmosphere with fluorescent particles, while the excitation and detection of the fluorescent light was carried out with a confocal microscope setup.

One challenge, in comparison to former experiments with completely liquid environments, is the small concentration of fluorescent particles. Less than 1 % of the recorded data contains a fluorescence event. Due to this scarcity of useful information, the current research work is focused on designing appropriate signal filtering algorithms and a model-based calculation of the object geometry, combining fluid dynamics, optics and statistical and numerical models.

The figure shows the first result of a three-dimensional geometry measurement of one of the stars on the number-side of a 1 € coin. The star protrudes by approx. 50 µm, which is in agreement with the nominal embossing height.

[1] A. Tausendfreund, B. Espenhahn, G. Behrends, A. Fischer: Indirect geometry measurement method based on confocal microscopy and fluorescent microparticles. SPIE Optical Metrology, München, 26.-29.6.2023, Vol. 12618, 126180P (8 pp.).

hyBit

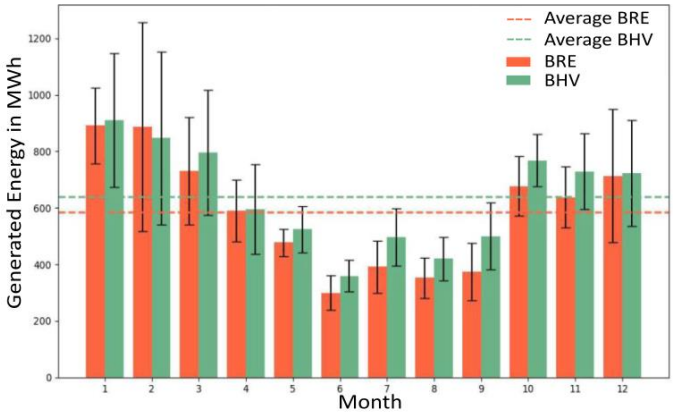
Hydrogen for Bremen's industrial transformation

Funding organization: BMBF
Funding ID: 03SF0687A
Duration: 1 Sept 2022 – 28 Feb 2026
Project scientists: Caroline Dorszewski,
Jakob Dieckmann

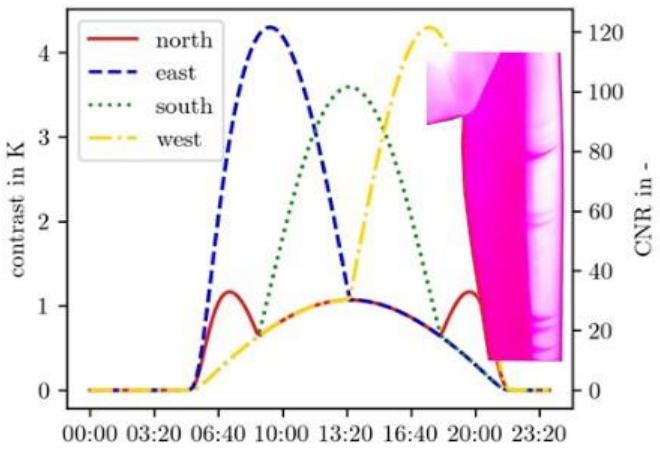
The project *hyBit* aims to investigate the possibilities of hydrogen for northern Germany and especially Bremen and its surroundings. The goal is to initiate the industry's transformation towards a renewable and climate-neutral future.

As our part, we will describe the regional potential of regenerative energy with a high resolution and based on real, measured data. The data are collected at different locations, and a regional database is formed with energy-related data for northern Germany. From these data, the energy weather will be derived, which describes the potential of renewable energy generation.

Furthermore, we contribute to the reliable prediction of renewable energies. Here, the potential of thermographic flow visualization measurements on wind turbines is investigated for different weather conditions, to improve the understanding of wind turbine efficiency. The measurement quality for measurements at different times over the day and the year was clarified [1], and a Bayesian inference was demonstrated to minimize the measurement uncertainty of the laminar-turbulent flow transition for low-contrast conditions [2].



Average produced energy for every month from two identical wind turbines in Bremen and Bremerhaven.



Theoretically-achievable contrast and contrast-to-noise-ratio (CNR) over a summer day, for a flow transition measurement on a wind turbine in operation, depending on the orientation of the turbine.

[1] C. Dorszewski, J. Dieckmann, N. Balaresque, A. von Freyberg, A. Fischer: Weather-dependency of the thermographic flow visualization of the laminar-turbulent transition on wind turbines. Measurement Science and Technology 35(9):095301, 2024.

[2] J. Dieckmann, C. Dorszewski, N. Balaresque, A. von Freyberg, A. Fischer: Bayesian-based approach for the thermographic measurement of flow transition on wind turbine rotor blades. Applied Sciences 14(3):1166, 2024

Measurement services for the industy

Measurement services

Dimensional measurements

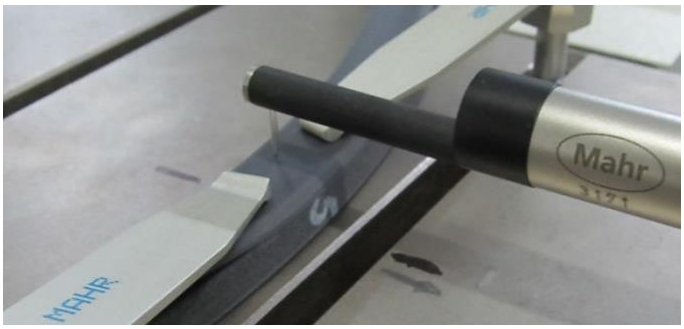
Duration: continuously

Contact: a.freyberg@bimaq.de

With its extensive measurement equipment, BIMAQ offers measurement services for the local industry.

The measurement tasks range from dimensional measurements on metallic and fibre composite materials for the automotive, energy, aerospace and space industry to roughness measurements on flexible sealing elements. Depending on the application, geometrical features are acquired on coordinate measuring machines with tactile or optical probes and dimensional, shape and position deviations are evaluated. Other applications require the optical acquisition of free-form surfaces by means of stripe pattern projection systems.

Roughness measurements are performed either with a stationary measuring device or with a mobile device, e. g. on bearing rings with diameters up to 2 m.



Roughness measurement on a flexible sealing element

Thermographic flow visualization

Duration: continuously

Contact: a.freyberg@bimaq.de

In a close cooperation with the Deutsche WindGuard Engineering GmbH, measurement services for flow visualizations are performed in wind tunnel experiments and on rotor blades of wind turbines in operation. The thermographic method for flow visualization is non-invasive and provides the location of different flow regimes as well as a localization of the laminar turbulent transition. The flow regimes can be distinguished by different surface temperatures and fluctuations in time. In wind tunnel experiments the acquisition, the automated processing and the evaluation of the results are part of the offered services. Combined with a telephoto lens, the high performance IR-cameras are capable to detect small temperature differences on the rotor blade surface for a visualization of the flow conditions on wind turbines in operation. The information can be determined without the expensive instrumentation of conventional methods. The measurements are carried out at a distance of several hundred meters and enable an overall evaluation of the flow conditions on the rotor blade as well as the study of influences on the flow by contamination and erosion of the leading edge.

Teaching

Teaching activities, student projects, graduation works

Teaching activities

Lecture	PT	MuV	SE	WING	BB	Sem. BSc	Sem. MSc	CP	Students WiSe 23/24 and SoSe 2024
Messtechnik (SE)			●	○	○	3rd		4	48
Grundlagenlabor Produktionstechnik			●			3th		2	23
Regelungstechnik + Labor	●			○		5th		5	36
Grundlagen der Qualitätswissenschaft	●		●	●		5th	1st	3	92
Messtechnik (MuV)		●				2nd		3	45
Strömungsmesstechnik		●				3nd		3	28
Autonome mechatronische Systeme 2		●				2nd		3	40
Regenerative Energien	●		○	○	○	4th 6th	1st	3	2
Prozessnahe und In-Prozess-Messtechnik	●		●	●		4th 6th	1st 2nd 3rd	3	10
Geometrische Messtechnik mit Labor * AUKOM	●		●	○		5th	1st	3	24
Methoden der Messtechnik - Signal- und Bildverarbeitung	●		●	●		5th	1st 2nd	3	4
Einführung in die Automatisierungstechnik mit Labor	●		●	○	○	5th	1st 2nd	3	15
Produktion von Verzahnungen + Labor (held by several chairs)	●		○				1st 2nd	9	1
Messtechnisches Seminar	●		●	●		4th	1st 2nd	3	14

- ● mandatory (Pflicht/Wahlpflicht/Wahlfach)
- ○ facultative

PT Produktionstechnik
MuV Maschinenbau und Verfahrenstechnik
SE Systems Engineering
WING Wirtschaftsingenieurwesen Produktionstechnik
BB Berufliche Bildung

* AUKOM Certificate: AUKOM is a manufacturer-independent association for training in the field of geometric measurement technology. AUKOM offers the students to earn the level 1 basic certificate at cost.

Student projects

Kind of project	Title	Semester	Course of studies
Anwendungsprojekt	Realisierung eines 3D-Laserscanners mit Signalauswertung und Geräteansteuerung	SoSe 2023	BSc MuV
Anwendungsprojekt	Berührungslose 3D-Formmessung mit Signalauswertung und Geräteansteuerung in Python	WiSe 2023/2024 SoSe 2024	BSc MuV
Informatikprojekt	Ansteuerung eines 3D-Laserscanners (Bilderfassung und -auswertung in Python)	SoSe 2024	WING PT

Teaching

Graduation works

Bachelor theses

- H. ***Paul***:
  Strategien zur Prognose der Stromerzeugung aus erneuerbaren Energien auf Basis von Wetterdaten.
  Colloquium: 14.11.2023
- S. ***Richter:***
  Untersuchung von Trockeneispartikeln als Messsonden für die indirekte Geometriemessung.
  Colloquium: 23.05.2024

Master theses

- M. ***Talati:***
  Flow and adhesion behavior of microparticle seeding.
  Colloquium: 16.08.2023
- F. J. ***Kenne Ngningaye***:
  Aufbau und Charakterisierung eines Multi-Sensor-Systems mit Datenfusion zur berührungslosen Werkzeugpositionsmessung beim inkrementellen Blechumformen.
  Colloquium: 29.08.2023
- A. ***Rehfeldt:***
  Drohnenbasierte optisch-scannende 3D-Geometriemessung.
  Colloquium: 19.12.2023
- H. T. ***Dasanayake***:
  Evaluating Infrared Thermography Measurement Data with Computer Vision & Machine Learning.
  Colloquium: 14.05.2024
- J. ***Heinrich:***
  Indikatoren zur Bewertung von Zuverlässigkeit und Nachhaltigkeit von Windenergieanlagen in Energiesystemen.
  Colloquium: 19.06.2024

Publications and qualification of young academics

Publications

Books

- G. ***Behrends***:
  Berührungslose kontinuierliche Topografiemessung auf bewegten Körpern.
  Staats- und Universitätsbibliothek Bremen, 2023.
- D. Feldmann, F. ***Oehme***, L. von Germersheim, R. López Parras, A. Fischer, M. Avila:
  Towards indirect assessment of surface anomalies on wind turbine rotor blades.
  In: New Results in Numerical and Experimental Fluid Mechanics XIV. (Eds.: A. Dillmann, G. Heller, E. Krämer, C. Wagner, J. Weiss), pp. 529-538, Springer, Cham, 2023.
- A. ***Fischer***, F. Härtig (Eds.):
  Metrological competence center for wind energy.
  In: tm - Technisches Messen 90(9), De Gruyter, Berlin, 2023. (special issue)
- M. ***Pillarz***:
  Modellbasierter Multi-Distanz-Messansatz zur optischen Messung der Verzahnungsgeometrie.
  Staats- und Universitätsbibliothek Bremen, 2023.
- Y. ***Schädler***:
  Modellierung der Energiesystemtransformation in Deutschland basierend auf spatiotemporal hochaufgelösten Messdaten.
  Staats- und Universitätsbibliothek Bremen, 2023.
- L. ***Schweickhardt***:
  Erweiterte laserspecklebasierte Oberflächenmesstechnik mittels adaptiver Optiken.
  Staats- und Universitätsbibliothek Bremen, 2024.
- F. ***Oehme***:
  Thermografische Detektion und Lokalisierung von Strömungsablösung an Windenergieanlagen.
  Staats- und Universitätsbibliothek Bremen, 2024.

Publications and qualification of young academics

Publications

Journals

- J. ***Dieckmann***, C. Dorszewski, N. Balaresque, A. von Freyberg, A. Fischer:
  Bayesian-based approach for the thermographic measurement of flow transition on wind turbine rotor blades.
  Applied Sciences 14(3):1166 (18 pp.), 2024.
- C. ***Dorszewski***, J. Dieckmann, N. Balaresque, A. von Freyberg, A. Fischer:
  Weather-dependency of the thermographic flow visualization of the laminar-turbulent transition on wind turbines.
  Measurement Science and Technology 35(9):095301 (12 pp.), 2024.
- B. ***Espenhahn***, L. Schumski, D. Meyer, D. Stöbener, A. Fischer:
  Optical measurement approach to analyse the tool-workpiece interacting flow of grinding processes.
  Flow Measurement and Instrumentation 93:102407 (11 pp.), 2023.
- A. ***Fischer***:
  Capabilities and limits of surface roughness measurements with monochromatic speckles.
  Applied Optics 62(14):3724-3736, 2023.
- A. Roß, N. Balaresque, A. ***Fischer***:
  Temperature and pressure effects on the response behavior of anemometers.
  tm - Technisches Messen 90(9):604-612, 2023.
- R. Sato, X. Li, A. ***Fischer***, L. C. Chen, C. Chen, R. Shimomura, W. Gao:
  Signal processing and artificial intelligence for dual-detection confocal probes.
  International Journal of Precision Engineering and Manufacturing 25(1):199-223, 2024. (invited review article)
- D. ***Gleichauf***, F. Oehme, A.-M. Parrey, M. Sorg, N. Balaresque, A. Fischer:
  On-site contactless visualization of the laminar-turbulent flow transition dynamics on wind turbines.
  tm - Technisches Messen 90(9):613–623, 2023.
- P. ***Helming***, A. Intemann, K.-P. Webersinke, A. von Freyberg, M. Sorg, A. Fischer:
  Assessing the rotor blade deformation and tower-blade tip clearance of a 3.4 MW wind turbine with terrestrial laser scanning.
  Wind Energy Science 8:421-431, 2023.

- F. ***Jensen***, J. F. Jerg, M. Sorg, A. Fischer:
  Active thermography for the interpretation and detection of rain erosion damage evolution on GFRP airfoils.
  NDT & E International 135:102778 (10 pp.), 2023.
- F. ***Jensen***, M. Sorg, A. von Freyberg, N. Balaresque, A. Fischer:
  Detection of erosion damage on airfoils by means of thermographic flow visualization.
  European Journal of Mechanics - B/Fluids 104:123-135, 2023.
- Y. Bouraoui, L. Rathmann, C. ***Niehaves***, M. Mikulewitsch, A. Fischer, T. Radel:
  Material removal in laser chemical processing with modulated laser power.
  Journal of Laser Applications 36(1):012013 (8 pp.), 2024.
- L. ***Schweickhardt***, A. Tausendfreund, D. Stöbener, A. Fischer:
  Digital speckle photography in the presence of displacement gradients.
  Journal of the European Optical Society-Rapid Publications 19(1):16 (10 pp.), 2023.
- M. ***Terlau***, A. von Freyberg, D. Stöbener, A. Fischer:
  Shadow-imaging-based triangulation approach for tool deflection measurement.
  Sensors 23(20):8593 (20 pp.), 2023.
- M. ***Terlau***, A. von Freyberg, D. Stöbener, A. Fischer:
  Optical tool deflection measurement approach using shadow imaging.
  Measurement: Sensors 33: 101162 (11 pp.), 2024.
- A. ***von Freyberg***, M. Terlau, D. Stöbener, A. Fischer:
  Optische Messung der Werkzeugablenkung in der inkrementellen Blechumformung.
  tm - Technisches Messen 90(6):365-373, 2023.

Publications and qualification of young academics

Publications

Conference contributions

- Y. Bouraoui, L. Rathmann, C. ***Niehaves***, M. Mikulewitsch, A. Fischer, T. Radel:
  Material removal in laser chemical processing with modulated laser power.
  42nd International Congress on Applications of Lasers & Electro-Optics (ICALEO), Chicago, USA, 16.-19.10.2023.
- A. ***Fischer***, A. Tausendfreund, R. Hess, T. Petersen, D. Stöbener:
  In-process measurement of mechanical loads during electrical discharge machining.
  72nd CIRP General Assembly, Dublin, Ireland, 20.-26.8.2023, No. P05.
- B. ***Espenhahn***, G. Behrends, A. Tausendfreund, A. Fischer:
  Wenn Strömung und Oberfläche aufeinandertreffen – ein neues Paradigma zur Messung von Mikrogeometrien.
  30. GALA-Fachtagung "Experimentelle Strömungsmechanik", München, 5.-7.9.2023, No. 13 (8 pp.).
- F. ***Jensen,*** A. von Freyberg, M. Avila, A. Fischer:
  Thermografische Untersuchung des Einflusses unterschiedlicher Aspektverhältnisse auf den Strömungsnachlauf von Kavitäten an Tragflächenprofilen.
  30. GALA-Fachtagung "Experimentelle Strömungsmechanik", München, 5.-7.9.2022, No. 6 (8 pp.).
- L. ***Schweickhardt***, D. Stöbener, A. Fischer:
  Speckle-basierte Charakterisierung anisotroper Oberflächen.
  XXXVII. Messtechnische Symposium des AHMT, Freiburg, 27.-28.9.2023.
  tm - Technisches Messen 90(S1):61-66, 2023.
- P. Zeuschner, Y. ***Schädler***, S. Drebber:
  BrewFlex – Wie können Brauereien im Kontext der Energiewende ihr Last- flexibilisierungspotenzial optimal nutzen?
  VLB-Oktobertagung, Berlin, 9.-10.10.2023
- A. ***Fischer***:
  Optical in-process measurements for the quality control in production systems.
  Seminar of Jernkonturet (Technical area "Non-destructive testing and measurement techniques"), Stockholm, Schweden, 24.04.2024. (talk invited by Dr. J. Gurell).
- M. ***Terlau***, A. von Freyberg, A. Fischer:
  In-process tool pose measurement in incremental sheet forming.
  27th International ESAFORM Conference on Material Forming (ESAFORM 2024), Toulouse, France, 24.-26.4.2024, pp. 1353-1362.

- T. M. H. ***Rahman***, D. Stöbener, A. Fischer: *Scatterometry-based assessment of defective nanograss surfaces – a virtual experimentation setup for uncertainty analysis.* 125. Jahrestagung der Deutschen Gesellschaft für angewandte Optik e. V. (DGaO), Aachen, 21.-25.5.2024, No. A21.
- C. ***Dorszewski***, J. Dieckmann, N. Balaresque, A. von Freyberg, A. Fischer: *Influence of solar radiation and outside air temperature on the thermographic flow visualization of wind turbines.* TORQUE 2024 - The Science of Making Torque from Wind, Florence, Italy 29.-31.5.2024.
- J. ***Dieckmann***, C. Dorszewski, N. Balaresque, A. von Freyberg, A. Fischer: *Bayes'scher Ansatz für die thermografische Messung von Strömungsübergängen an Rotorblättern von Windkraftanlagen.* 22. GMA/ITG-Fachtagung "Sensoren und Messsysteme 2024", Nürnberg, 11.-12.6.2024, No. D5.3.

Publications and qualification of young academics

PhD theses

Enhanced laser-speckles-based surface measurments by means of adaptive optics

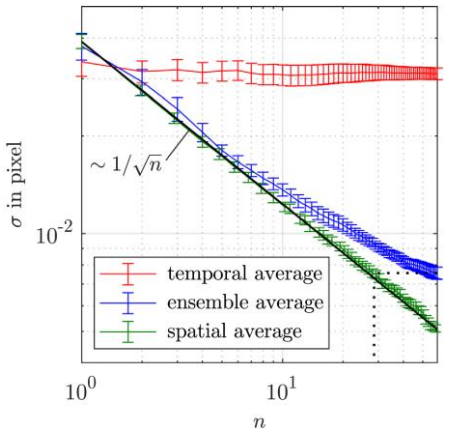
Dr.-Ing. León Okko Schweickhardt
Date of thesis defense: 12 Jan 2024
Supervisor: Prof. Dr.-Ing. habil. Andreas Fischer

Surface texture and surface deformation information enable the determination of material properties and local loads of a mechanical component, and both is measurable with fast, non-contact laser-speckle-based methods.

With digital speckle photography, laser speckles are used to determine two-dimensional deformation fields using image correlation. However, it is prone to deviations due to the random speckle distribution and local deformation gradients. Therefore, a large number of speckle patterns was generated with a digital micromirror device, allowing multiple measurements with varied speckle patterns. Thus, through ensemble averaging, the measurement uncertainty was reduced by an order of magnitude, while retaining the spatial resolution. Additionally, it was investigated which random and systematic measurement deviations occur due to deformation gradients. By means of an optical simulation, it could be shown that the random deviation depends on the first order gradient and is caused by a decorrelation of the speckle patterns. The systematic deviation is related to the second-order gradient and is predominantly caused by the image correlation algorithm.

Furthermore, laser speckle methods and image processing algorithms in combination with simulations and emulated surface measurements with a phase-only spatial light modulator were implemented to derive multiple surface texture parameters like the machining direction, the lateral correlation length perpendicular to it, the root mean square height in and perpendicular to the machining direction from a single captured speckle pattern.

Overall, the speckle-based surface measurement technique was enhanced by means of adaptive optics regarding the measurands and the achievable uncertainties.



Uncertainty σ of the deformation measurement over the number n of averaged speckle patterns, comparing the temporal, spatial and ensemble averaging.

[1] L. Schweickhardt, A. Tausendfreund, D. Stöbener, A. Fischer: Noise reduction in high-resolution speckle displacement measurements through ensemble averaging. Applied Optics 60(7):1871-1880, 2021.

[2] L. Schweickhardt, A. Tausendfreund, D. Stöbener, A. Fischer: Digital speckle photography in the presence of isplacement gradients. Journal of the European Optical Society-Rapid Publications 19(1):16 (10 pp.), 2023.

Thermographic detection and localization of flow separation on wind turbines

Dr.-Ing. Felix Oehme

Date of thesis defense: 29 Febr 2024

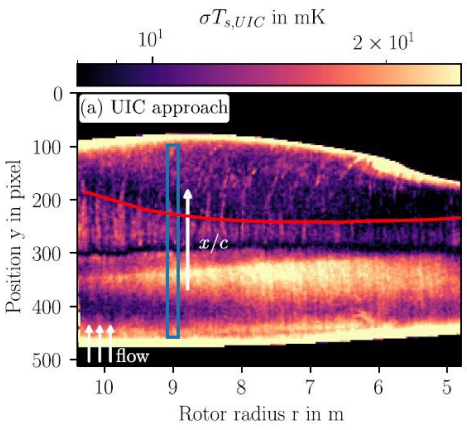
Supervisor: Prof. Dr.-Ing. habil. Andreas Fischer

Flow separation on wind turbine blades leads to a reduction in aerodynamic efficiency, social acceptance and the lifetime of the turbines. Therefore, the aim of this work was to characterize the measurement capabilities of an Infrared thermography (IRT)-based measurement system for the non-invasive and spatio-temporally resolved detection and localization of steady and unsteady flow separations.

In order to enable IRT for an unambiguous detection and localization of flow separation, physically interpretable signal processing approaches (UIC approach, DIT approach) were combined with a principal component analysis (PCA). In wind tunnel experiments, the suitability of the UIC-approach for the unambiguous detection of stationary flow separation was proven, and an increase in the distinguishability of attached-detached flow regions was achieved by the PCA-based evaluation. By the subsequent transfer to field measurements, an IRT-based detection and localization of static flow separation at an operating wind turbine was presented and verified for the first time [1].

In addition, the temporal resolution capability of IRT with respect to dynamic transition positions and unsteady flow separation was assessed by a numerical simulation as a function of the measurement conditions, and it was shown that the inertia of the thermal response behavior limits the spatiotemporal resolution limits for the detection of unsteady flow separation. In field measurements under conditions of low solar heating, the designed and implemented image processing approach nevertheless enables the detection of unsteady flow separation with the maximum spatio-temporal resolution of the measurement system.

As a result, the suitability of IRT for the detection and localization of steady-state *and* unsteady flow separation on wind turbines was theoretically clarified and experimentally demonstrated.



Thermogram evaluated by the UIC-approach with the resulting detected line of beginning stall (red).

[1] F. Oehme, D. Gleichauf, N. Balaresque, M. Sorg, A. Fischer: Thermographic detection and localisation of unsteady flow separation on rotor blades of wind turbines. Frontiers in Energy Research 10:1043065 (15 pp.), 2022.

Publications and qualification of young academics

Awards

Deutsche WindGuard
Young Scientists Award 2023 for Measurement Technology, Automation and Quality Science

In 2023, the DWG Young Talent Award was presented for the seventh time at BIMAQ for outstanding student work at the Bremen Institute for Metrology, Automation and Quality Science (BIMAQ) in the Faculty of Production Engineering at the University of Bremen. The prize is intended to promote young engineers and is sponsored by Deutsche WindGuard GmbH (DWG).

In awarding the prize, particular emphasis was placed on progress for science, metrological system understanding and the relevance of the research results for practical measurement tasks. The award is associated with prize money of 500 euros per master thesis.

2023 the award went to:

Philipp ***Thomaneck*** for his master thesis:

„Validierung eines ganzheitlichen bionischen Leichtbaudesigns für Verzahnungen hinsichtlich dynamischer Belastungen"

Congratulations from the BIMAQ team!

Prof. A. Fischer, P. Thomaneck

Events & News

Participation at events and conferences

Date	Event / Conference	Location	Participant(s)	
21 – 25 Aug 2023	**72st CIRP General Assembly**	Dublin	A. Fischer	oral presentation
5 – 7 Sep 2023	**30. GALA-Fachtagung „Experimentelle Strömungsmechanik“**	München	A. Fischer B. Espenhahn	oral presentation
27 – 28 Sept 2023	**XXXVII. Messtechnische Symposium des AHMT**	Freiburg	A. Fischer L. Schweickhardt	oral presentation
13 Nov 2023	**hyBit - Workshop on research data management**	Bremen	J. Dieckman	-
19 Nov 2023	**hyBit - Workshop on power grid simulation with PowerWorld**	Bremen	C. Dorszewski	-
24 – 26 Apr 2024	**International ESAFORM Conference 2024**	Toulouse	M. Terlau	oral presentation
11 – 22 Apr 2024	**Workshop on the conceptualization of the Excellence Cluster “The Martian Mindset”**	Bremerhaven	A. Fischer	oral presentation & session chair
24-25 Apr 2024	**SPP2402 - Workshop and lectures on machine learning**	Hamburg	J. Xiang D. Stöbener	-
24 Apr 2024	**Invited talk: Jernkonturet seminar, in the technical area "Non-destructive testing and measurement techniques"**	Stockholm	A. Fischer	oral presentation
21 – 25 May 2024	**DGaO - 125. Jahrestagung**	Aachen	T. Rahman	oral presentation
29 – 31 May	**TORQUE 2024**	Florenz	C. Dorszweski	poster presentation
11 – 12 Jun 2024	**22. GMA/ITG- Fachtagung Sensoren und Messsysteme 2024**	Nürnberg	J. Dieckmann	oral presentation

Events & News

Events @ BIMAQ

Date	Event
5 Sep 2023 & 7 Dec 2023	**Field measurement campaign: When the BIMAQ rotates with the wind turbine …**
7 Nov 2023	**BEST - Ring lecture Wind turbines: Challenges of on-site research**
9 Jan 2024	**Invited talk: Dr. Seefeld (BIAS): Process Monitoring in Additive Manufacturing of Metals**
12 Mar 2024	**Kids University 2024: We can see colors and temperatures, too?**
20 Mar 2024	**On-machine measurement campaign: When the robot takes over…**
25 Apr 2024	**Girls Day – Mädchen-Zukunftstag**
7 May 2024	**Invited talk: Dr. Soeren Ahmerkamp (MPI/MARUM): SensPIV: Connectivity between microorganisms and their environment**
29 May 2024	**Exciting seminar on in-process measurement technology for maritime systems**
18 Jun 2024	**Students meet BIMAQ**

- *Prominent guest speakers in BIMAQ's seminar on measurement techniques*

  Within the scope of our seminar, outstanding guest speakers gave inspiring presentations on their topical scientific work. The BIMAQ-team says thank you to:

  - Dr. Seefeld (BIAS): *Process Monitoring in Additive Manufacturing of Metals* 9 Jan 2024
  - Dr. Soeren Ahmerkamp (MPI/MARUM): *SensPIV: Connectivity between microorganisms and their environment* 7 May 2024

- *Field measurement campaign:*
  When the BIMAQ rotates with the wind turbine …
  To surpass the current resolution limits of thermographic flow visualization on wind turbines, multiple cameras/sensors are attached to a joint platform, and an image de-rotation is achieved by synchronizing the platform rotation with the turbine rotation. As a result, rotor blade images in the infrared and visible range as well as laser-scanning-based distance measurement are obtained – with significantly reduced image blurring, a sampling rate increase by more than one order of magnitude, and with continuous data acquisition over the entire rotor revolution cycle.

  The co-rotating measurement platform was successfully tested even under harsh weather conditions during the winter season, to provide in-process measurement data of flow and deformation dynamics with worldwide unmatched resolution.

- *On-machine measurement campaign:*
  When the robot takes over …
  How to obtain a large amount of data about the wear of tool, i.e. from multiple longterm experiments on a real turning machine? To achieve a high productivity in the sense of data output, a robot-assisted measurement approach is needed. This way, an automated tool wear measurement is achievable in situ, which means in the turning machine with no detachment and reattachment of the tool, and over the complete lifecycle of the tool.

  Together with our colleagues from the Leibniz Institute for Materials-oriented Technologies - IWT Bremen, a turning machine was equipped with a robot-assisted measurement setup. This will enable optical in situ measurements of the varying tool geometry and tool coating layer thickness at multiple, different stages of the tool wear process. Lots of data are expected and, thus, new insights into the tool wear mechanisms with an unmatched level detail.

Events & News

Events @ BIMAQ

- *Kid's University 2024 in Bremen*

Already for the 4th time, the BIMAQ was part of the Bremen Kid's University (https://www.uni-bremen.de/kinderuni).

In the contribution "We see colors ... and temperatures as well?" Prof. Fischer discovered together with the pupils a new, fascinating world. What would the world look like, if we could see infrared light with our eyes? With a colorful bunch of experiments and by making visible what is usually not visible, fundamental questions on the nature of light and heat radiation are answered.

In addition, the importance of contacless temperature measurements for our sociecty as well as for current research activities are highlighted.

- *Girl's Day*

Universität Bremen

Girls'Day Mädchen-Zukunftstag

25. April 2024

On April 25, 2024, the BIMAQ offered two activities for the Girl's Day. In the morning workshop, prepared by Mr. Behrendt, the girls in grade 7 and 8 were able to discover the world through electronic senses. By combining different electronic components like resistors into a bridge circuit, the girls were able to build a working thermometer or measure their own height.

For the afternoon workshop, Ms. Niehaves and Mr. Dieckmann provided an insight into the world of temperature visualization through thermal cameras. The girls from school grade 5 and 6 were able to experiment with water of different temperatures and explore how different materials, like balloons, appear in the thermal image. The session was concluded by a photo shoot with the thermal camera.

- *Exciting seminar "In-process measurement technology for maritime systems"*

  In addition to material science and their technologies, marine science is the biggest high-profile research area of the University of Bremen. And to initiate an interdisciplinary research cooperation between measurement science and marine science, the BIMAQ team organized a seminar on in-process measurement technology for maritime systems on May 29, 2024.

  The discussed questions are

  - What processes occur in maritime systems?
  - How do human activities affect these processes and how does it contribute to the climate change?
  - And finally, how to measure and, thus, to understand the dynamic maritime processes, and which challenging measurement conditions will occur?

  The seminar took place in Wremen at the coast line of the North Sea, so that the scientific discussions could be complemented by gaining a personal, direct insight into the dynamic maritime processes at the Wattenmeer. Here it was fascinating to see how biology and particle/fluid mechanics is shaping the 'nursery' of the sea.

Despite the rainy and windy weather, the participants enjoyed the newly gained perspectives on maritime systems and the required measurement technologies a lot.

- *Students meet BIMAQ*

  On June 18, 2024, Prof. Fischer and the BIMAQ team invited students of production engineering, systems engineering and industrial engineering to get in touch with the BIMAQ research topics and people.

  With its research focus in measurement and control, the BIMAQ has a lot to offer to students who are interested in non-contact optical measurement systems, signal and image processing tools, the analysis of flow and production processes, model-based quality controls and the inspection and optimization of wind turbines in operation.

  Topics for Bachelor and Master theses offer the opportunity to participate in current research projects.

  The event including a barbecue was well received by the students and provided an excellent platform for exchanging ideas.

Notes

Notes

Impressum

BIMAQ

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June 2024

Universität Bremen

Did you like what you read and you want to be a part of it?

We look forward to receiving *your* informative application at any time, preferably in the form of a pdf file by e-mail to

info@bimaq.de

with your
- cover letter,
- curriculum vitae and
- copies of certificates!