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FRAUNHOFER INSTITUTE FOR HIGH-SPEED DYNAMICS, ERNST-MACH-INSTITUT, EMI

ANNNUAL REPORT
2018/2019

Cover: Fraunhofer EMI explores possible applications of nanosatellites and focuses on the nanosatellite demonstrator ERNST developed in the business unit Space. ERNST features a scientific infrared camera, which can be used for Earth observation. The cover shows the additively manufactured optical bench together with the camera system of the nanosatellite.

ANNUAL REPORT 2018/2019

Dear Reader,

In the preface of the annual report, I usually highlight the major contributions and outstanding events of the report year. About one year after the decease of my predecessor and fatherly friend Prof. Dr. Klaus Thoma, please allow me to make this sad event my anchor point instead. With Klaus Thoma, the Ernst-Mach-Institut became a Fraunhofer institute. Certainly, according to its name and the Fraunhofer consecutive number 006, EMI is one of the oldest institutes of the Fraunhofer-Gesellschaft. However, everything that nowadays makes an institute a Fraunhofer institute has evolved under his leadership: Generating a third of the budget from industrial revenues. An agenda for strategic research and business unit management. A sustainable link with a university and the consequent cultivation of doctoral studies. Modern buildings for research and administration. In addition to these structural and strategic elements, Klaus Thoma developed and advanced EMI's core competences. For this reason, we are the partner of choice when it comes to analyzing highly dynamic processes, e.g. automobile crashes, with razor-sharp images from the structures' insides. X-ray crash, battery tests and airbag systems are the keywords that document the current state-of-the-art in this report.

The research fields of ballistics and detonation physics have become more topical than they have been since the end of the Cold War. With our staff, facilities and decades of experience, EMI is again central partner for conducting research regarding future armor options and aircrafts.

At the beginning of the Thoma era, a sustainable and versatile link with a university – as it now has become a standard for a Fraunhofer institute – did not exist for EMI. And yet, Klaus Thoma and the former director of Fraunhofer ISE, Eicke Weber, had envisioned a university department at the technical faculty of the University of Freiburg, in which all five Freiburg Fraunhofer institutes should be represented. Back then, this might have seemed just a dream – which now has become reality and a success: The Department of Sustainable Systems Engineering – INATECH – is the Sustainability Center Freiburg's core of engineering and the only department nationwide that is funded by Fraunhofer with a share of 50 %. After a very successful first phase, the Sustainability Center Freiburg has been evaluated positively and could continue its mission to realize a dualism between continuing fundamental and applied research. EMI has successfully applied for so-called demonstrator projects for the second phase, which puts a focus on transfer. Currently, INATECH has more than one hundred employees. In addition to the master program, a bachelor program on Sustainable Systems Engineering has now also been launched.

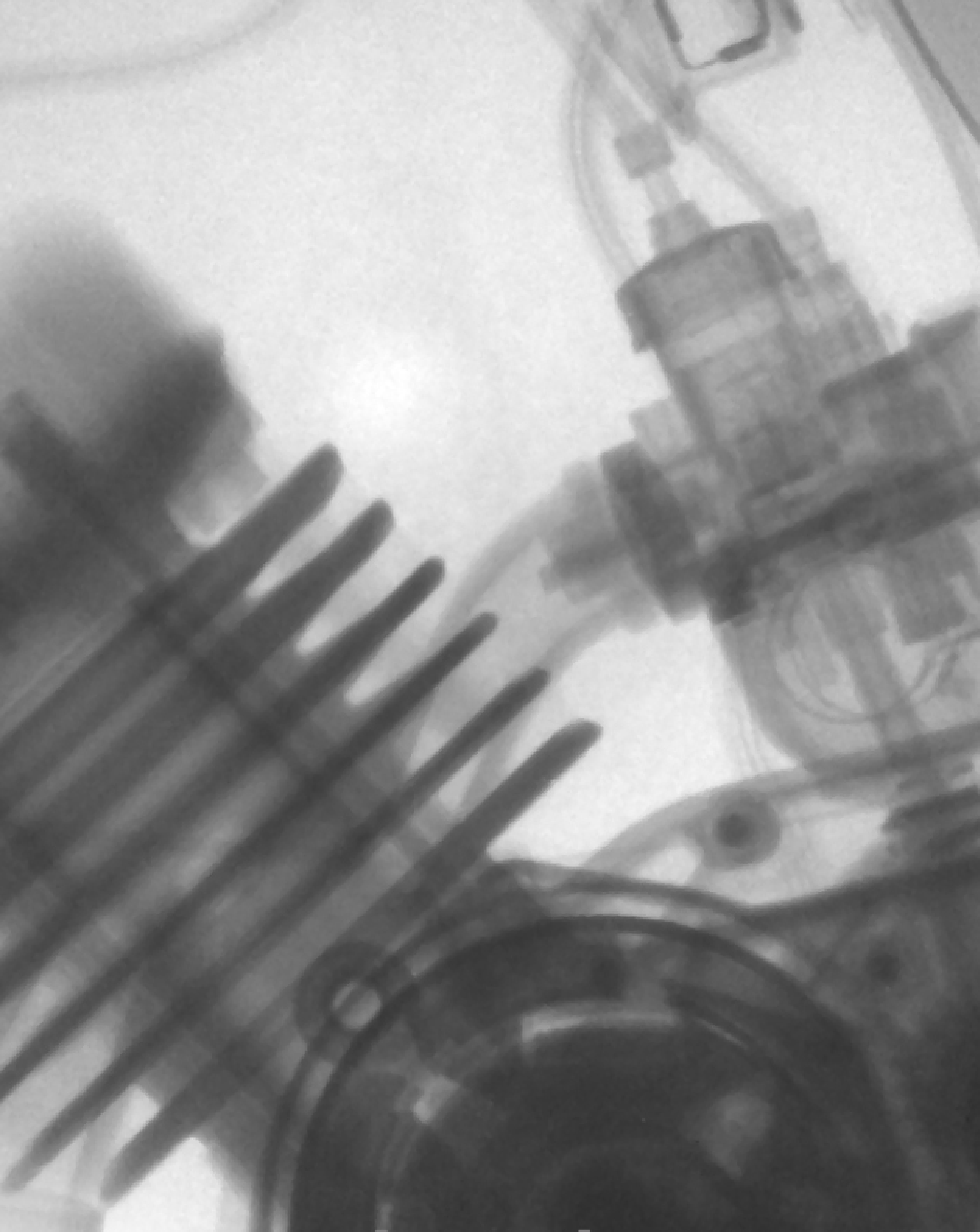
I am sure that the current performance of our institute, with stable indicators for the economic situation and exciting new and old fields of research, is entirely in line with Klaus Thoma's vision of a future-oriented, sustainable EMI. I want to thank all our partners, customers and colleagues from the fields of science, economy and politics for their constant trust in us. Enjoy reading!

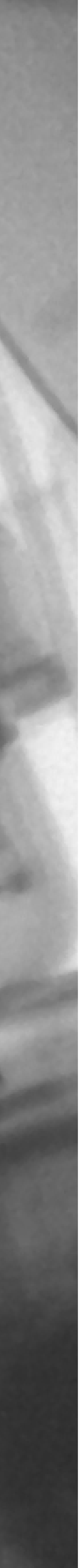
Sincerely Yours,
Stefan Hiermaier

Prof. Dr.-Ing. habil. Stefan Hiermaier
Director of Fraunhofer EMI

23 SCALING OF LASER EFFECTS

52 NEW RADIATION SOURCE OF X-RAY CRASH X-CC





BUSINESS UNIT DEFENSE

Process radiation during perforation of a plate made of carbon-fiber reinforced plastic using a high-energy laser beam.

BUSINSS UNIT DEFENSE

The German Federal Armed Forces (Bundeswehr) need sustainable systems for land, air and sea. As a strategic partner of the German Federal Ministry of Defence (BMVg) regarding high-speed dynamics research and technology, Fraunhofer EMI explores scientific and technological issues regarding armor and effect as well as defense-related security and systems.

The institute is equipped with high-performance test facilities, with which the behavior of materials, components and subsystems under extreme loading can be precisely investigated in laboratory tests. At EMI, dynamic processes are studied using specialized diagnostics for very high temporal and spatial resolution. On this basis, it is possible to derive suitable model descriptions. Subsequently, a numerical simulation with predictive power allows deriving technological solutions. The research results presented below have been scientifically investigated on the basis of BMVg funding.

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Complex and structured objects from the 3D printer, made out of special materials such as tungsten.

The powder bed based Laser Beam Melting (LBM) process allows the manufacturing of individual, lightweight and robust geometries. At Fraunhofer EMI, we have developed our own manufacturing parameters for the processing of materials used in defense technology. We have shown that even materials such as tungsten, which are difficult to process, can be additively generated in a high quality.

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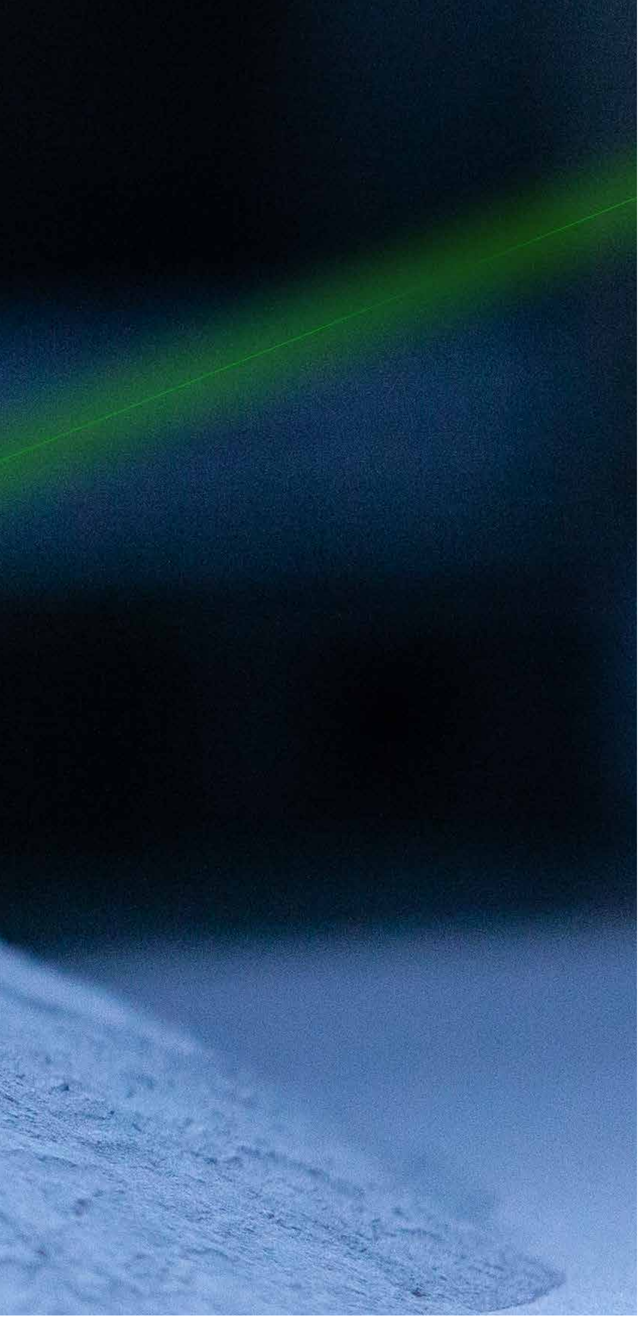


PRIMARY DEVELOPMENT OF PROCESS PARAMETERS FOR 3D PRINTING OF HEAVY METALS AND UNIQUE MATERIALS

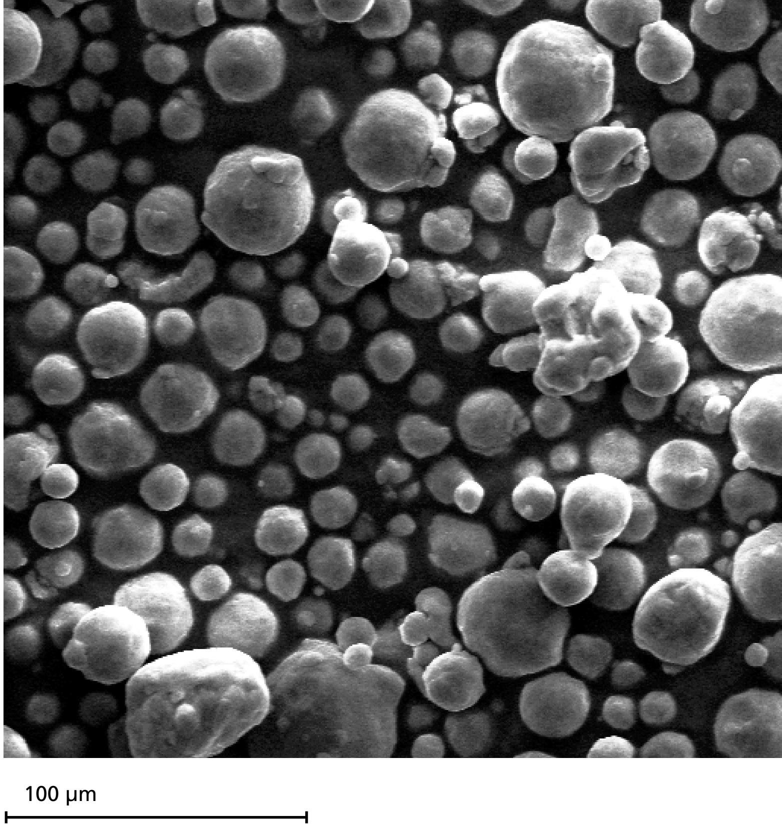
Additive manufacturing (3D printing) technology has experienced a rapid progress within the last years and is increasingly applied in the industry for small-series production. Due to the various fields of application, the material portfolio of the versatile 3D printing technologies is continuously growing.

Additively manufactured samples made from heavy metal (tungsten) for the investigation of optimized process parameters.

With its particularly distinctive material flexibility, the Laser Beam Melting (LBM) technology is the most widely used method for 3D printing of metals. Thin layers of metal powder are applied to a substrate, melted locally through laser energy and are fused with the previous layer. This way, a three-dimensional object is created from multiple layers, and a new freedom of design results from this additive principle. Furthermore, complex geometries can be generated for materials that, e.g. because of their hardness, are very difficult to process. Other advantages of LBM are flexibility, the opportunity of integral design, integration of functions, improved logistics, reduced development times, and individual products. Essentially, in comparison with conventional methods, LBM offers comparable material density and excellent material properties. This technology is particularly suitable for the manufacturing of highly loaded machine parts optimized in terms of lightweight design, or for functional applications in defense technology.

Few alloys serve specific fields of application

Due to the currently complex and expensive parameter development for new alloys for LBM-based 3D printing, only few selected alloys are used for a wide range of applications. Aluminum and titanium alloys address the lightweight design sector. Nickel alloys are suitable for high temperature applications, stainless steel for engineering and the manufacturing of art objects. Cobalt chrome and titanium alloys serve the medical engineering market, and high-strength steels are used for the production of tools. However, fields of application with a need for alternative materials have yet only been covered to a limited extent. Especially for dynamic applications, such as car crashes and, particularly, defense



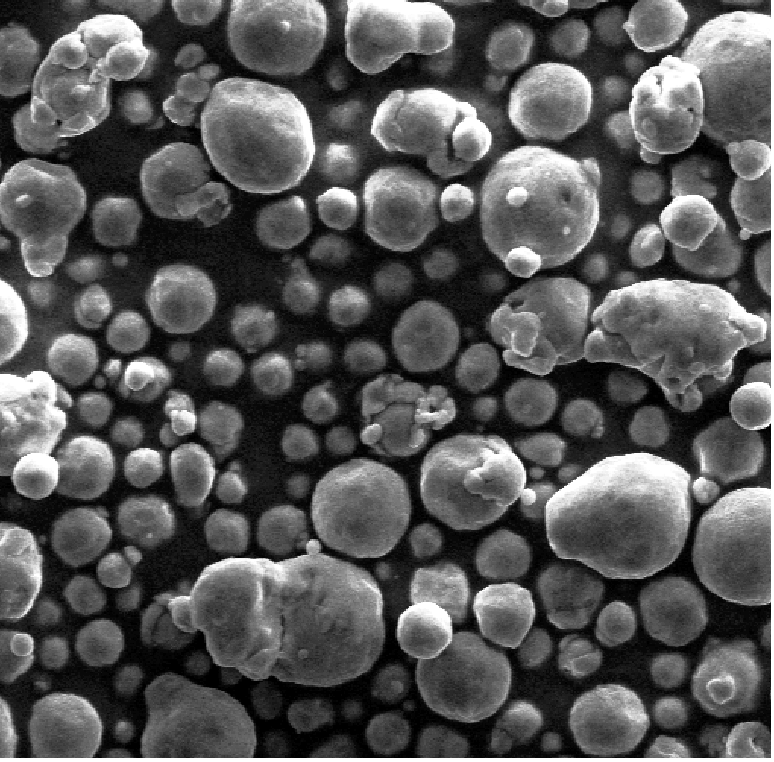
technology, there are currently no suitable materials commercially available. At Fraunhofer EMI, we thus develop our own manufacturing parameters for the processing of special materials. The defense sector of armor and effect is a particular focus in this development.

Additively manufactured high quality heavy metals

At EMI, parameters for the manufacturing of high quality tungsten have been developed. Tungsten is characterized by its high density and the highest melting point of all metals. The manufacturing of refractory metals such as tungsten shows that with the LBM method, even metals that are difficult to machine with conventional methods can be processed, even though they are considered to be difficult to weld and the LBM method basically resembles a laser welding process. During the parameter development for tungsten, the EMI scientists were faced with special challenges. Due to the high local energy application and resulting rapid cooling rates during the processing of the material by a laser beam, cracking occurs in the microstructure. The formation of micro cracks was successfully minimized during the studies. The result is a brittle material with a density of approximately 19.2 grams per cubic centimeter, an additively manufactured, pure tungsten with strongly reduced micro cracks and optimized density. This material can for example be used for ammunition or special applications such as collimators for X-ray detectors. Further fields of application are electrical engineering, medical engineering, and domains with extreme thermal requirements.

Efficient parameter development and optimization with in-house methodology

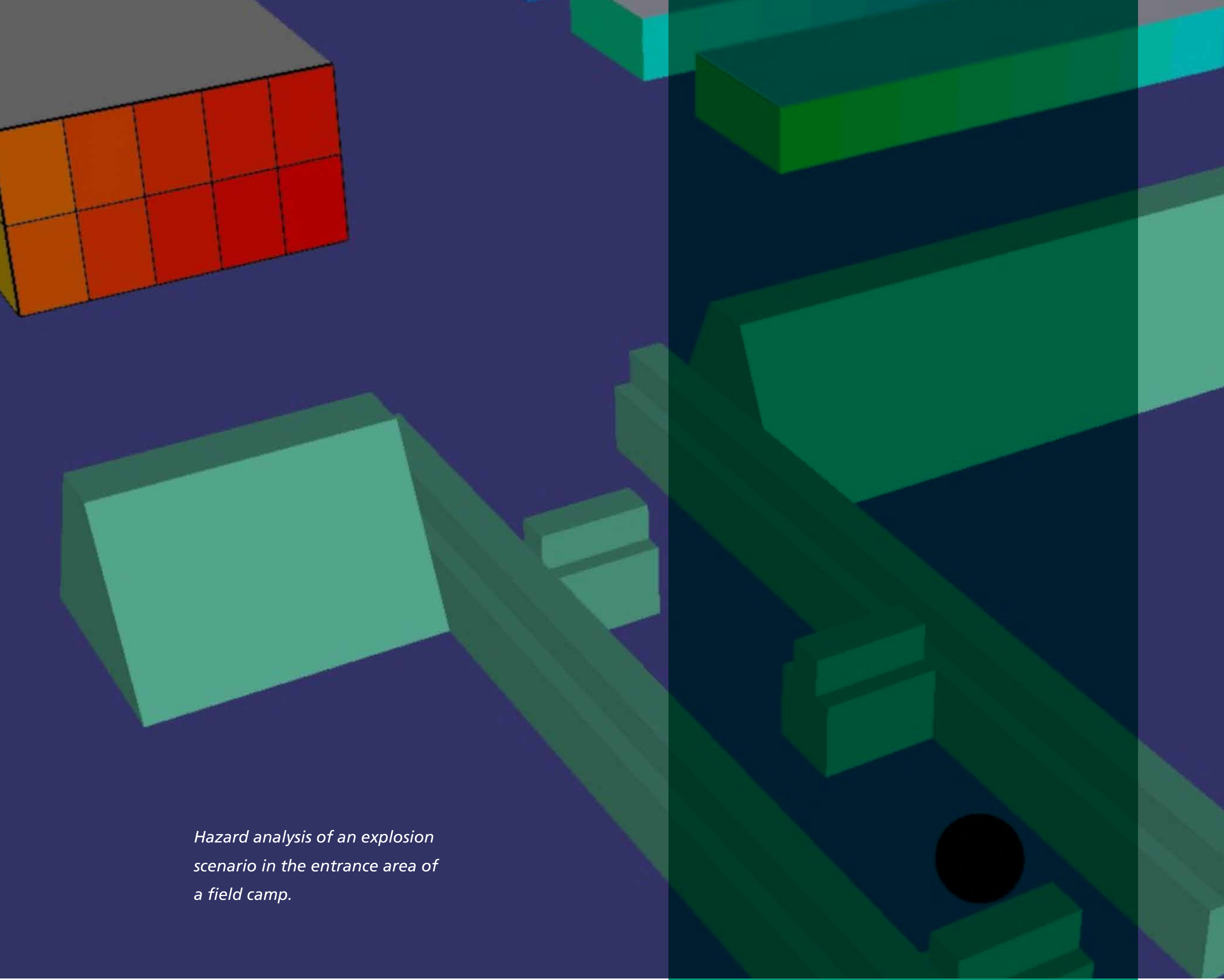
For the development of parameter sets, an efficient in-house solution is used, which allows a comparably fast and simple development of the process parameters. This way, particularly expensive special materials can be generated more cost-effectively. The method is based on the observation of the interaction between the laser beam and the metal powder as well as on a statistical experimental design. The obtained findings are later used for the application-specific parameter optimization and the parameter adaptation for specific structural components and their manufacturing requirements.



Investigation of the raw material powder with a scanning electron microscope.

For initial characterizations of the resulting materials, fast techniques, such as density determination, are applied. If the parameter set is well-developed, the material is characterized using the latest measuring technology (e.g. electron backscatter diffraction (EBSD) or micro CT imaging), and the parameters are further refined.

The use of an in-house methodology for parameter development for LBM materials allows the efficient generation of manufacturing parameters, and thus, the use of optimized materials for specific fields of application. We have shown that with this method, even materials that are difficult to process can be produced in high quality. It is conceivable that in the future, novel alloys can be elaborated that cannot be realized with conventional methods. For example, the high cool-down rate of the process might facilitate a higher solubility of alloy elements and, thus, new material properties. For the choice of future alloys, we do not only have to take into account the field of application but also the extended possibilities regarding the new freedom of design. Conventionally, requirements are for example met using geometries based on semi-finished products, (e.g. plates), whereas in additive methods, the solutions can be more efficient thanks to alternative geometries (e.g. lattice structures). A suitable material has to be chosen based on the new geometry.



Hazard analysis of an explosion scenario in the entrance area of a field camp.

The launch of military operations in conflict areas commonly implies the consideration of complex safety and security issues for soldiers onsite. One of these issues is related to the assessment of explosive events in build-up areas and the corresponding potential consequences for structures and inhabitants of these structures. Typical problems that need to be resolved are the definition of safety ranges around an ammunition storage in field camps and the assessment of deliberated attacks with explosives in urban areas within the context of a military operation in urban terrain (MOUT).

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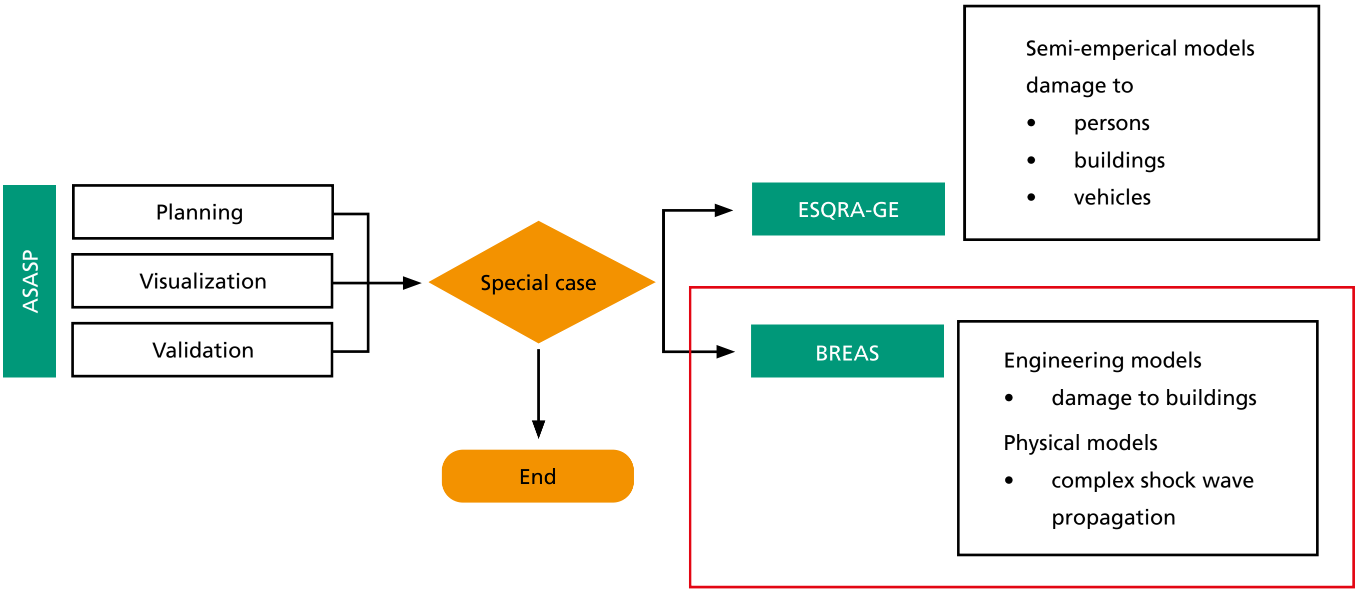
THE BREAS EXPERT SOFTWARE

BLAST RESPONSE ASSESSMENT OF STRUCTURES

The German Federal Armed Forces (Bundeswehr) are currently involved in several globally important deployments abroad. This requires the accommodation of personnel and the necessary infrastructure at the site of deployment. The storage of ammunition onsite constitutes a hazard within the accommodation infrastructure that is to be assessed. The provisioning of ammunition has the same hazard potential in basic operations of the Bundeswehr. In case of ammunition detonation, individuals or objects are considerably at risk. With its expertise and the development of software solutions, Fraunhofer EMI is part of a board for the assessment of ammunition storage safety. Besides EMI as scientific partner, Bundeswehr departments dealing with this topic are actively participating in this board, e.g. the Technical Center for Protective and Special Technologies (WTD 52), the Federal Office for Infrastructure, Environmental Protection and Public Service, the Bundeswehr Territorial Tasks Command and the Bundeswehr Logistics Command. Thanks to the successful long-term collaboration, the results of EMI's studies and the resulting tools have meanwhile been integrated in the Bundeswehr guideline for risk management in ammunition storage. In dependence of troop strength and current regulations, the demands and proper storage can be assessed with the EMI software ASASP (Ammunition Storage and Site Planning Tool). By comparing the simulations with the real spatial situation, it can be examined whether safety distances are complied with. When the safety distances are deceeded, the EMI tool ESQRA-GE (Explosives Safety Quantitative Risk Assessment Germany) allows the assessment of potential risks, thus offering decision support. Hazards resulting from fragments, debris and shock waves as well as their effects on persons, vehicles and buildings are assessed. Specifically, the expected building damage is merely examined with phenomenological models.

Thus, we were looking for a way to compute the component behavior under blast loading in a pragmatic yet precise manner. The software tool BREAS (Blast Response Assessment of Structures), which completes the Bundeswehr software tool portfolio in terms of ammunition safety, is the result of this research project. BREAS is an expert software developed at EMI that serves the detailed damage assessment of building structures under blast loading. In contrast to the majority of finite element methods, BREAS allows a fast and simple assessment of the behavior of structural components under highly dynamic loading. Arbitrary building configurations can be considered and visualized on a graphical interface. The absolute loading capacity is analyzed, and a damage assessment of the infrastructure is carried out using a color scale. The basis of assessment is an engineering model at plane loading assumption, where the critical structure deflection during blast loading is computed and



Software tools developed at Fraunhofer EMI (green) and their possible applications.

visualized. Single buildings or building clusters can be analyzed in detail. The user is guided through the configuration and positioning by a three-dimensional graphical interface. For an efficient damage analysis, buildings as well as containers are broken down into their elements and assessed individually. For the container types, these attributes are set by default, whereas the buildings can be configured freely. Thus, even longer façade sides can be examined.

In addition to typical elements found at deployment sites, such as containers and buildings, safety measures by crossbeams and barriers with bulk material or structural reinforcements are also taken into account. Setup and type of the crossbeams and barriers are based on common variables as listed in the guideline for safe storage of ammunition. The calculation of factors that mitigate the detonation effects forms the basis for taking into account the protective effects of crossbeams or barriers with bulk material. Furthermore, the correlation with cost factors facilitates the assessment of the efficiency of various protective measures. Two different methods are employed to assess the hazard potential: with semi-empirical assumptions, the loading of structural components or buildings can be calculated via the quantity of hazardous substance and the distance. Via a finite volume scheme, an interface to the APOLLO Blast-Simulator software allows the consideration of focusing and shading effects that occur during complex blast wave propagation scenarios in densely built urban environments. Besides the evaluation of potential damage of ammunition storage, the BREAS software can be used in explosive ordnance clearance in order to assess potential hazards and to offer decision support for explosive ordnance disposal teams.

BREAS is an EMI-developed expert software for damage assessment of building structures during detonation events.

Investigation of the structural behavior of a protective barrier system in a detonation test (near-field detonation event).

LOADING CAPACITY AND FUNCTIONALITY OF PROTECTIVE BARRIERS

For the enclosure of protective zones, simple but effective solutions are needed that protect individuals and material against extreme events, e.g. detonations. Basket systems, which can be filled with soil available on-site, are often used in this context. In this manner, a barrier, which provides the required protection through its large mass, can be built fast and with only little logistic effort.

Fraunhofer EMI investigates the structural behavior and the functionality of such barrier systems with experimental and numerical methods. Furthermore, analytical approaches are employed for the calculation. Since the loading capacity primarily depends on the soil mechanical properties of the used filling material, the analysis comprises the laboratory experiments required in this context.

The gained knowledge can be further employed in the future, for example to develop comparable barriers for non-military purposes, which take the different requirements of civil applications into account.

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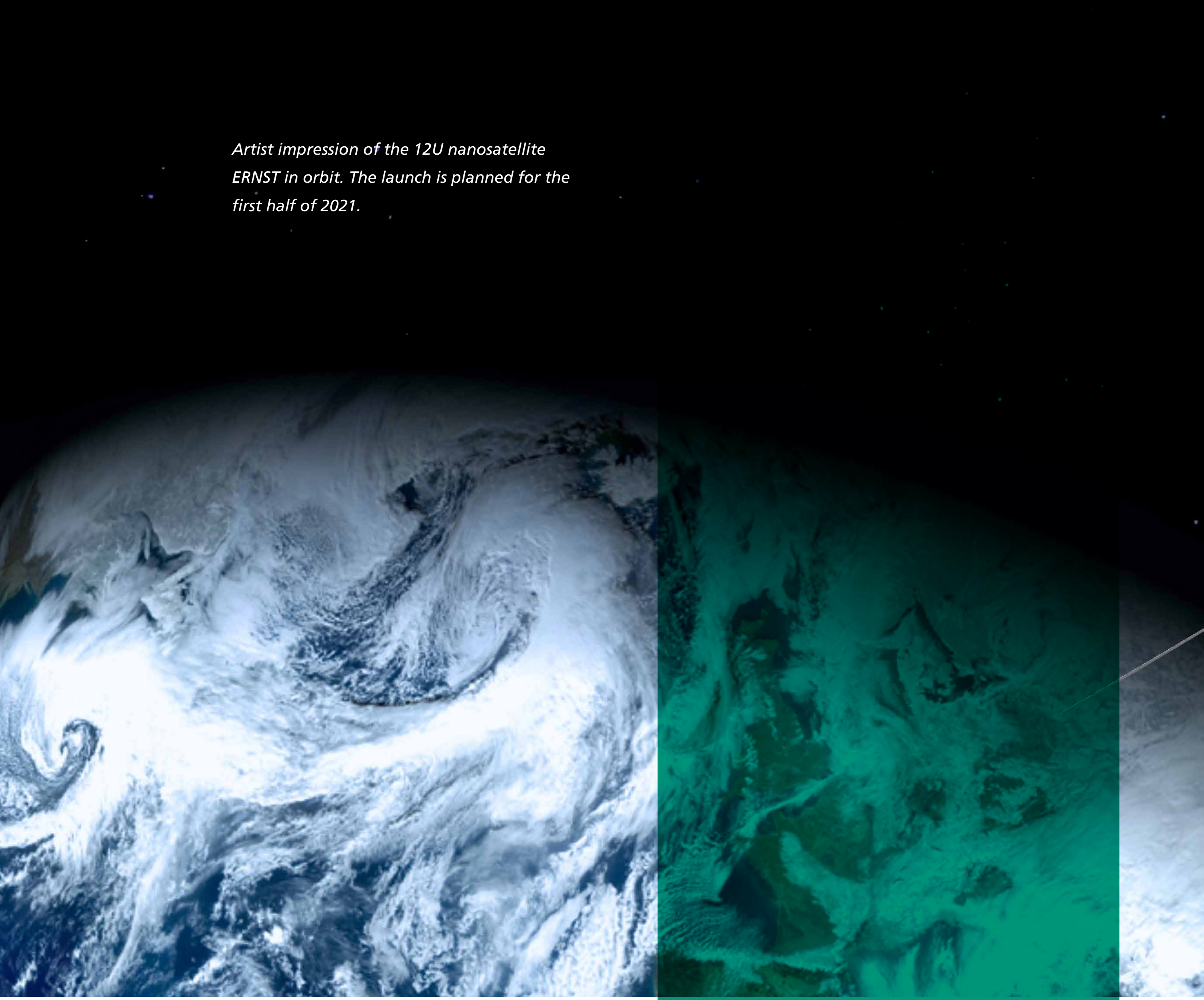

Artist impression of the 12U nanosatellite ERNST in orbit. The launch is planned for the first half of 2021.

The space sector is currently undergoing great changes by the new space business. Large constellations of small satellites produced in series, backed by considerable venture capital, are being developed. Fraunhofer EMI develops the nanosatellite ERNST to demonstrate the potential of small satellites for military purposes.

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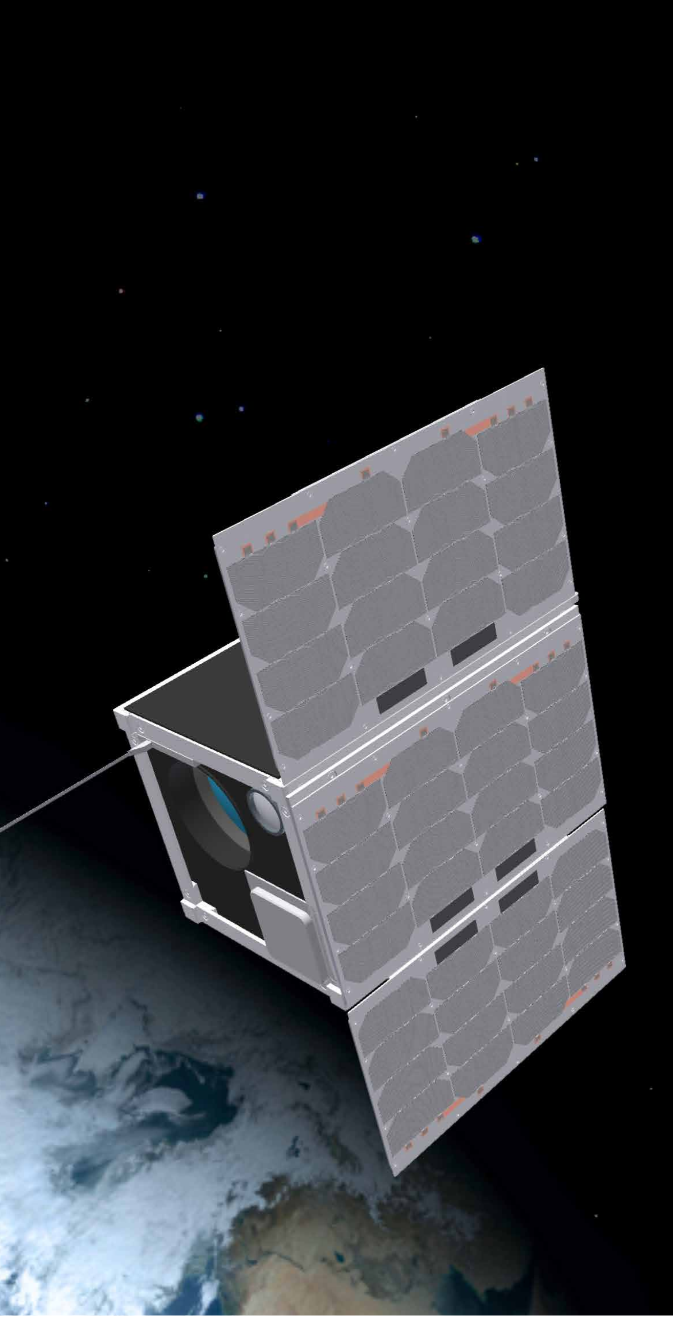


Mars image taken from MarCO-B, a JPL-built 6U nanosatellite with 13.5 kg mass. Two of these CubeSats have been successfully used for relaying the radio link of the InSight spacecraft after landing on Mars surface. © NASA

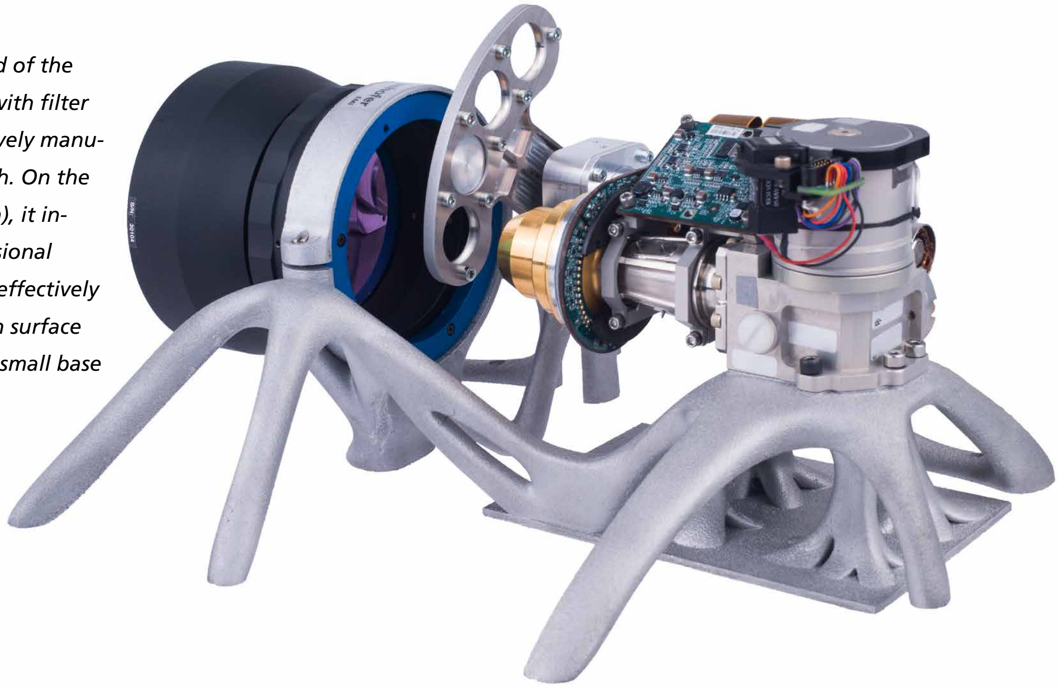
NANOSATELLITES FOR MILITARY PURPOSES

New competitors attracted substantial venture capital investments to create a new space industry. Their promise is to establish new space technology for faster and cheaper access to space apart from governmental agencies and large system integrators. The new space technologies include launchers, services and constellations of small satellites. We define a small satellite, or smallsat, as a spacecraft having a mass below 100 kilograms. Far from being a new invention, smallsats have been developed since the beginnings of the space era, mostly by radio amateurs, universities and research institutes. A smallsat characteristic is a rideshare launch that uses free mass capacities of a primary spacecraft. However, this drawback is changing as new dedicated launch systems are being developed and multiple smallsats can be launched in a dedicated launch to build up a constellation.

The first commercial smallsat constellation in orbit is Planet Labs's earth observation constellation of 150 active 3U CubeSats. A CubeSat is a nanosatellite consisting of one or multiple cube units ("U") with 10 centimeters side length and a maximum mass of 1.3 kilograms. This standard was defined in 1999 and laid the foundation for an unexpected boom of this satellite class with more than 1000 CubeSats launched until the end of 2018. NASA demonstrated the technological potential of these smallsats through their Mars mission InSight, which involved two interplanetary 6U CubeSats.

The smallsat industry at the infliction point to commercial use leads us to the question how the military sector can benefit from the technology development and how smallsat technology can be utilized for military applications. In contrast to the obvious drawback of the performance being limited by the small size, the essential advantage are low costs and short development times. Nanosatellites allow for a cost-effective and quick assembly, integration and verification programs. The timely, low-risk verification allows for the involvement of commercial off-the-shelf components and the implementation of latest technology advances. Going back to the Planet Labs example, the commercial nanosatellite constellation provides a daily coverage with 3 m to 5 m ground resolution. The latter may be one order of magnitude below the data of high-performance earth observation satellites, but the low data latency through the

Infrared main payload of the nanosatellite ERNST with filter pendulum and additively manufactured optical bench. On the underside (not shown), it includes a three-dimensional radiator surface that effectively increases the emission surface area while keeping a small base area.



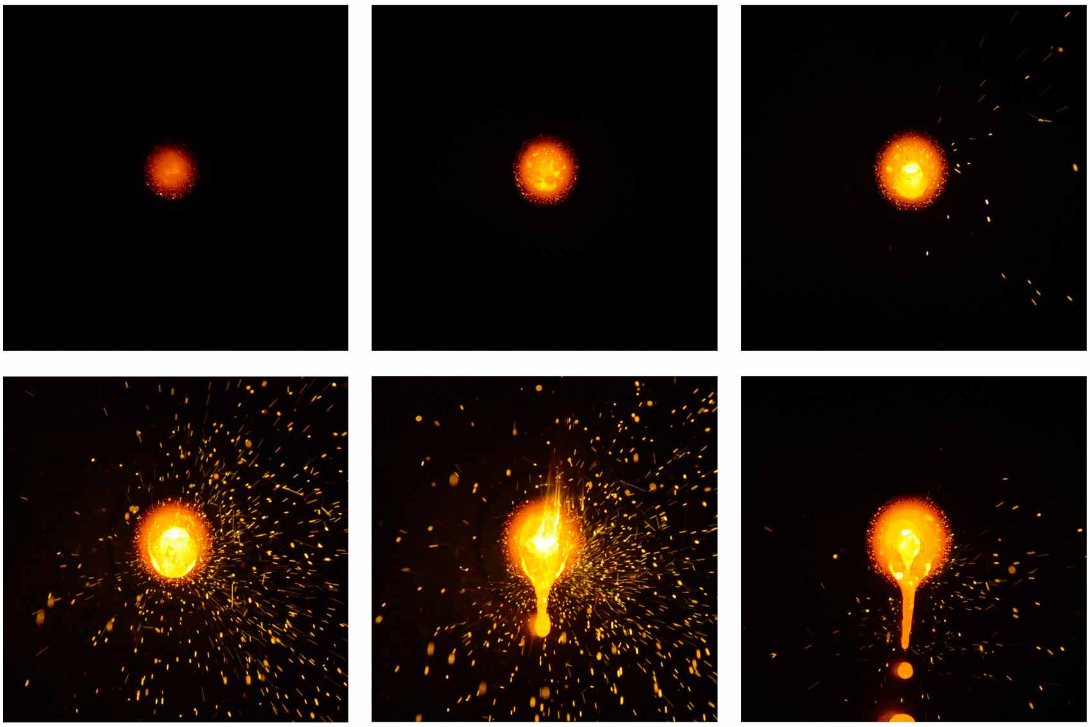
global coverage is unrivalled. The maximum benefit can be derived from a combination of both space systems, smallsat constellations and individual high-performance platforms. An object can be tracked globally through the high temporal resolution of a constellation and precisely identified through a large satellite with higher spatial resolution. Another advantage of a smallsat constellation is its system redundancy that hinders blinding, manipulation or even warfare in space.

Fraunhofer EMI develops the nanosatellite ERNST to demonstrate the military utility of smallsats for the German armed forces. It is a modular 12U-CubeSat platform having a volume of 236 × 236 × 340 cubic millimeters. For its demonstration mission, it carries the following payloads: 1) a cryo-cooled infrared detector for rocket-motor detection in cooperation with the Fraunhofer IOSB, 2) a camera for earth observation in the visible range, and 3) a Fraunhofer-INT-built detector for monitoring the radiation environment in orbit. The technology highlights are an additively manufactured optical bench and a de-orbit drag sail. The optical bench includes a 3D-structured radiator surface as functional element to emit the heat dissipated by the main payload. The drag sail is deployed at the end of mission in order to increase the atmospheric drag for fast de-orbit, thus sustaining an orbit environment free of space debris. The launch for its demonstration mission is planned for the first half of 2021.

SCALING OF LASER EFFECTS

Efficient high-energy lasers have been established tools in industry, research and development for a long time. In addition to their application for material processing and additive manufacturing, Fraunhofer EMI is also examining novel applications in the fields of security and defense research. These research activities take advantage of the laser's property to transmit energy in form of a highly directed beam even over long distances.

Whereas many techniques of material processing are carried out with a laser power in the order of a few kilowatts, there are also high-performance systems with a laser power of more than 100 kilowatts commercially available. In order to be able to assess the potential of such laser systems, EMI carries out studies regarding the scaling properties of high-power laser effects. For this purpose, experimental as well as numerical and analytical approaches are used, which investigate for example non-linear effects occurring in the interaction of intense laser beams with matter. These studies allow the classification of the potential of the next generation of laser systems for future applications.



Behavior of a metallic sample during fast heating using intense laser radiation.

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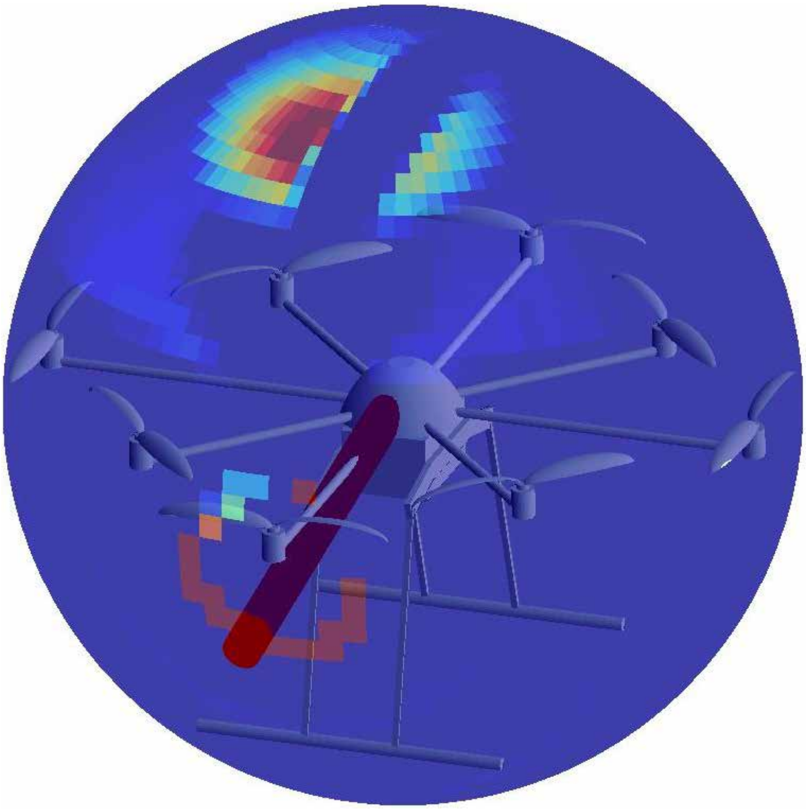
LSQRA
LASER SAFETY QUANTITATIVE RISK ANALYSIS

High-power lasers are characterized by their capability to direct energy at an object over long distances with high precision and have rendered possible a broad range of material processing applications such as e.g. welding and cutting. Currently, high-power lasers are gaining importance in defense applications as well. For several years, high-power lasers have been used by armed forces of several nations for the neutralization of explosive devices at a safe distance without the need for individuals to be in the immediate vicinity of the explosive device. National studies also consider high-power lasers for the defense against drones (UAVs, Unmanned Aerial Vehicles).

For an application of high-power lasers in such scenarios, it is necessary to analyze in detail the laser propagation and to identify potential threats by laser radiation. For this purpose, Fraunhofer EMI develops the safety analysis tool LSQRA (Laser Safety Quantitative Risk Analysis) for 3D-visualization of simulated operational scenarios with laser effectors.

In addition, Fraunhofer EMI's high-energy laser lab offers the possibility to develop physical models for the melting and reflection behavior of samples during the interaction with laser radiation. For a detailed analysis of the propagation of the laser radiation, specific aerosol models for the calculation of absorption and scattering in the atmosphere and the influence of atmospheric turbulences can be taken into account. For the analysis of these influencing factors, a close exchange is taking place among national research institutes and working groups.



Modeling of reflection effects of a laser beam directed onto an Unmanned Aerial Vehicle (UAV) within the safety analysis tool.

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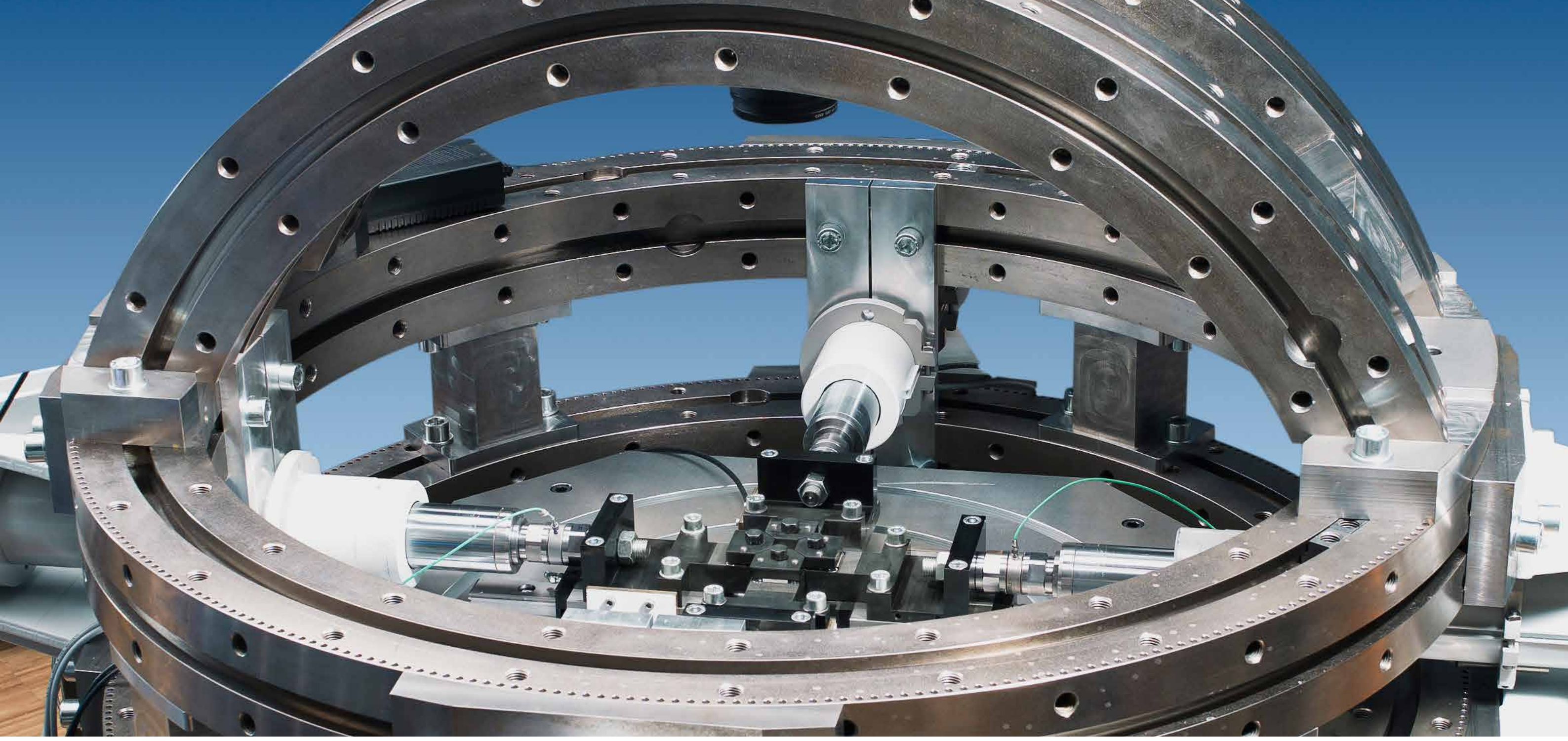

The multi-axial test bench allows testing under a multitude of loading combinations.

HIGH-STRENGTH STEEL UNDER MULTIAXIAL LOADING

The deformation and failure behavior of a material is experimentally often studied on simple loading cases. To do so, uniaxial tensile and compressive tests are for example conducted. In reality however, materials often fail under complex, multiaxial loading. High-strength steels are used in order to protect passengers from gunfire. During impact of a projectile, complex loading conditions, such as tensile and compressive loads but also bending and shear stresses, occur, e.g. depending on the angle of impact. In addition to that, such an event is a highly dynamic process, which can also be characterized by a significant local increase in temperature.

At EMI, material tests are carried out with a special multiaxial test bench in order to reproduce such loads in the laboratory. Thus, specimens made from a range of materials, from steel to textile fabric, can be exposed to various loading combinations using up to six actuators that can be moved separately. The loading rate can be varied between quasistatic and dynamic in a practice-oriented manner. A database is thus experimentally created to be able to exactly simulate specific loading scenarios by means of numerical methods. The aim is the predictable modelling of deformation and failure behavior in dependence on stress multiaxiality, strain rate and prior damage. High-strength steels thus become predictable regarding extreme application conditions and threat scenarios.

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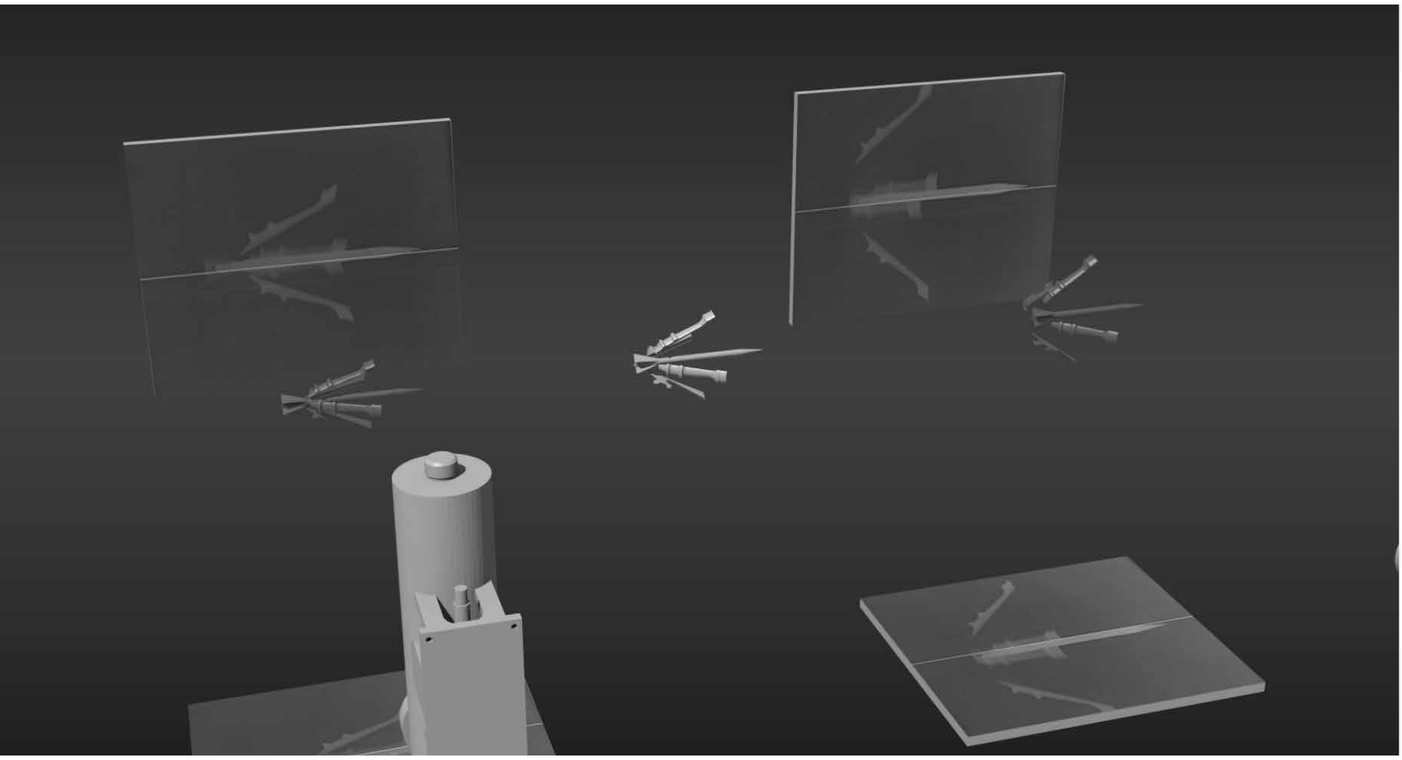
3D X-RAY ANALYSIS OF SABOT SEPARATION

For the investigation of transitional ballistics of sub-caliber projectiles, an innovative, X-ray-based measurement technique was developed which opens up new possibilities of examination. The sabot separation after leaving the muzzle is of major importance for accuracy. Since, especially near the muzzle, the exhausting propellant gases hamper or obstruct the optical access, flash X-ray technology was chosen. Two orthogonal radiographs are taken at several different distances to the muzzle. Thanks to the use of feature-based registration methods, the spatial position and orientation of the individual parts can be determined. Since these data are only available at few discrete points in time or distances, respectively, the intermediate steps have to be calculated through model-based interpolation. To this end, methods from the fields of data fusion and data assimilation are employed. The new measurement method allows advanced evaluations and very detailed insights into the dynamic processes.



Dynamics of sabot separation of a model projectile.

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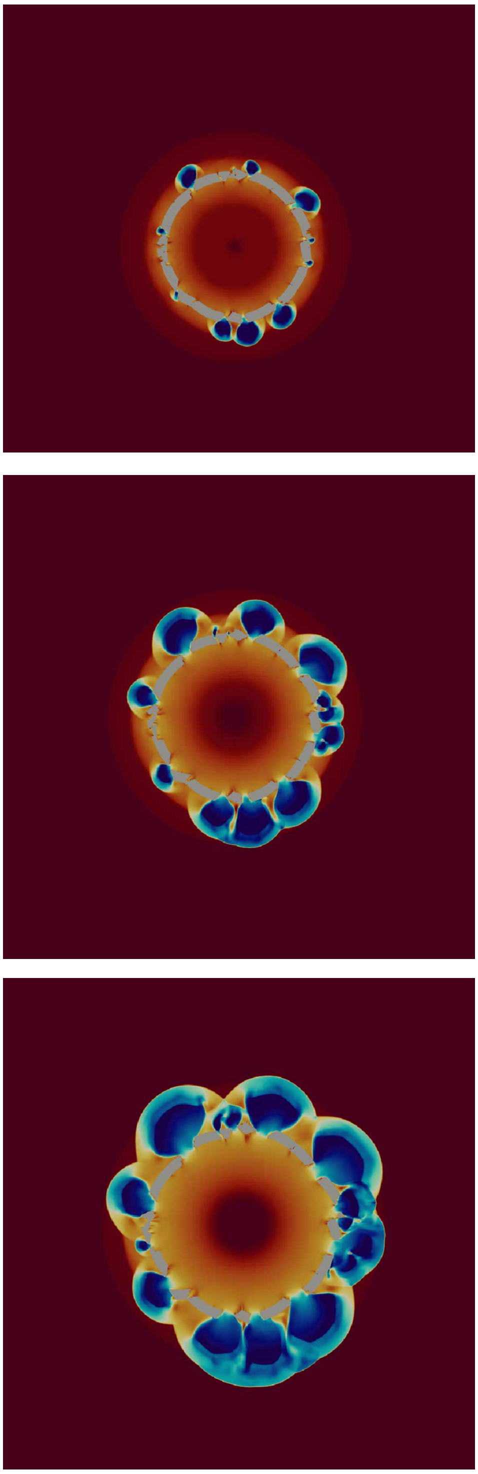
CO-SIMULATION FOR FLUID-STRUCTURE COUPLING

Co-simulation is a computational approach that enables the simulation of a system through parallel and coupled simulation of its parts. At Fraunhofer EMI, simulation methods are developed which permit the co-simulation of fluid structure coupled systems.

These methods are particularly suited for the analysis of explosively loaded engineering structures. This analysis goes beyond the verification that a structure can safely sustain the loading. It shall also cover the opposite case: the dynamic behavior of the failing structure has to be evaluated if the limits of the load bearing capacity is exceeded. In this case, the number, sizes and velocities of generated fragments must be analyzed to provide a quantitative assessment of hazards.

Suitable physical models are the basis for a successful application of our simulation methods in day-to-day research as well as efficient numerical methods and implementation into practice-oriented software tools. For this reason, we are continuously improving our software products: the APOLLO Blast Simulator for the fluid dynamics of explosion processes and the finite element code SOPHIA for structures under dynamic loading conditions.

Both codes have been extended by a universal interface for the co-simulation of fluid structure coupled systems. This way, new perspectives for the simulation-based analysis of complex physical interactions are gained.



The image series shows the simulated fragmentation of a thick-walled ring structure under internal pressure and the supersonic outflow of the high-pressure gas through the generated cracks.

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MECHANICAL MATERIAL MODELS FOR POLYMER-BONDED HIGH EXPLOSIVES

Modern ammunitions are usually based on polymer-bonded high explosives (PBX). These explosives are heterogeneous materials whose actual reactive components (such as octogen or hexogen crystals) are embedded in a polymer matrix. This composition determines the special mechanical properties of PBX. Crystals are characterized by high stiffness and brittleness, while the polymer matrix shows a typical viscoelastic behavior. Furthermore, the bonding of the matrix to the crystals plays a decisive role regarding the mechanical behavior and possible reaction mechanisms under dynamic loading.

Fraunhofer EMI studies how these phenomena can be included in the material modeling of PBX. Currently, material models are used that combine viscoelastic behavior with crack formation processes, and thus are suitable for describing debonding phenomena between crystal and matrix. For the determination of the material parameters, Fraunhofer EMI has developed the corresponding experimental facilities. Besides a hydraulic press for the realization of high compressive loads, a split Hopkinson pressure bar for highly dynamic loads is employed. The derived material models are used for the evaluation of safety aspects during deployment and operation of ammunitions.

1 cm

PPX sample for material characterization.

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At Fraunhofer EMI, handguns, which consist of several subsystems, are analyzed.

SYSTEMS TECHNOLOGY ANALYSIS

Holistic consideration of the interaction of weapon, ammunition, and mounting parts

Handguns are usually made up of the subsystems weapon, ammunition and rifle scope, all of which are produced by different manufacturers. In combination, these subsystems have to fulfill the requirements imposed by the German Federal Armed Forces (Bundeswehr) in various environmental conditions.

An interdisciplinary approach is required in order to be able to fully apprehend new requirements on aspects of ballistics, functional safety, accuracy performance and the interaction between components, some of which have newly been combined with each other.

One focus of the research conducted in the Systems Technology Analysis Group is the development of methods that can be applied for the analysis and testing of weapon, ammunition, and attachment parts. Over the past few years, studies on gun barrel vibration, the inhomogeneous heating of the entire system, and on muzzle signature have been conducted. Findings from this research have been incorporated in the corresponding sets of regulations and have been used for the formulation of requirements for future Bundeswehr equipment.

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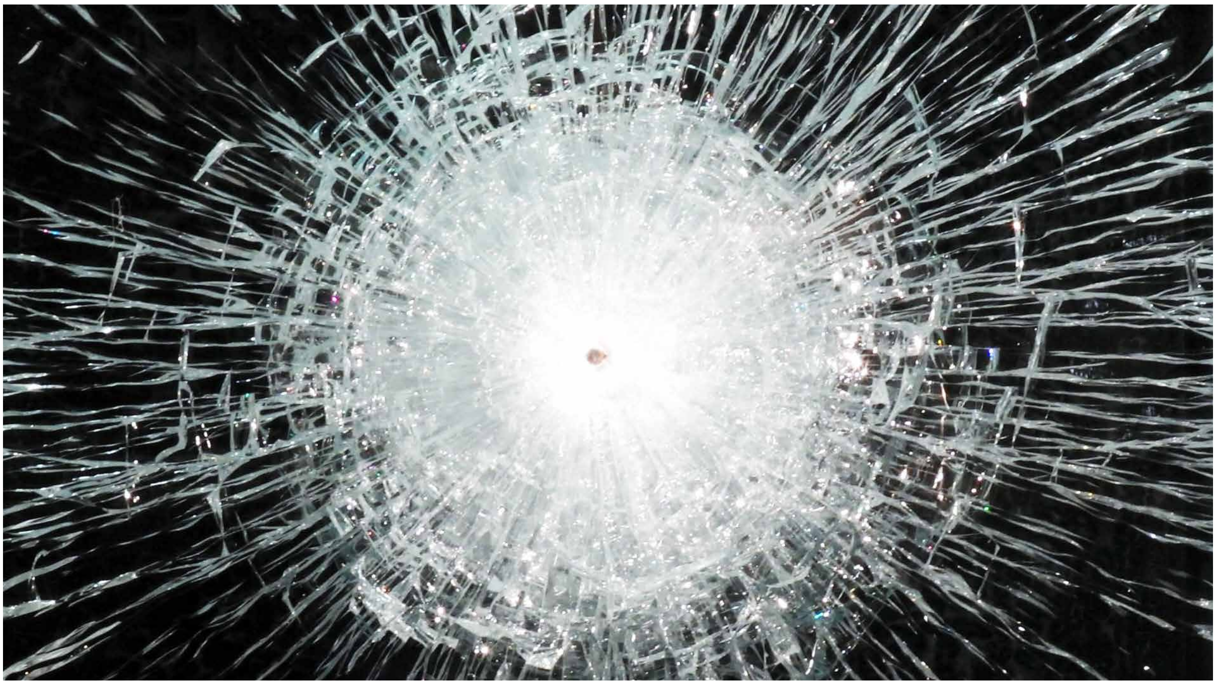
CHARACTERIZATION OF GLASSES USED AS TRANSPARENT PROTECTION

Bulletproof windows typically consist of several glass layers, which are bonded to a laminate using polymer interlayers. When a projectile impacts a glass layer, cracks, which propagate with velocities between 1500 meters per second to 2200 meters per second – depending on the type of glass – form immediately after impact. The strain waves that are generated during the impact of the projectile propagate with velocities between 5600 meters per second and 6500 meters per second and lead to additional damage of the glass. For this reason, the projectile always penetrates pre-damaged material.

In order to be able to describe the interaction between the pre-damaged glass and the projectile, Fraunhofer EMI develops methods to pre-load glass in a defined way using planar plate impact to detect and analyze the damage quantitatively via X-ray tomography, and to determine the strength properties. With these measurements, improved material models can be developed and the predictive power of simulations can be advanced, especially regarding the calculation of the remaining ballistic resistance after several impacts.



Glass laminate specimen after impact.

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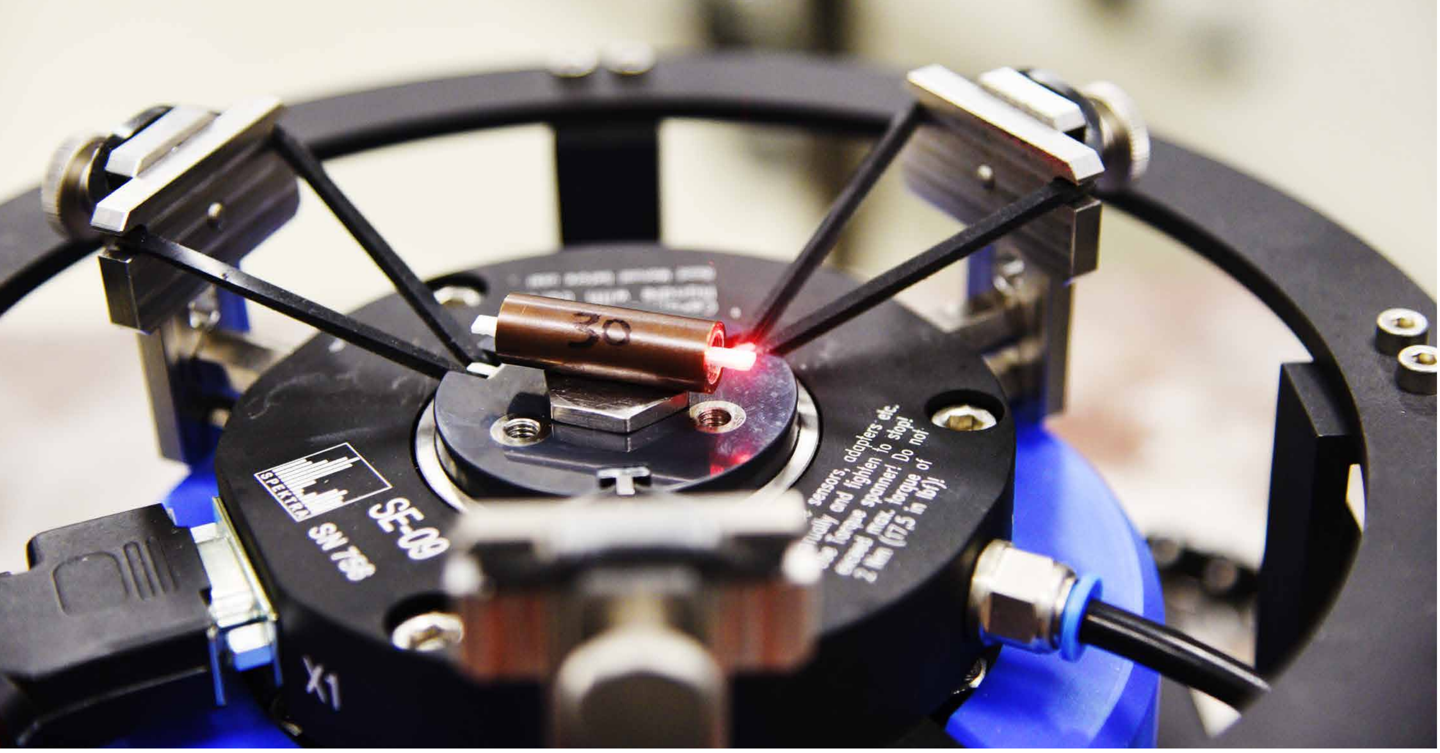

Sensor system on a shaker for determining the resonance.
Measurement of the displacement with laser vibrometer.

EHARSH

SENSOR SYSTEMS FOR HARSH ENVIRONMENTS

The aim of the Fraunhofer lighthouse project "eHarsh" is the development of a technology platform intended for the design and manufacturing of sensor systems for the application in extreme harsh environments. Eight Fraunhofer institutes with their respective expertise have joined forces in an interdisciplinary cooperation in order to offer a comprehensive solution that can be applied on a system level.

In the framework of the project, the involved institutes develop and advance a variety of assembly and interconnection technologies and joining processes, which have to sustain specified challenges such as a wide temperature range, shock loading, and vibration loading. Thus, it is an integral part of the project to test these assembly and interconnection technologies regarding their robustness under harsh environmental conditions. Here, the analysis of the sensor systems under combined loads is especially important since new error patterns can occur, which do not exist or are not so distinctive when the sensor systems are examined in isolated tests.

To this end, special test benches, e.g. for the combined testing under temperature and vibration loading, are set up. This allows analyzing simplified sensor systems for the early assessment of different assembly and interconnection technologies and to verify the functionality of the future demonstrator sensor systems.

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BUSINESS UNIT SECURITY

Security is a fundemental social need.

BUSINESS UNIT SECURITY

Security is a fundamental social need and is often defined as a state free of unacceptable risks. Due to the growing complexity of our society and the concomitant risks, it is an ongoing challenge to ensure security.

Not only the scientifically calculated risk plays a role, but also the perception of it: even though the security statistically increases continuously, a growing sense of insecurity can be observed. It is important to answer the question: How do people perceive security?

Furthermore, the need for security is expanded by the demand for resilience – the ability to recover quickly after unpredictable events. These issues set out completely new requirements, and it is important to assess their effectiveness and efficiency. The following contributions try to answer these important questions.

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Assessment and visualization of expected building damage caused by earthquakes.

Earthquakes create chaos and rubble. For fast and life-saving decisions, search and rescue teams need assistive technology to obtain a better situational awareness. Solutions from the INACHUS project support the faster coordination of rescue missions for the location and retrieval of trapped individuals.

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INACHUS

SUPPORT OF EMERGENCY FORCES IN THE CASE OF EARTHQUAKES

Earthquake events can quickly result in chaotic and unclear situations as well as adverse working conditions for search and rescue teams, as became apparent for example after the earthquake of L'Aquila in 2009. It is imperative to make instant decisions in order to localize potentially trapped individuals.

In the framework of the EU project I NACHUS (Technological and Methodological Solutions for Integrated Wide Area Situation Awareness and Survivor Localization to Support Search and Rescue Teams), a consortium of 20 partners has elaborated a concept that provides search and rescue crews with assistive technology for an improved wide-area situation awareness. The solutions increase the reaction speed regarding the detection and rescue of trapped victims using new sensors, simulation methods, and new possibilities of situation assessment. As the leader of one Work Package, Fraunhofer EMI has made an important contribution to the simulations. On two different scales, entire city quarters or single buildings were evaluated, and the following questions were answered:

- City quarter analysis: How does the rescue mission have to be prioritized?
- Building analysis: Where are cavities in collapsed buildings?

Detailed comparison between simulation (right) and real building damage.

For the evaluation of entire city quarters, the software VITRUV (Vulnerability Identification Tools for Resilience Enhancements of Urban Environments) was improved and used to efficiently characterize potential damage resulting from earthquake events. For this means, a functional correlation between seismic activity and expected structural damage was elaborated. The European macroseismic scale, use of real-time data, and semi-empirical models on magnitude and epicenter allow the assessment of soil acceleration at random positions in urban areas. In the next step, the expected damage can be assessed with an engineering model. This method was applied for a variety of different types of construction in order to evaluate an urban area. Furthermore, a method was developed that allows estimating the number of individuals present in a building depending on the use of the building, day of the week, and time of day. For example, more people will be inside residential buildings than in school or office buildings on a Sunday morning. This information can be combined with the predicted damage in order to identify vulnerabilities and to provide decision support for prioritization during a rescue mission.

INACHUS
Technological & Methodological Solutions for Integrated Wide Area Situation Awareness & Survivor Localization to Support Search & Rescue Teams

The research leading to these results has received funding from the European Commission's 7th Framework Program within the EU project INACHUS under grant agreement no. 607522. The authors would like to thank all partners within INACHUS for their cooperation and valuable contribution.

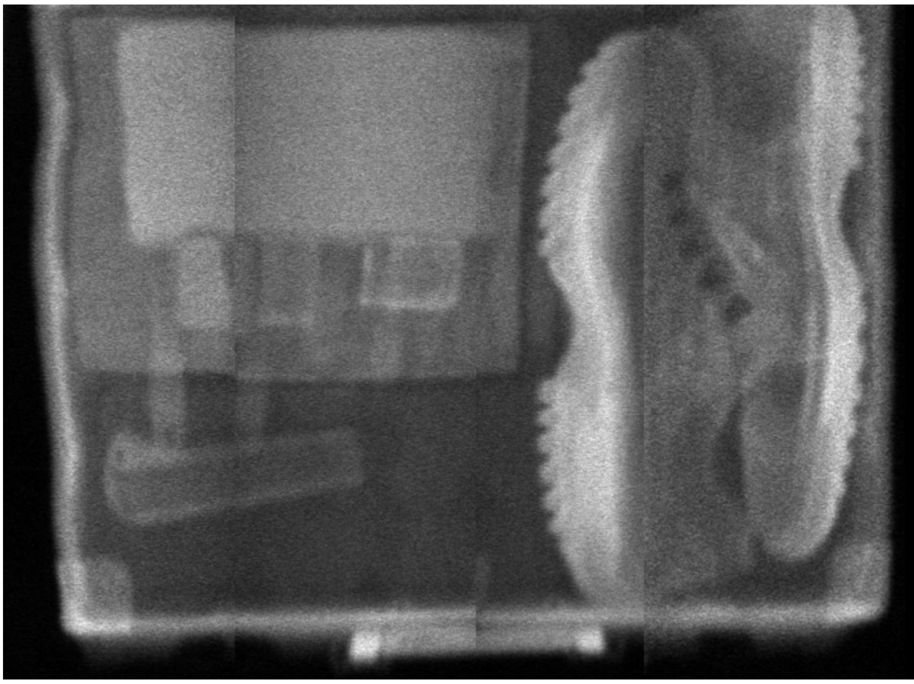
AN ABANDONED SUITCASE

FORGETFULNESS OR INTENT? THE DAILY LIFE OF A BOMB DISPOSAL OPERATOR

Bomb disposal squads face a challenging task: Every day, they have to decide very quickly whether a suspicious object is dangerous or not. To do so, robots are important devices. The bilateral project DURCHBLICK, which is coordinated by Fraunhofer EMI and funded by the German Federal Ministry of Education and Research (BMBF), wants to make this procedure safer by supplying robots with new detection technologies. Since the suspicious object should not be moved, it is important that the examination methods are contactless. For this reason, the German and Austrian project partners focus on such technologies. One of these is the X-ray backscatter technology, with which it is possible to look inside an object that is only accessible from one side. This is important if the object is placed in a corner or in a locker, and no X-ray detector can be positioned behind it as is needed for classical X-ray imaging methods. The localization and identification of radioactive sources from a distance as well as the optical tracking of the environment are also in the focus of research. For all possible technical solutions, the ethical and legal situation as well as the consequences for the bomb disposal squad and the public are considered. Besides the coordination of the entire project, EMI's research focus is on X-ray backscatter technology, data fusion and data editing of all obtained information. The aim is to provide this information to the bomb squad in a manner that is quickly and unambiguously interpretable even under considerable stress.

More information on DURCHBLICK and the partner project in Austria can be found at *www.durchblick-projekt.de*

Image of a toolbox with a simili of an improvised explosive device (IED).



X-ray backscatter image of the toolbox.

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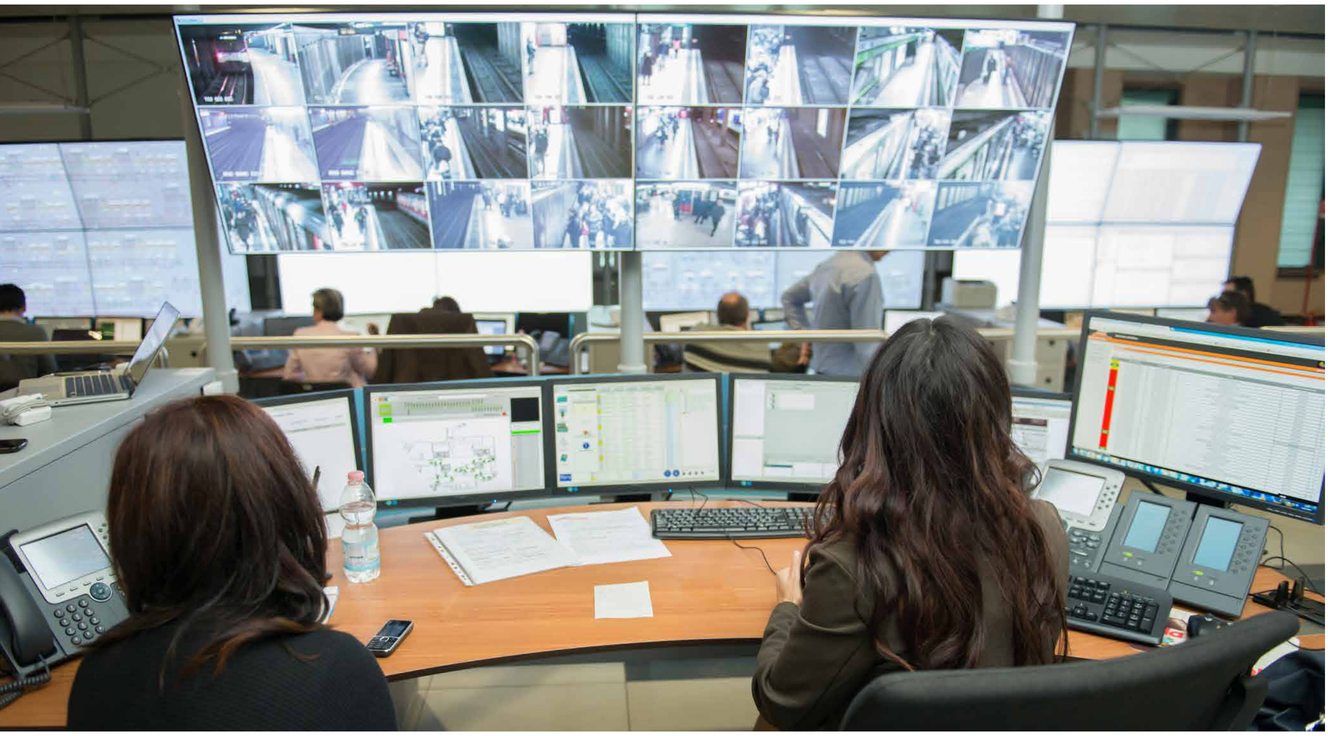
PROMPT

TIME IS LIFE

In the case of major catastrophic events, to have more time means a higher chance for the victims to survive. At such catastrophic events, rescue operations are coordinated by integrated control centers that collect and provide information. For efficient coordination, a holistic overview of the situation is required. To this end, various sources of information have to be considered and classified.

The PROMPT project (Programmatic Selection of Immediate Action for the Scheduling of Operations during Major Catastrophic Events) pursues the task of developing a system for comprehensive assessment of the situation that decreases the time between the occurrence of a catastrophic event and the initiation of directed rescue operations. Based on an integrated fuzzy logic interference system, vague messages, such as "many casualties", are translated into interpretable and quantifiable information. The system combines all incoming, fuzzy and discrete information from all sources. Based on a set of rules, PROMPT identifies interrelated single events, from which useful proposals for action are generated. As an operation support system, PROMPT contributes to the main goal of rescue and relief organizations: saving lives.



During major catastrophic events, control centers function as nodes for the coordination of information. In the PROMPT project, this process is accelerated.
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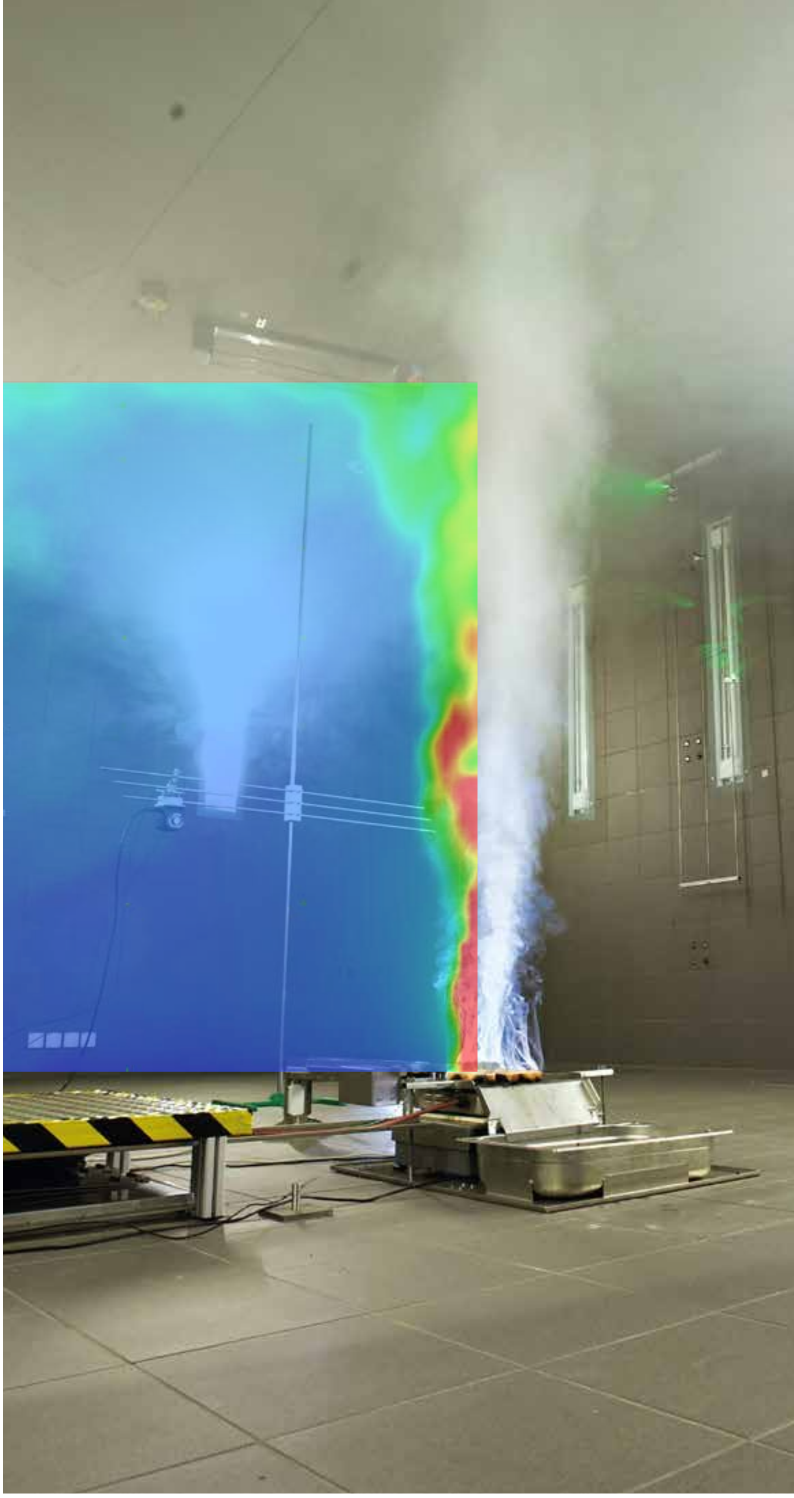
GAS-O-CHROM

COMBUSTION GAS DETECTION AT AN EARLY STAGE

To detect fires at an early stage and raise alarm can save lives and prevent substantial material damage. Especially at the early stage of a fire, even before the development of smoke, typical combustion gases are emitted. The joint research project GAS-O-CHROM, which is funded by the German Federal Ministry of Education and Research (BMBF), addresses this problem: A consortium of partners from industry and research is developing a warning system for the detection of these combustion gases. To this end, research on special sensors, which change color upon contact with specific combustion gases, is also conducted. The detection of the color change is then employed to initiate the alarm.

Besides real fire experiments for testing the sensors, numerical methods are used in the project. In this context, Fraunhofer EMI is working on the modeling of the combustion gas release and the simulation of its propagation. For example, we investigate the influence of the interior design and ventilation on combustion gas propagation. The aim is to obtain generalized propositions regarding the temporal and spatial progression of the combustion gas concentrations in order to find optimized positions for fire detectors.



Smoldering beechwood fire in the fire lab with superposition of a fire dynamics simulator (FDS) simulation. © Hekatron Brandschutz

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URBAN SECURITY 3D

In the project Urban Security 3D, the main focus is on the assessment and improvement of the subjective sense of security among urban dwellers. Structural and spatial factors which influence the subjective perception of safety in urban environments are identified and operationalized. Emphasis is placed on the identification of places that are perceived as dark, out of sight and out of hearing range.

Based on experience from best practice examples and on-site measurements, the identified elements are incorporated into the algorithms that serve as the core of a software-based planning tool. The software can then be applied to existing three-dimensional city models and thus allows an improved security assessment.

For the first time, a software tool that is based on numerical modelling is developed with which security assessments can be made systematically and empirically. The tool helps city planners and security experts to create more security in urban environments and can be used in participative decision processes.

A new software helps to evaluate how safe individuals feel in cities.
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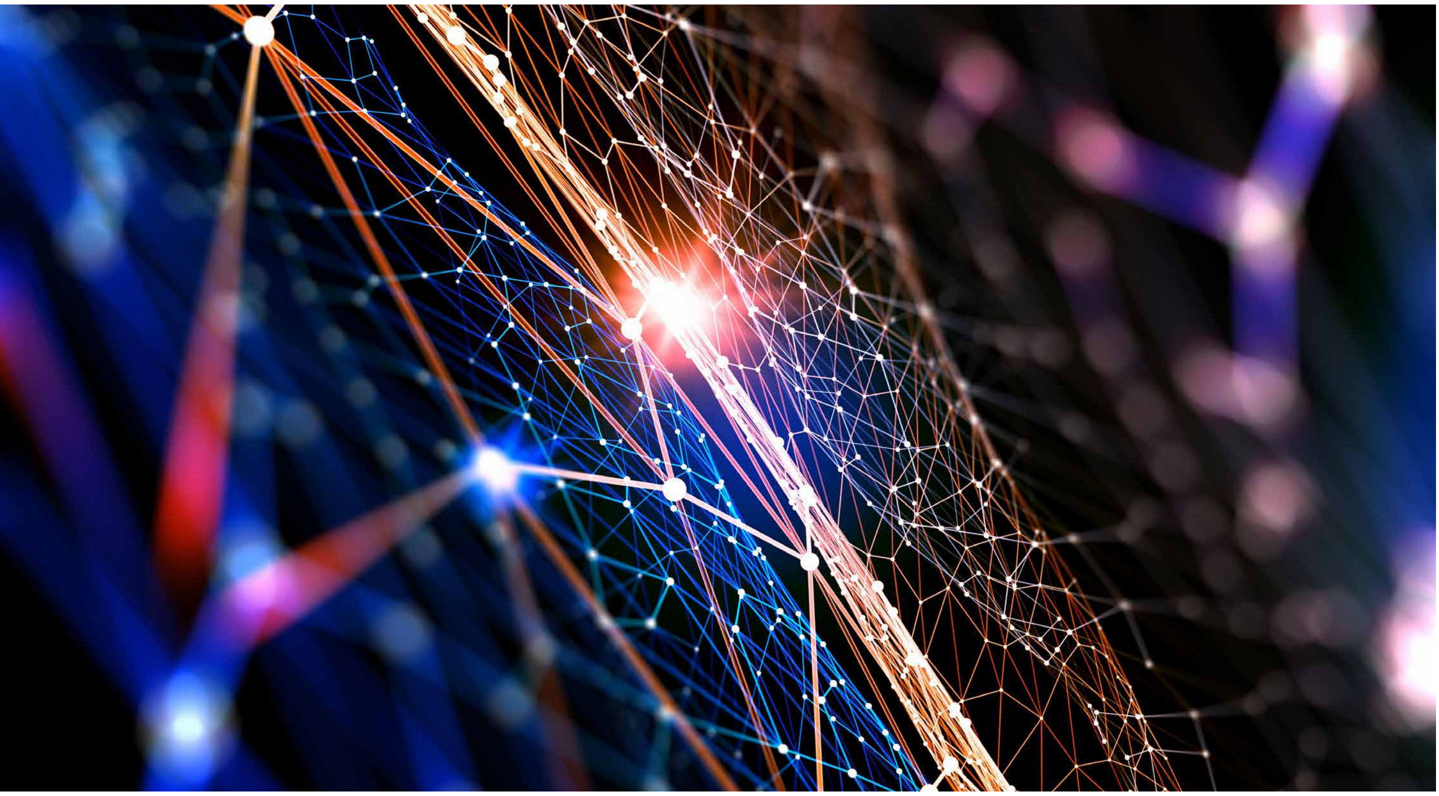
RESISTO
RESILIENT COMMUNICATION

The reliable and secure operation of telecommunication networks, specifically within the context "internet of things" and the evolution of 4G/LTE networks to 5G networks, plays a decisive role for economy and society.

In the framework of the EU project RESISTO (Resilience Enhancement and Risk Control Platform for Communication Infrastructure Operators), physical attacks, cyber-attacks and combined cyber-physical attacks and threats to current 4G/LTE networks and future 5G communication networks are studied.

Methods and applications for decision support for network operators are combined in a user interface with the main goal of attaining a significant improvement of resilience in telecommunication infrastructures. An extended risk and resilience management process based on the ISO-31000 standard for risk management plays a central role. With this process, critical risks and potential countermeasures are identified. The resilience of the infrastructure and its improvement by any countermeasures are quantified based on dedicated network simulations, allowing for a qualified risk and resilience evaluation.



The aim of the RESISTO project is the improved resilience of telecommunication infrastructures. © AdobeStock

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BUSINESS UNIT AUTOMOTIVE

Crash using X-ray car-crash (X-CC) technology.

BUSINESS UNIT AUTOMOTIVE

Mobility is an essential characteristic of modern society. Crash safety is a decisive requirement for the approval and acceptance of new generations of vehicles. However, new technological trends such as electric mobility and autonomous driving, the constant tightening of approval criteria and ratings, and the continuous shortening of development cycles result in steadily increasing safety requirements for vehicles. In order to fulfill these requirements, it is important to intensify the digitalization and virtualization of the integrated design via simulation and experiment. For this, a precise understanding of both the behavior of materials and components as well as of the passenger kinematics is essential.

In the business unit Automotive, these challenges are addressed through novel approaches, such as in-situ high-speed X-ray diagnostics and the evolution of numerical human models.

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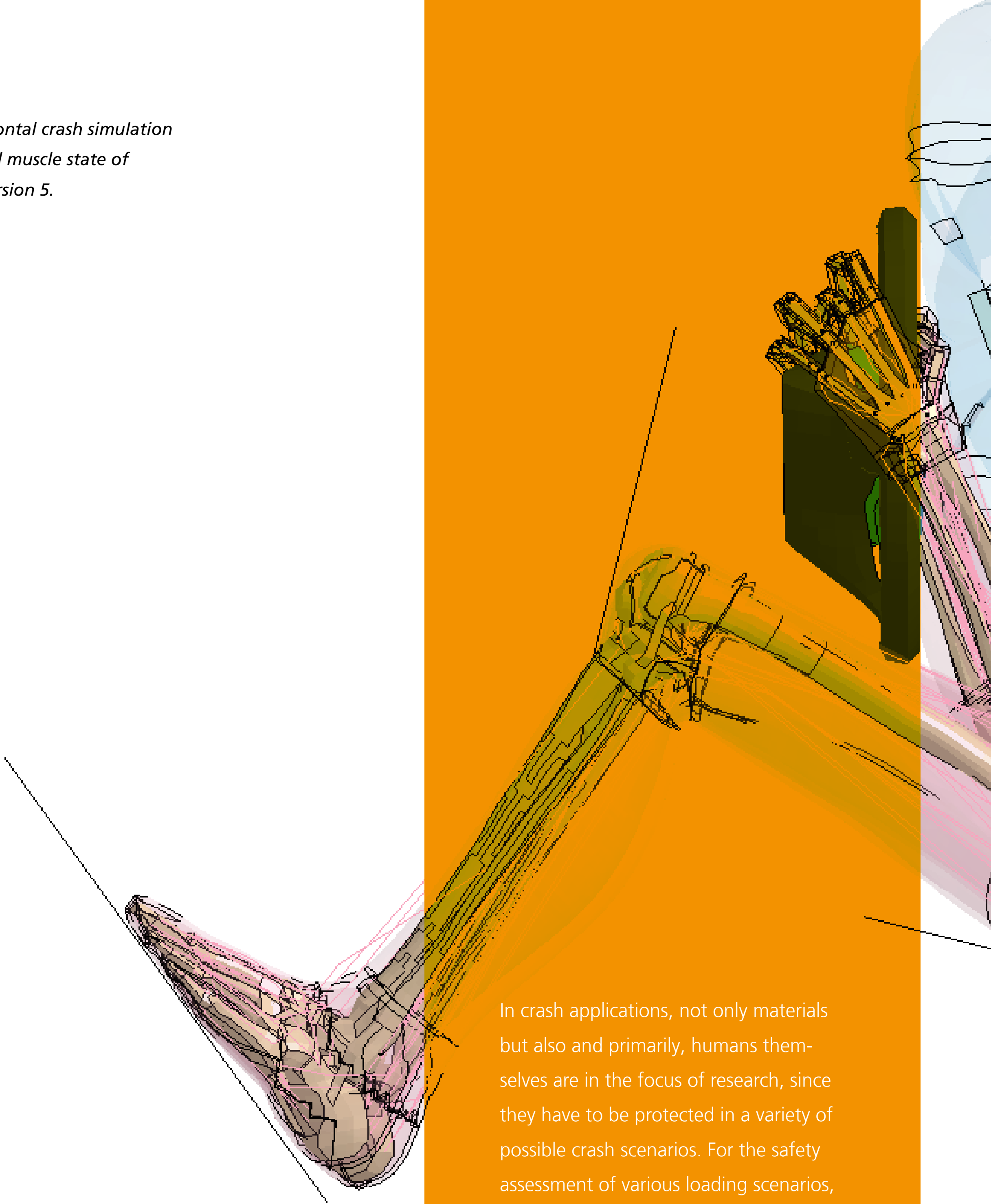
Simplified frontal crash simulation in contracted muscle state of THUMS™ Version 5.



In crash applications, not only materials but also and primarily, humans themselves are in the focus of research, since they have to be protected in a variety of possible crash scenarios. For the safety assessment of various loading scenarios, human models are increasingly used in the automotive sector. A prominent human model is the commercially available THUMS™ (Total Human Model for Safety), which was used at EMI in Version 5.

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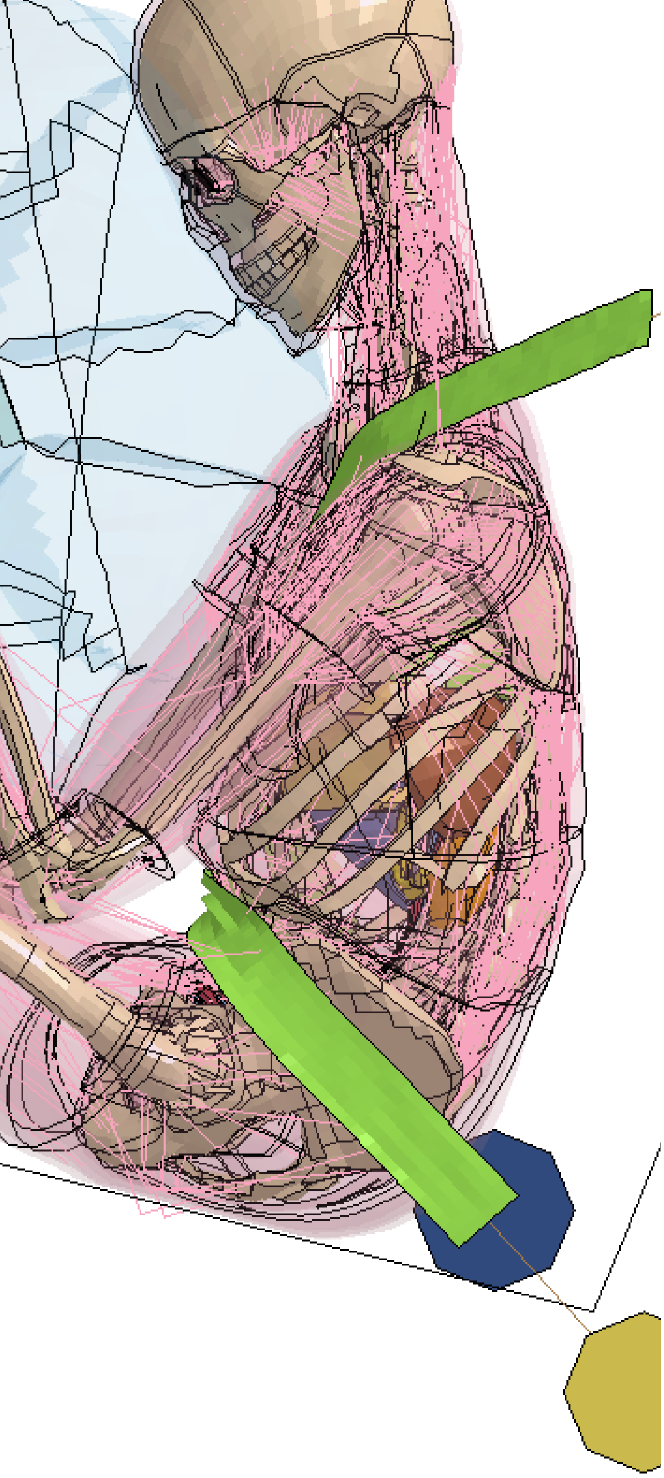


RELEVANCE OF MUSCLE STIFFNESS FOR OCCUPANT SAFETY

In crash applications, not only materials but also and primarily, humans themselves are in the focus of research, since they have to be protected in a variety of possible crash scenarios. For the safety assessment of various loading scenarios, human models are increasingly used in the automotive sector. A prominent human model is the commercially available THUMS™ (Total Human Model for Safety), which was used at EMI in Version 5.

Focus on the human being

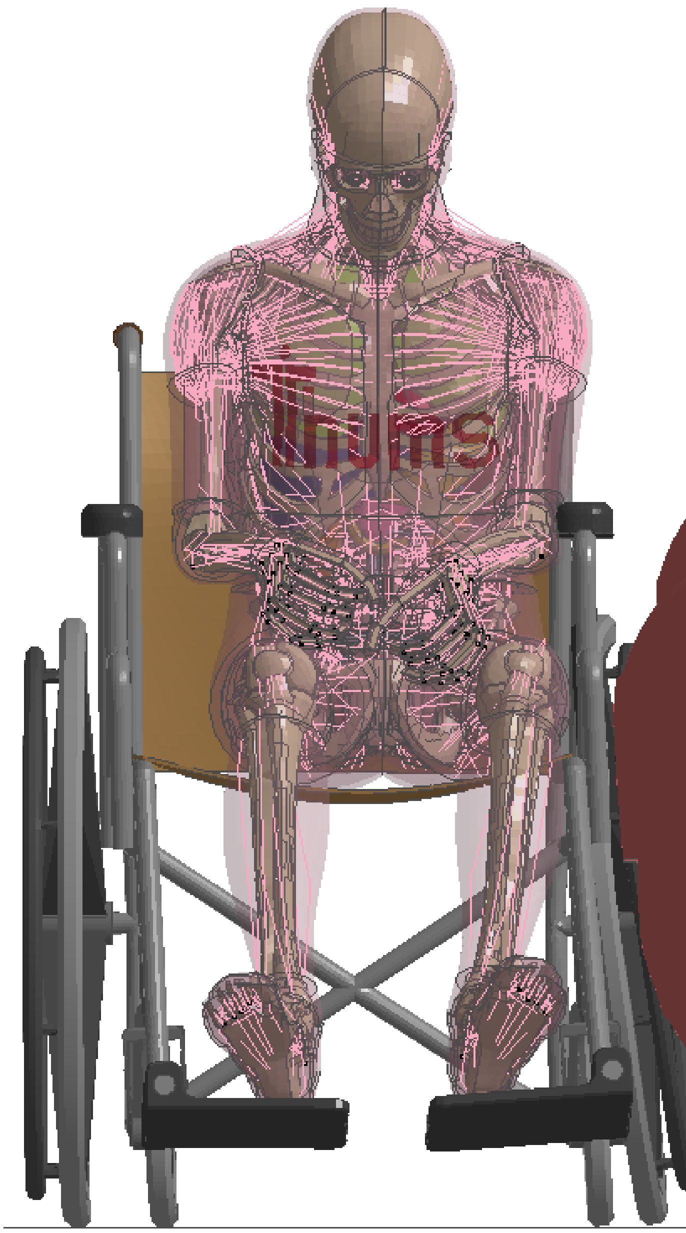
Since crash victims are often prepared for the impact, certain muscle groups are not relaxed during impact but contracted, which has been proven in past studies. This fact could already be implemented in the past for influencing the musculoskeletal system using contractible 1D elements that are connected to the THUMS model's bones. Thus, the THUMS in the current version can for the first time describe active and reactive movements during a crash impulse, e.g. when the model supports itself against the steering wheel or pushes the brake pedal. These movements are typical for real drivers shortly before and during impact. In biology, not only the decrease in muscle length and the resulting skeletal movement play a role, but also the associated change of the material properties: the muscle stiffness increases due to the contraction. However, the muscle tissue in the used THUMS model is divided into two independent systems: one system consisting of contractible 1D elements that allow skeletal movement at the joints, and the other being a volumetric system that depicts the three-dimensional muscle. The increase in stiffness of the 3D muscle is hence not triggered by the contraction of the 1D elements. However, the degree of contraction of the 1D system could be used for the definition of the 3D system's degree of stiffness.

Studies on 3D muscle stiffness effects in THUMS™ Version 5

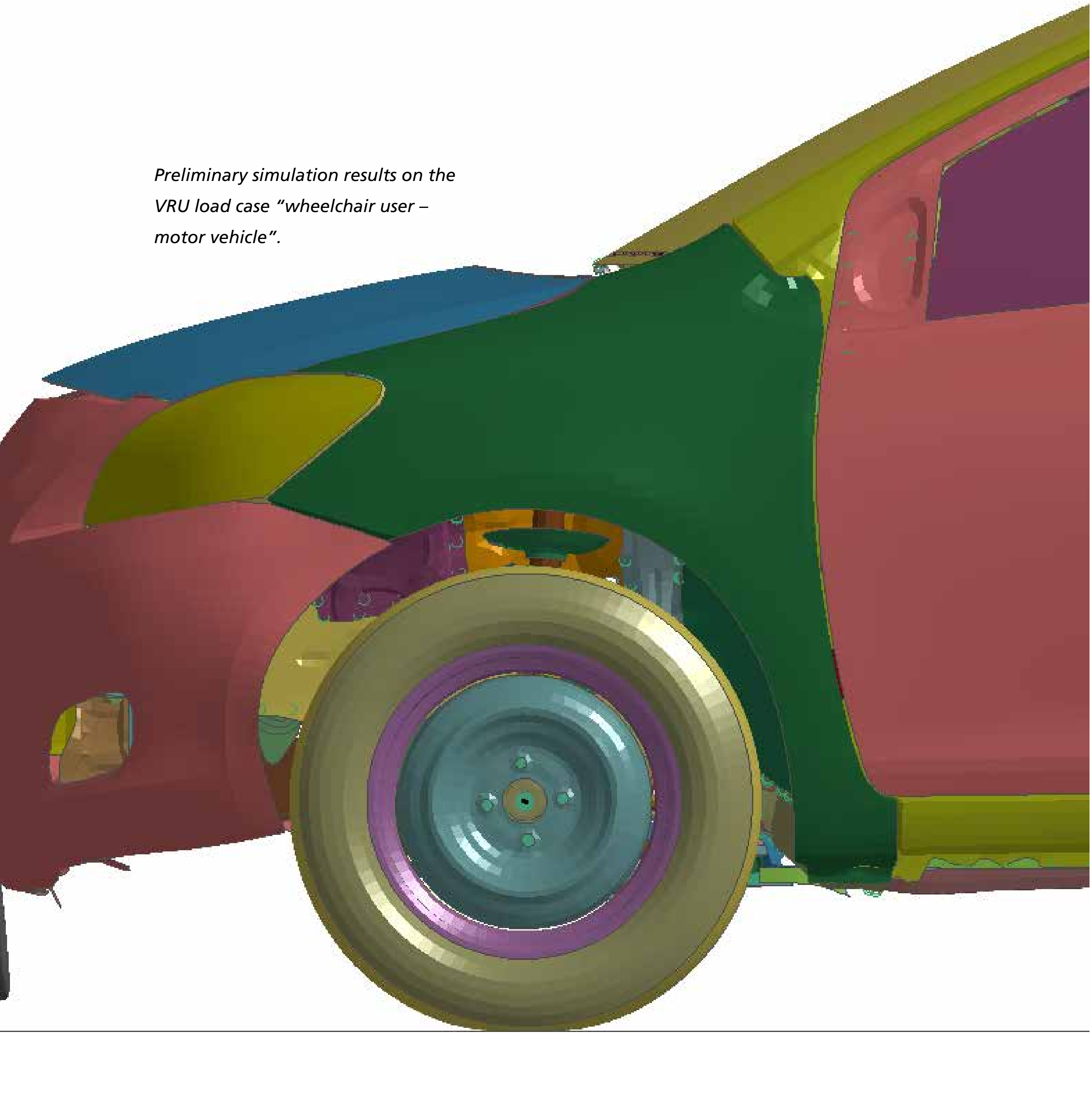
Since a relaxed muscle state is the default setting in the human model, the right parameters for the stiffness degrees have to be identified a priori. According to a comprehensive selection of available literature data on muscle stiffness, a scaling of stiffness across several orders of magnitude was carried out. Subsequently, the influence of these changes was analyzed for a simulated frontal crash pulse in the framework of a parameter study. This showed that the muscle stiffness has a major influence on occupant behavior and that potentially different loads are to be expected depending on the degree of stiffness in a crash loading scenario.

Prospects

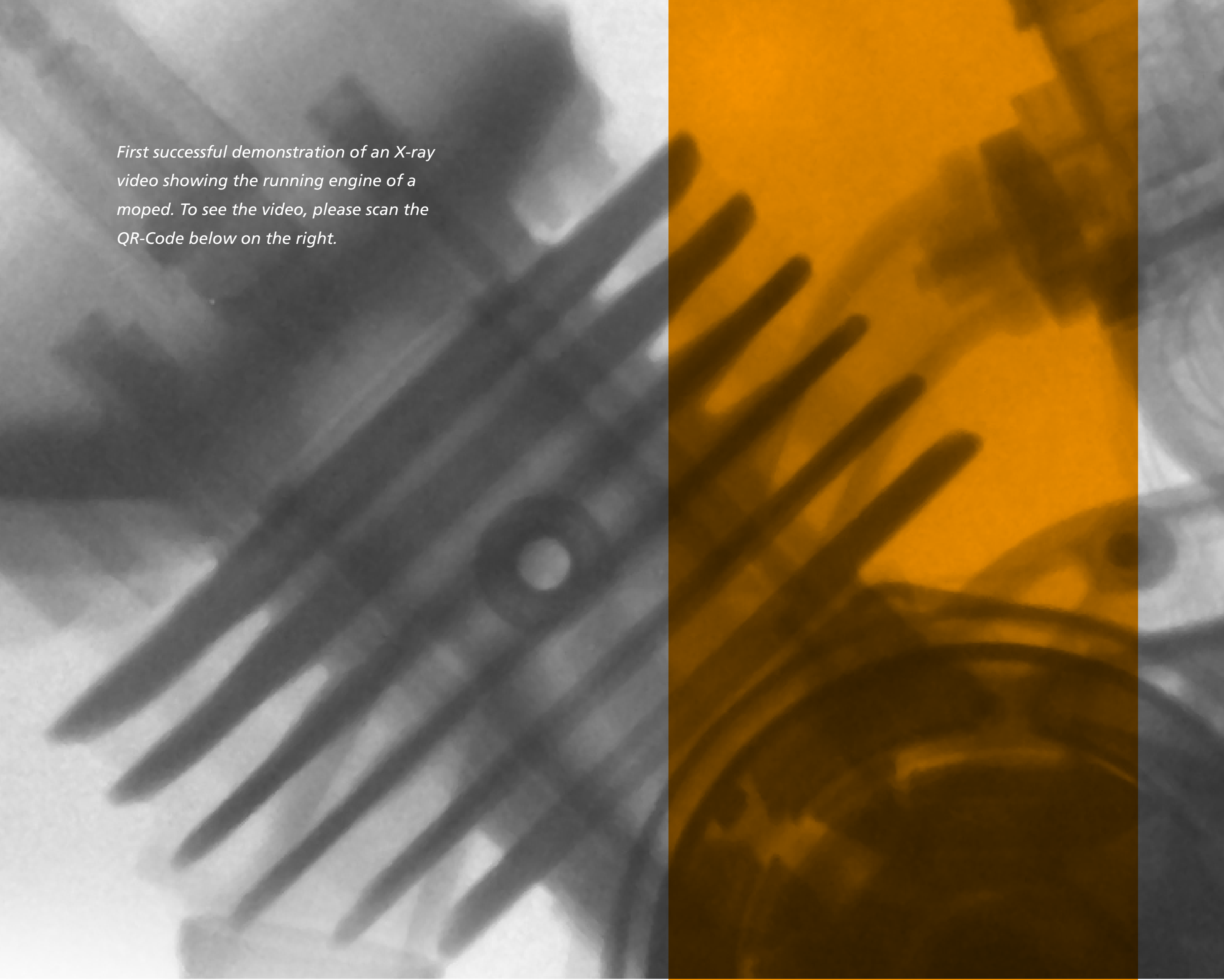
These insights form the basis for more applications in individual muscle models, in entire human models, and, specifically, in special fields of application, e.g. seating comfort analyses, studies on the safety of vulnerable road users (VRU), and applications in the fields of sport and medical technology. VRU comprise all vulnerable road users, such as pedestrians and cyclists. Since January 2019, it has been laid down in the Euro-NCAP guidelines that the VRUs' safety has to be taken into account by automobile manufacturers.



Rainer Hoffmann (left), CEO of carhs GmbH, hands over the Young Scientist Award to Niclas Trube (right).



Preliminary simulation results on the VRU load case "wheelchair user – motor vehicle".



First successful demonstration of an X-ray video showing the running engine of a moped. To see the video, please scan the QR-Code below on the right.

A big step towards the X-ray crash test has been taken: With the linear accelerator LINAC, EMI is equipped with a radiation source with which all materials commonly used in automotive manufacturing can be X-rayed. The short X-ray pulse duration allows tracing deformation processes that occur during a crash.

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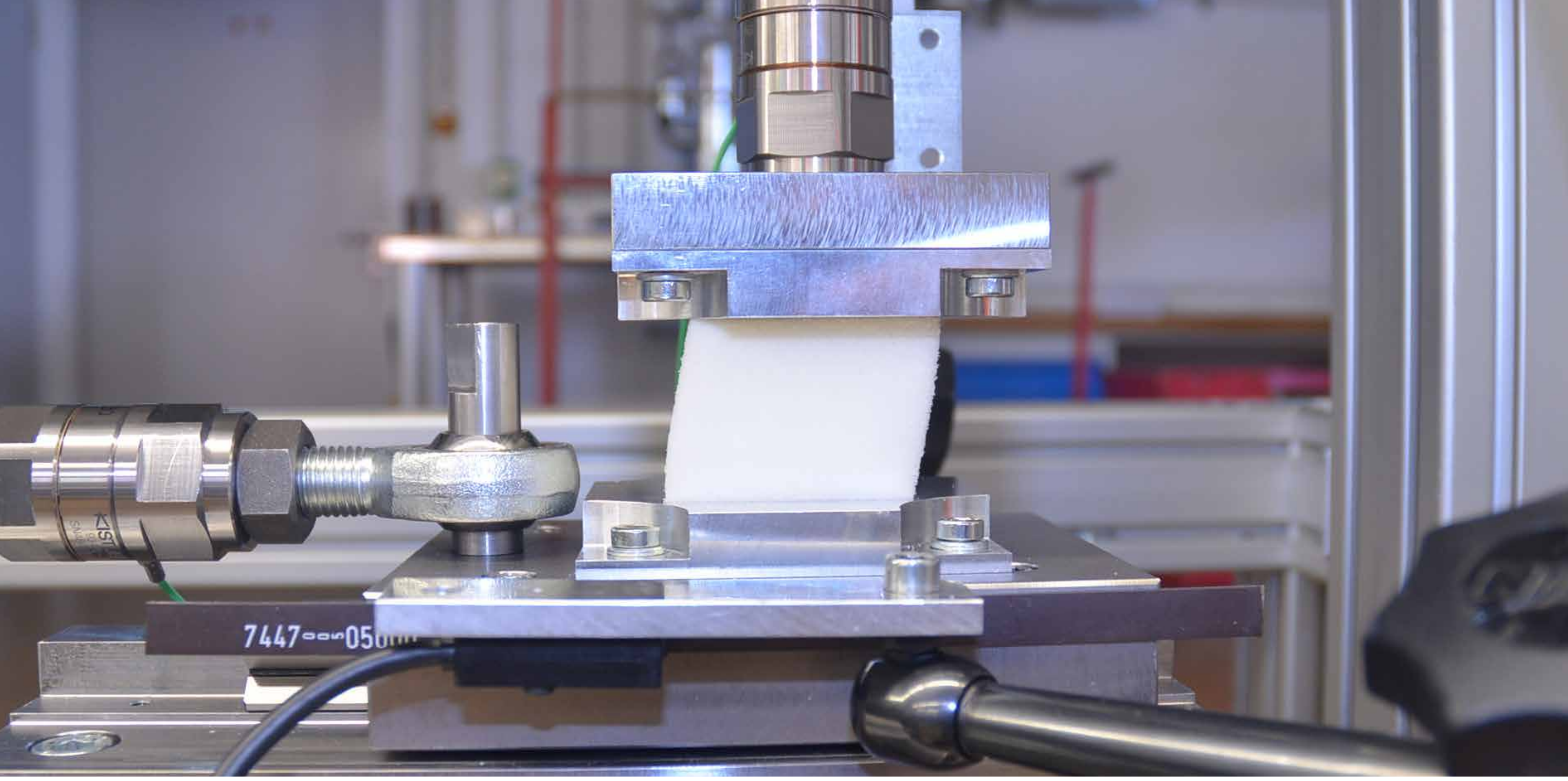
The EMI crash hall at the Crash Center of the Fraunhofer-Gesellschaft.

NEW RADIATION SOURCE FOR X-RAY CRASH X-CC

In X-ray crash testing, EMI has reached the next milestone. With the purchase of a linear accelerator (LINAC), the Fraunhofer-Gesellschaft now has a radiation source at its disposal that distinguishes itself from all other radiation sources so far available with regard to its experimental potential.

With a photon energy of up to 9 MeV, this accelerator exceeds EMI's current systems by a factor of 20, and all materials that are commonly used in automotive manufacturing can now be X-rayed. Furthermore, a short X-ray pulse duration of a few microseconds enables the recording of deformation processes during crash tests without motion blurring. Most importantly, the LINAC generates a continuous current of X-ray pulses for image creation. By using a continuously emitting radiation source, the currently existing limitation to only few images is outperformed.

These properties beat the path for the first high-speed X-ray video worldwide of a running motorbike engine, which was chosen as object of examination. With an idle speed of 1900 revolutions per minute, the movement of the piston and the motor components are clearly visible. The simultaneous visibility of both massive, highly absorbing motor block parts as well as light components, such as the insulation of the spark plug wires, is particularly noteworthy. This shows the technology's high range of contrast, which is essential for the visibility of the broad spectrum of materials in the vehicle.



Test setup for compressive shear tests on a flexible foam.

TESTING OF FLEXIBLE FOAMS

Foams are used in many fields of application. Their application spectrum ranges from sneaker soles to safety- and crash-relevant vehicle components. In the era of digital development, many products made from foam are – regarding form and function – designed and tested using numerical finite element simulations. However, the fundamental requirement for predictable simulations are extensive material tests and a comprehensive understanding of the typical material properties of foams.

Fraunhofer EMI has been conducting research on this subject for several decades in close cooperation with software developers and computational engineers from the automobile industry. The experimental methods we have at our disposal are unique. Alongside the classical tensile, compressive and shear tests, numerous special test setups, including high-precision measurement technology, complete our experimental portfolio. For example, the influence of the air in open pore seating foams on their mechanical behavior could be investigated with special air permeability and vacuum tests.

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DYNAMIC MATERIAL CHARACTERIZATION FOR INCREASED CRASH SAFETY OF TRUCKS

In cooperation with leading automobile manufacturers, suppliers, and small and medium-sized enterprises who deal with the simulation of crash processes, Fraunhofer EMI conducts research to improve the crashworthiness of utility vehicles. The project of the German Federation of Industrial Research Associations (AiF) addresses the characterization and modelling of cast iron materials that are used in safety critical components, such as chassis and cabin suspensions of trucks.

The precise knowledge of the materials' deformation and failure behavior is decisive in order to ensure the controlled energy absorption through the component in the event of a crash. The materials are subjected to a variety of experiments in order to study their mechanical behavior in detail. In addition, imaging methods, such as computed tomography and 3D laser scanning, are employed in order to visualize deformations of the specimens and components in 3D. Such digitalized data are used to validate the simulation results and to ensure their predictability. In this way, the project facilitates the optimization of component design and material application for cast iron, and, consequently, improves the crashworthiness of utility vehicles.

At Fraunhofer EMI, research to improve the crashworthiness of utility vehicles is conducted.
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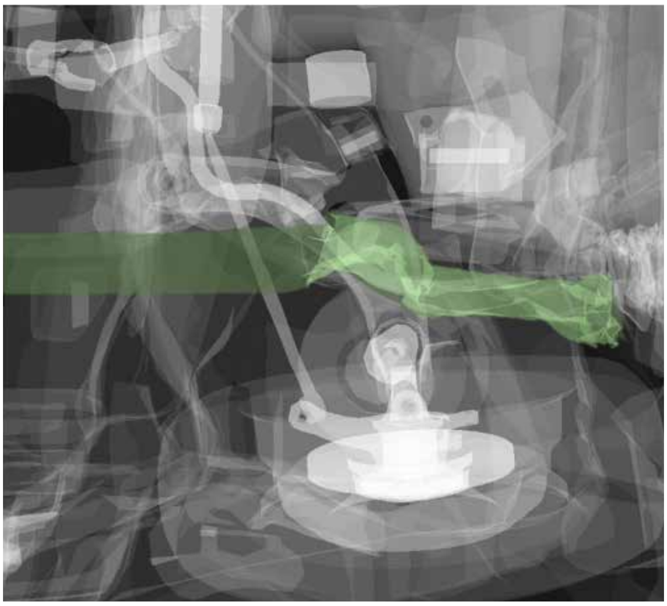
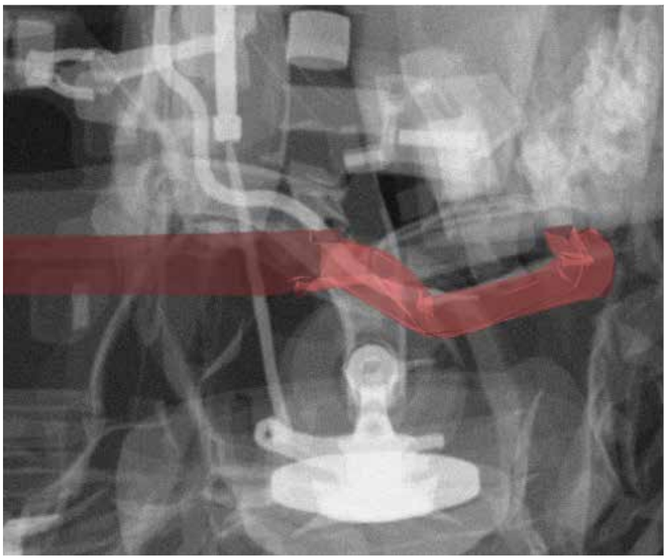


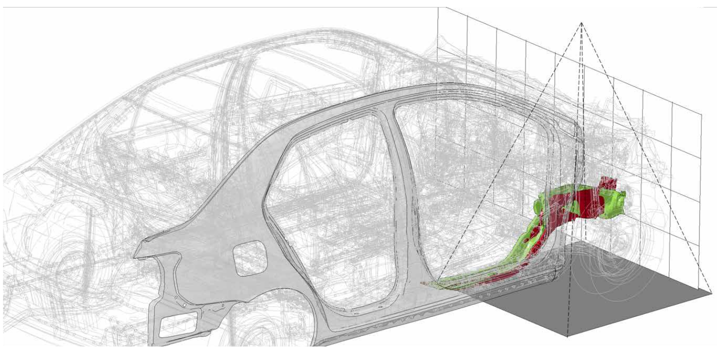


Raytracing projection of an FE simulation (above). Raytracing projection of a "virtual experiment" (below).

CRASH TESTS IN X-RAY VISION

Up to now, the exact deformation processes taking place deep inside car structures during crash remained hidden. The dynamic processes can be reproduced approximatively in simulations. However, it has so far been very difficult to analyze them experimentally. Using the X-ray car-crash (X-CC) technology, the possibility of observing the said dynamic behavior of hidden structures under crash loading is investigated at the Crash Center of Fraunhofer EMI. The enhanced validation and optimization of the predictive power of crash simulations is the overall objective of this project.

In this context, scientists of Fraunhofer EMI and of the Development Center X-ray Technology (EZRT, Fraunhofer IIS) are developing an integral measuring and evaluation method within the framework of the Fraunhofer-internal research project MAVO fastXcrash. The goals of the project range from the development of a high-energy panel detector module to the development of an extensive analysis software. Since this method has the potential to offer a valuable contribution to the process of automotive development, the research activities are supported both by EMI funds as well as interinstitutionally by the Fraunhofer headquarters.



Visualization of an X-ray car-crash test setup. A virtual experiment (red) and a reference simulation (green) are depicted. The crash simulations and the raytracing projections shown in the figures are based on the 2010 Toyota Yaris Finite Element Model, Center for Collision Safety and Analysis at the George Mason University, Federal Highway Administration.

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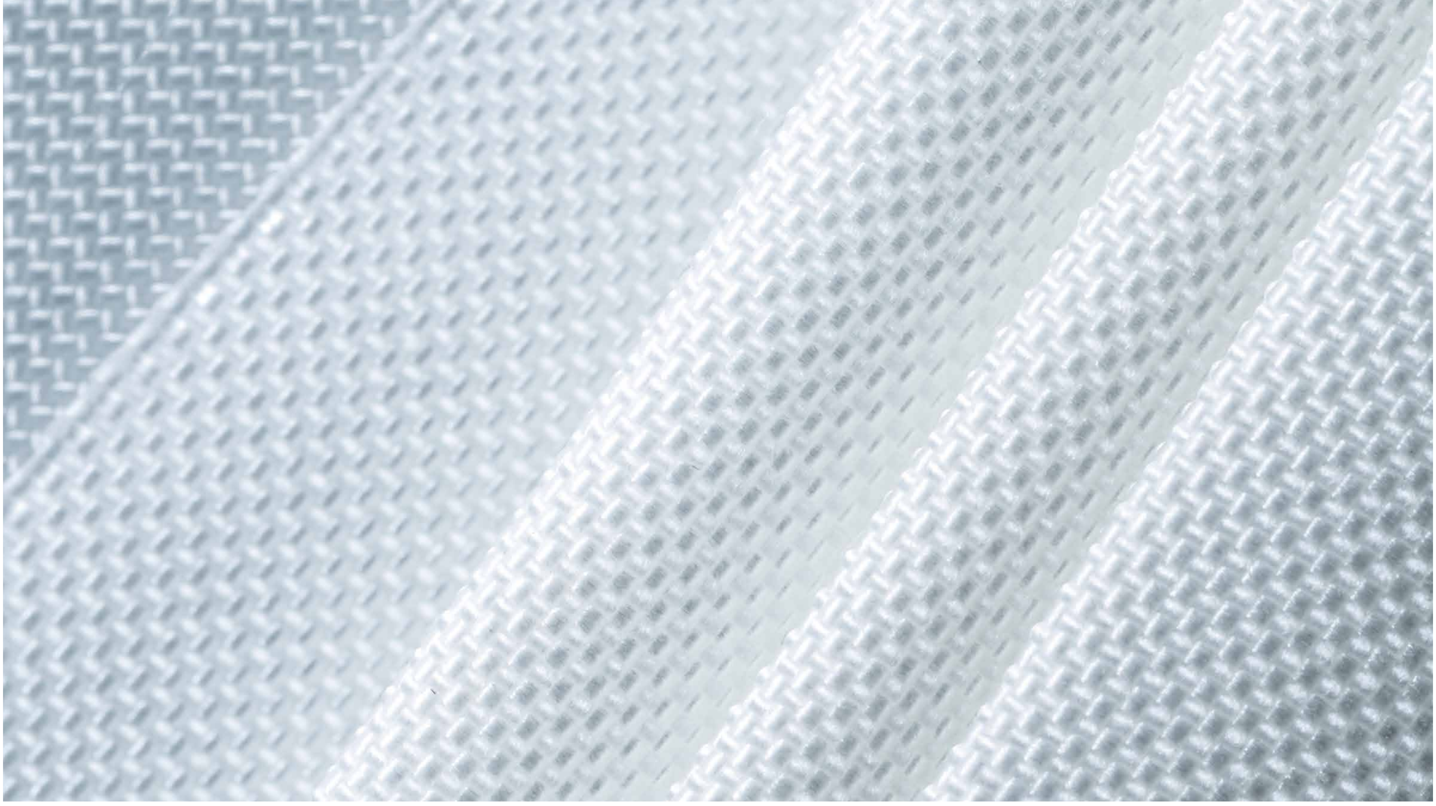

Commercially available airbag fabric. The distinct textile weaving structure is clearly visible.

AIRBAG WOVEN FABRICS

TEMPERED TESTS FOR SIMULATION

For the predictable simulation of airbag deployment processes, all relevant material characteristics have to be defined in the computational model. In order to be able to measure the influence of temperature on the material behavior, the experimental possibilities at Fraunhofer EMI were expanded such that all relevant characterization tests for airbag fabrics – especially biaxial tension tests – can be conducted within the temperature range of -40 degrees Celsius to +120 degrees Celsius. This can all be carried out both cyclically , i.e. for loading and unloading, as well as dynamically up to strain rates of ten per second! Simultaneously, the influence of asymmetric, biaxial loading ratios was investigated in a study in order to be able to assess current trends in material model development. The study showed that common formulations already yield sufficiently accurate results. Furthermore, the study revealed that for the investigated material, the temperature had a stronger influence than the strain rate, and that the experimental slippage of the specimens in the clamping region needs also to be modelled in the simulations so that the test results can be reproduced accurately in the simulation.

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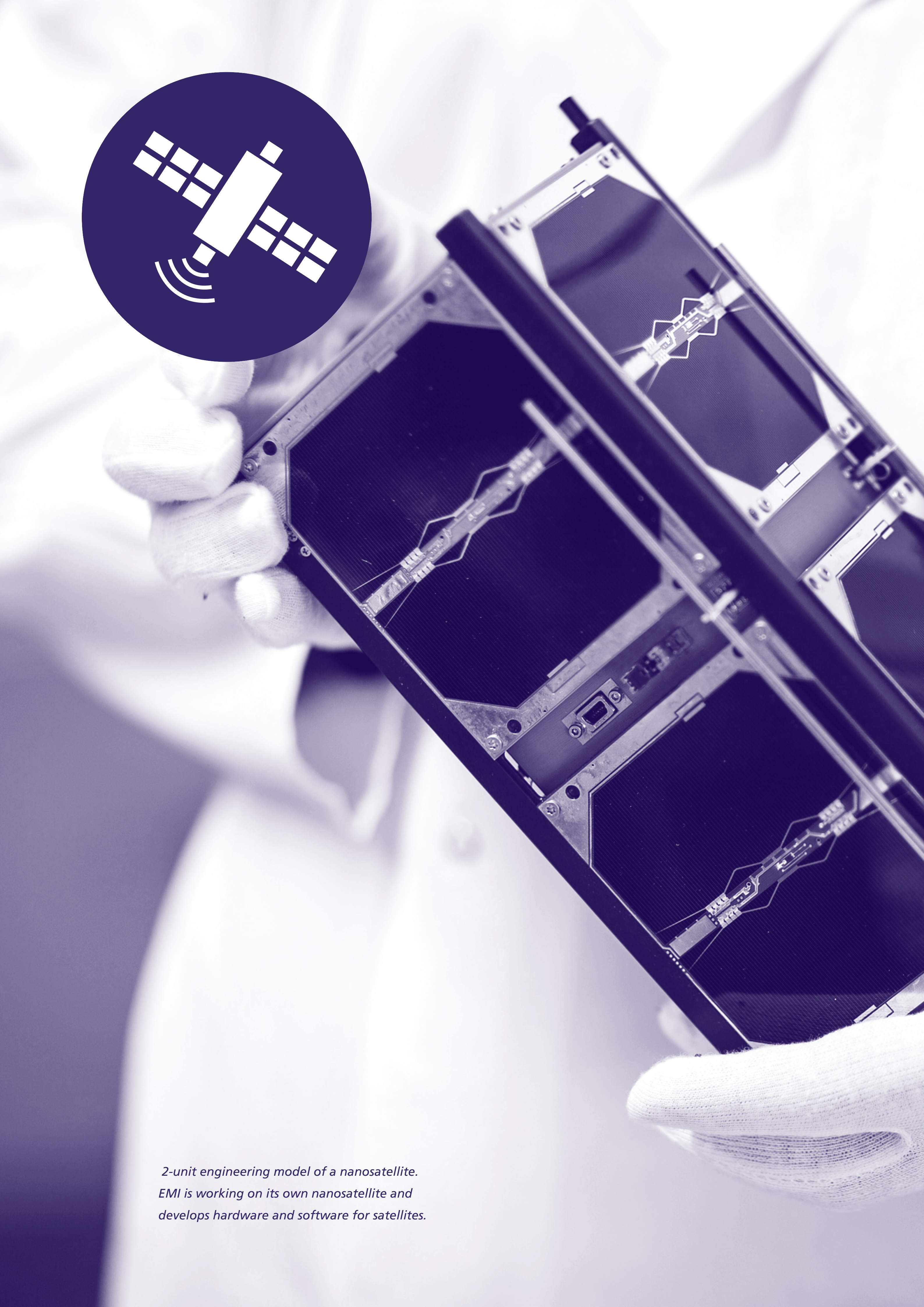
BUSINESS UNIT SPACE



2-unit engineering model of a nanosatellite. EMI is working on its own nanosatellite and develops hardware and software for satellites.

BUSINESS UNIT SPACE

The digital transformation initiated within the framework of New Space has resulted in the development of huge constellations of small satellite platforms, which have become the expression of the profound change in the satellite industry. In order to shape the dynamics of this change, we pool Fraunhofer EMI's expertise in the fields of scientific payloads, additive manufacturing, mechanisms, system integration, and space flight qualification in the Business Unit Space. This way, we can continue to provide trend-setting small satellite technology solutions for partners in industry and the public sector. Our nanosatellite demonstrator ERNST is our flagship, featuring an infrared camera as the main payload. The engineering qualification model (EQM) will be finalized and qualified for space flight this year.

The growing number of satellites in near earth orbit also leads to an increased risk of collision between objects in said orbit. Protective shields can mitigate the effects; However, in the worst case, the satellite is destroyed. We analyze these complex processes with a unique simulation method, which we will introduce below.

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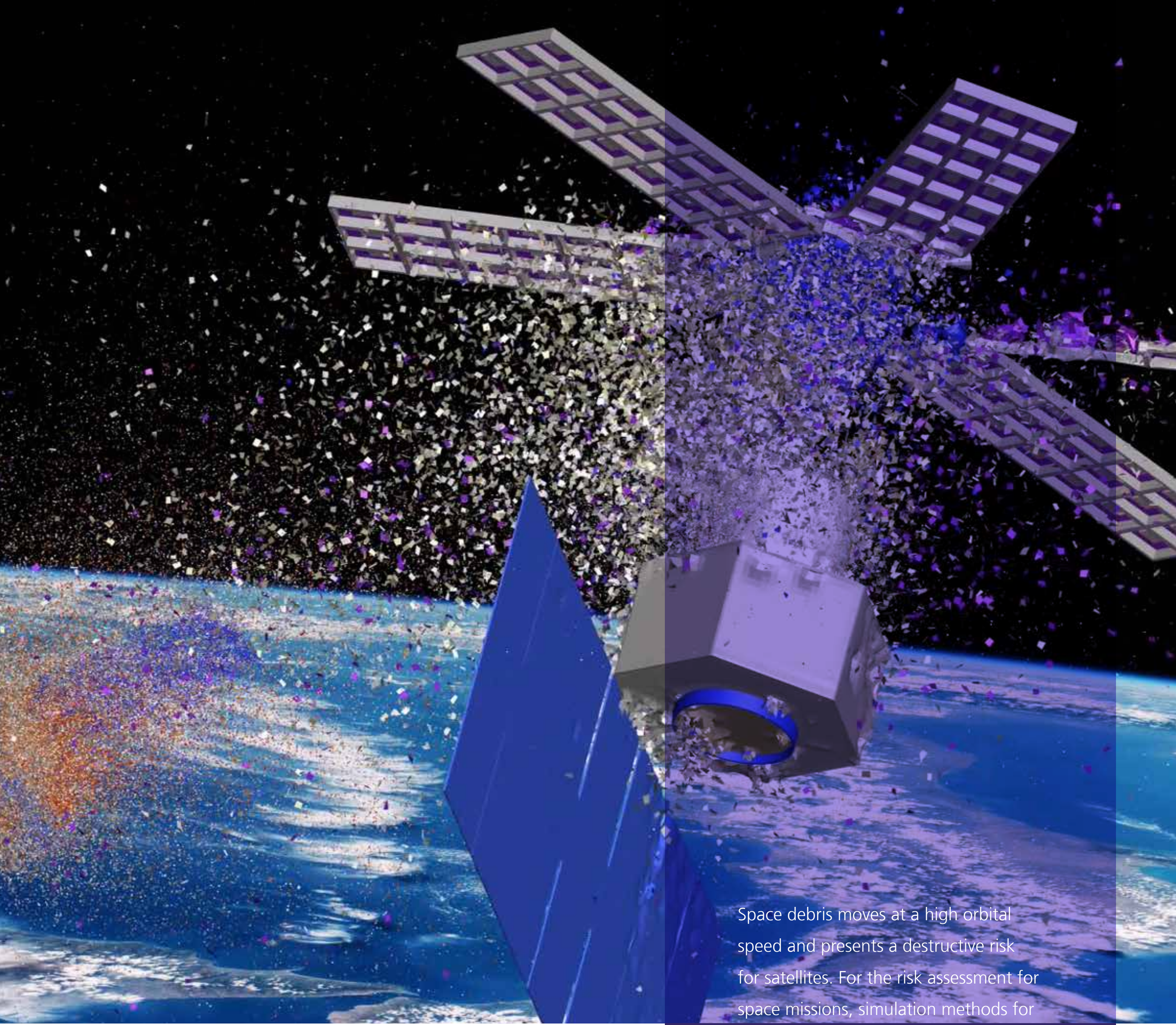

Space debris moves at a high orbital speed and presents a destructive risk for satellites. For the risk assessment for space missions, simulation methods for tracking the amount of space debris are used that are based on empirical databases and estimations. At Fraunhofer EMI, numerical methods for the virtual simulation of complex collision events in orbit are developed in order to gain a better and more realistic understanding of the risks.

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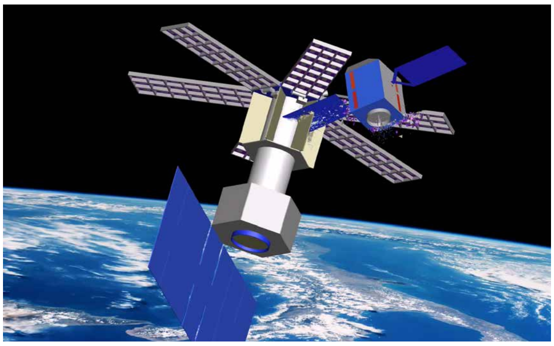
ESA-LOFT satellite, one millisecond after the simulated collision.



PHILOS-SOPHIA simulation of an impact onto a panel of the ESA-LOFT satellite.

NUMERICAL ANALYSIS OF SATELLITE COLLISIONS IN ORBIT

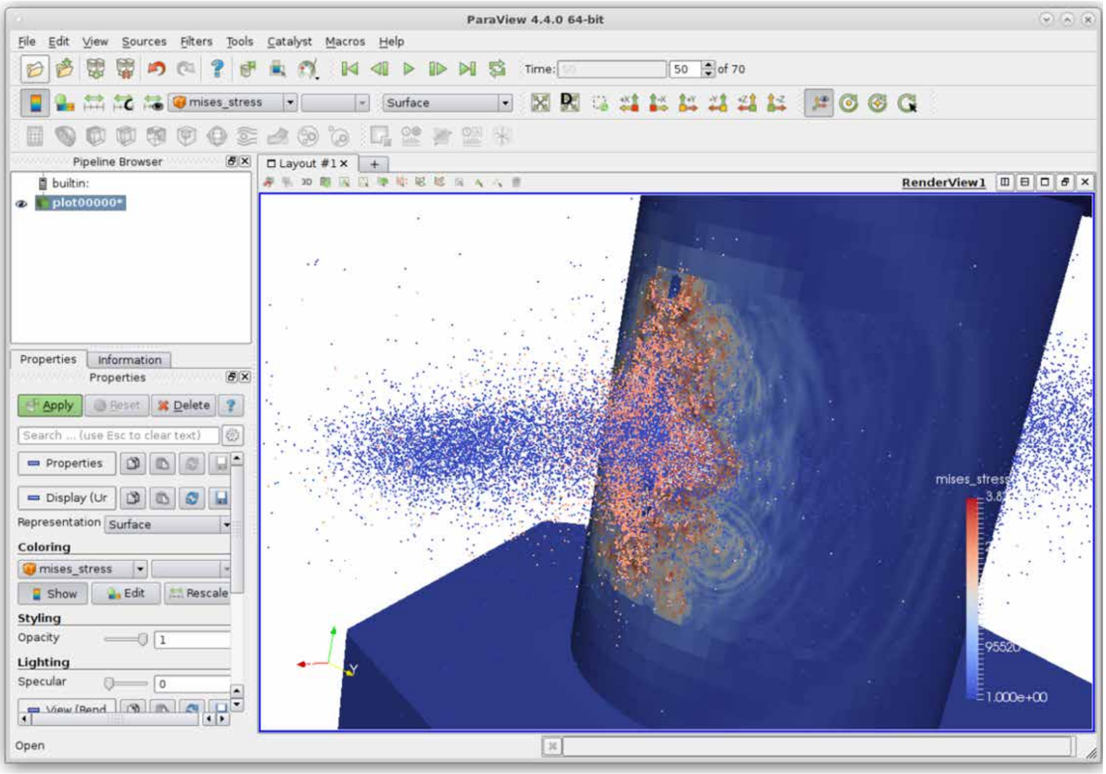
Space debris objects are remains of anthropogenic activities in space. Since the beginning of space travel, the number of said objects in near earth orbit increases continuously with the growing number of launched space systems. Fragmentation events caused by exploding tanks of decommissioned upper stages as well as accidental collisions of satellites cause an abrupt increase in the total number of space debris particles. Such fragmentation events are the major source of space debris objects. Specifically regarding collisions of satellites, the by far greatest number of objects is predicted to occur in the medium term, when the spatial density of satellites will have reached a critical level. This trend is even intensified by the installation of large satellite constellations. The only natural sink besides dedicated de-orbit maneuvers of decommissioned satellites is atmospheric drag. This drag, however, is already so low for relevant orbital altitudes in the low earth orbit that objects remain there for decades or even longer.

Modeling of space debris environment

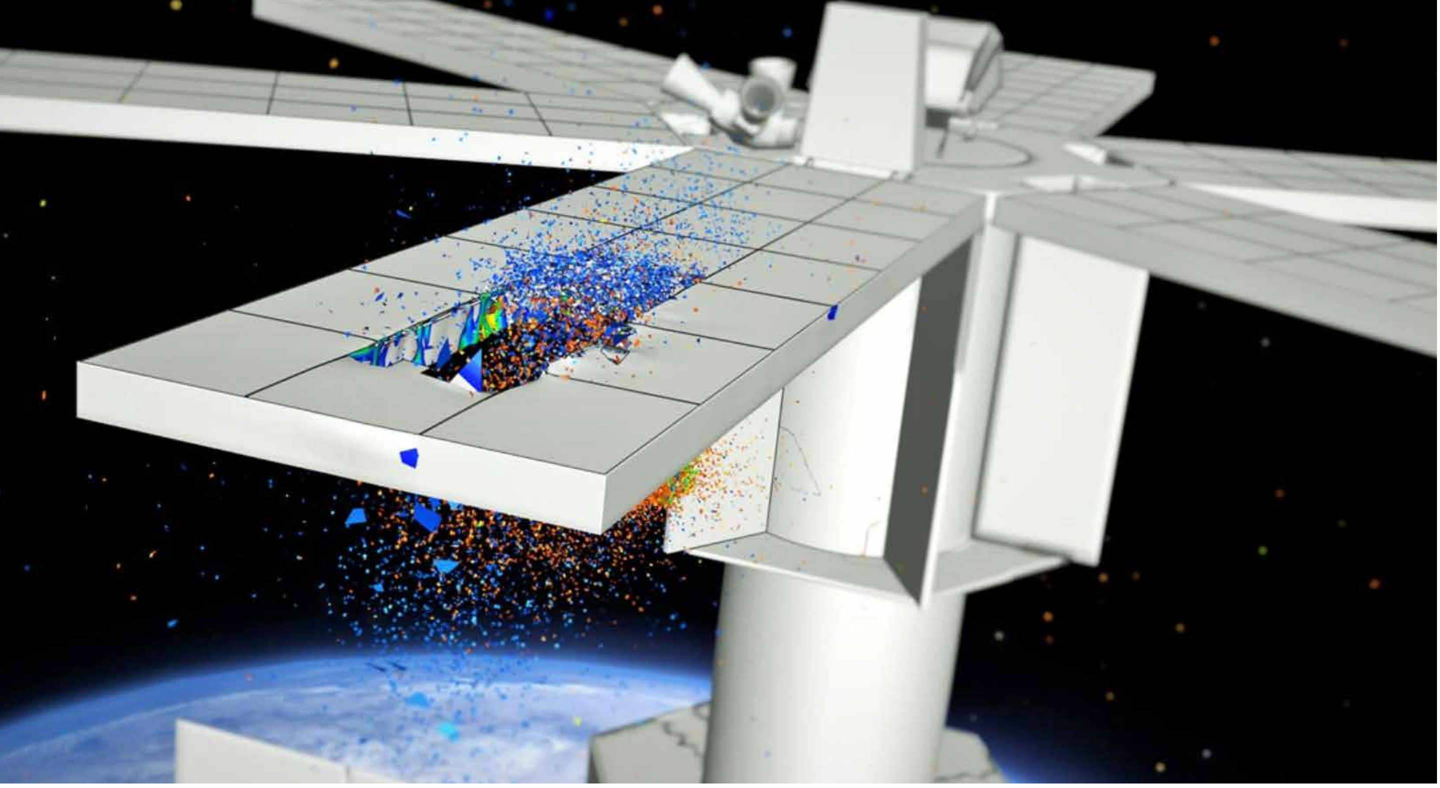
In the space debris environment, the high orbital velocities of the space debris objects and the resulting destructive effects of a collision are particular. At impact velocities of several kilometers per second, even impacts of objects with a size of merely centimeters can result in catastrophic satellite failure. Thus, it is important to analyze the space debris environment in order to assess the risk for a space mission and, if necessary, to take protective measures. The modelling of the space debris environment is based on event databases and catalogues of ground-based observational data. Even ultra-high definition observation radars, e.g. Fraunhofer FHR's space observation radar TIRA, only detect objects larger than five to ten centimeters. All smaller objects can hardly be observed but are instead estimated using models. For the dominant source of fragmentation objects, NASA's state-of-the-art Standard Satellite Breakup Model is used.

Analysis of satellite collisions

The NASA Breakup Model is a simple empirical model that only allows few input parameters: the mass of the colliding objects and the collision speed. The statistical database which the model is based on is scarce considering the difficulty of observation of real fragmentation events in orbit and the immense effort of reconstruction in the laboratory. Observations of more recent fragmentation events in orbit, such as the Chinese antisatellite test Fengyun 1C and the collision of the satellites Iridium 33 and Kosmos 2251, thus show significant deviations from the predictions made by the NASA Breakup Model. In order to increase the data basis and to allow the systematic analysis of fragmentation events, Fraunhofer EMI adopts the strategy to use numerical methods for the virtual simulation of complex collision events in orbit.



Screenshot of a PHILOS-SOPHIA application.



HILOS-SOPHIA simulation of an impact onto a panel of the ESA-LOFT satellite.

Numerical simulations

For the simulation of satellite collisions, we use the hydrocode EMI-SOPHIA developed at EMI, which has been optimized for the simulation of highly dynamic structure-mechanical processes and has been validated in numerous experiments. For the European space organization ESA, SOPHIA was expanded to PHILOS-SOPHIA in order to simulate satellite fragmentation. This enables even non-professionals to construct and compute collision scenarios and to perform analyses. We have demonstrated this with the example of the ESA satellite LOFT, a design study of a large X-ray telescope. We collided the numerical models of the LOFT satellite with a small satellite in various collision scenarios in order to analyze the number, properties and orbits of the generated fragments. Unlike as in the NASA Breakup Model, which does not take the collision geometry into account, we could discern significant differences in the occurring damage and fragmentation in dependence of the impact direction. Especially grazing collisions can cause either much larger or much smaller damage than a central collision. The collision geometry is the decisive factor here. The orientation, the impact location, and the direction of the collision partners to each other influence the extent to which the resulting debris clouds hit other parts of the satellite and thus generate even more fragments. With PHILOS-SOPHIA, such processes can be simulated in a physically consistent manner, and the properties of the individual fragments can be identified and tracked completely.

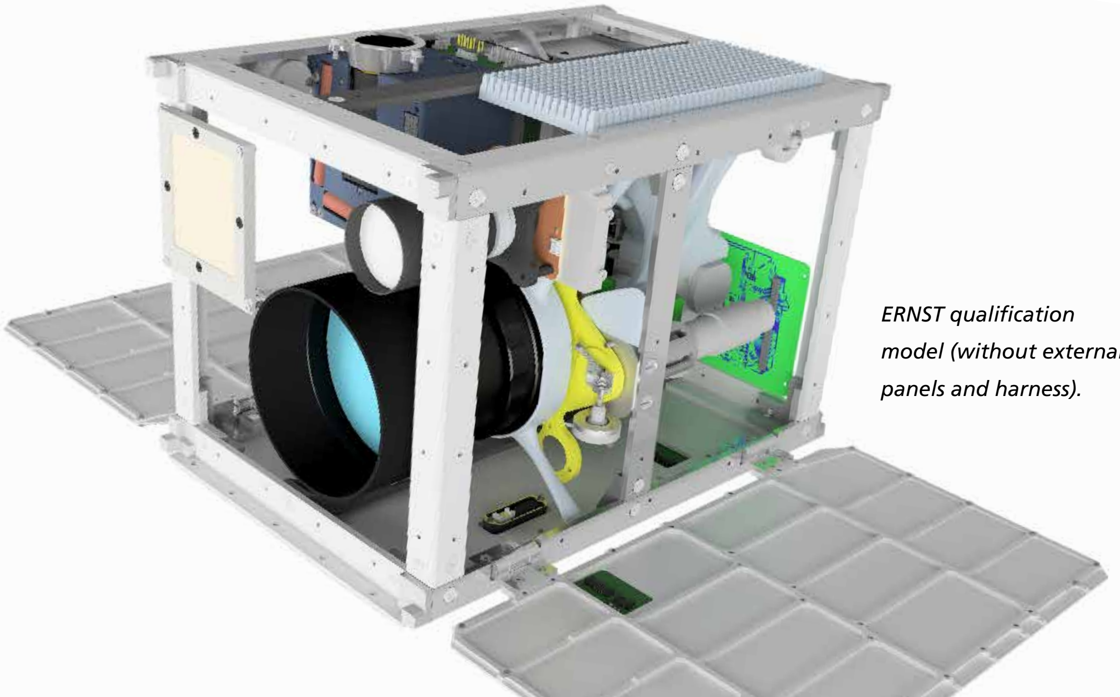
Prospects

In order to improve the methods for simulating the fragmentation of complex, large-scale satellites and to reduce computing time, we currently develop substitute models for sandwich components using fiber-reinforced composites. These sandwich components are increasingly put to use on modern satellites and, as impact tests show, generate a high number of small fragments in the subcentimeter range. With simplified substitute models that are developed using dedicated experiments in combination with cutting edge particle tracking methods, the simulations become more efficient. Thus, they enable a number of realistic and systematic investigations of complex satellite collisions. Such studies can become the basis for the improvement of the existing Standard Breakup Model and can foster the development of a more efficient European Model.

ERNST
TECHNOLOGY DEVELOPMENT FOR NEW SPACE

The space technology industry is currently undergoing major changes, which are termed "New Space" by its protagonists. These changes, propelled by considerable private investments, include the implementation of large constellations of small serially produced satellites. With the nanosatellite ERNST, we at Fraunhofer EMI are developing our own modular platform in order to demonstrate the performance potential of this satellite category and to also benefit from the dynamics of the small satellite market. In this context, we do not consider the development of nanosatellites as competition for the established high performance satellites but as a complement. The added value of the latter can be expanded and enhanced by cost effective and quick-response nanosatellite missions.

In ERNST, which is only 236 x 236 x 340 cubic millimeters in size and weighs 20 kilograms, we accommodate a cryogen-cooled infrared detector for the observation of rocket launches, a camera for earth observation in the visible range, and a radiation detector developed at Fraunhofer INT. Currently, we are integrating and testing the ERNST qualification model and are developing software, 3D-printed structures and a de-orbit drag sail. The launch is scheduled for 2021.



ERNST qualification model (without external panels and harness).

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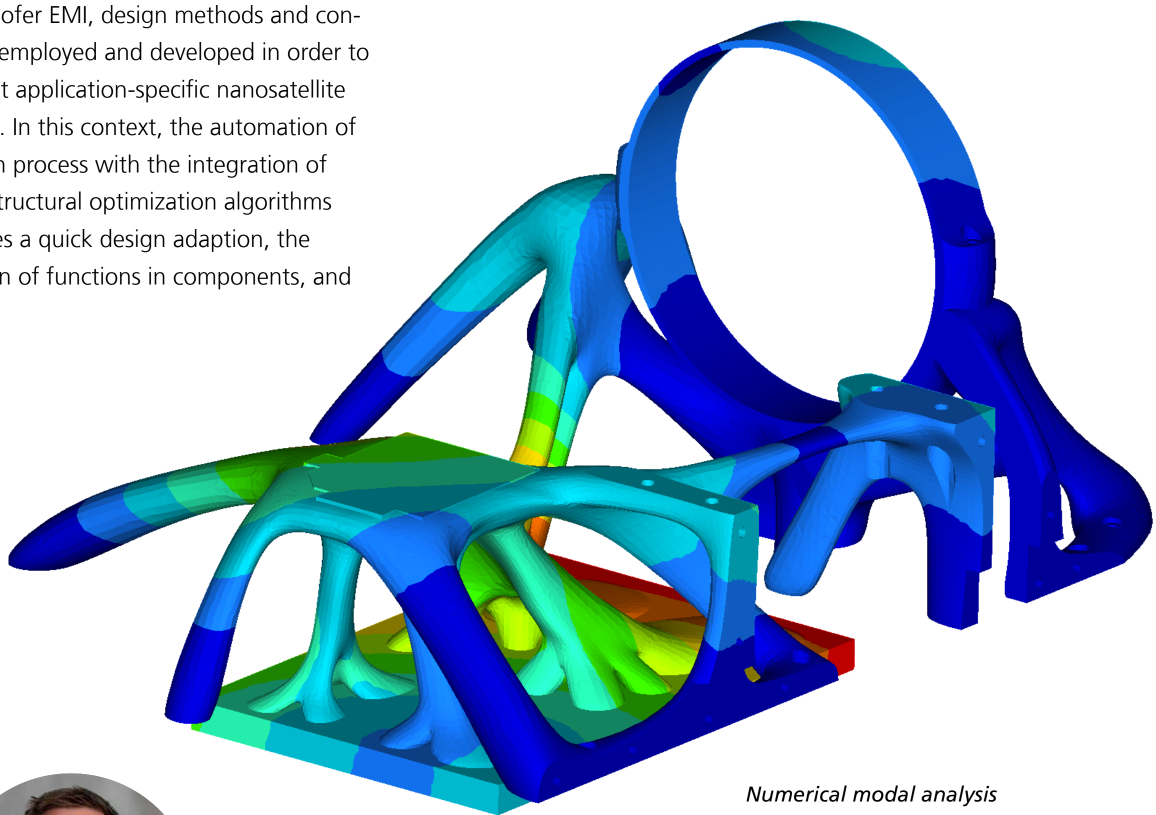
3D PRINTING FOR SATELLITE TECHNOLOGY

Satellite-based services such as weather forecasts, navigation, or communication applications influence our daily lives. To advance the development of such services even faster than before, utilizing so-called nanosatellites, which usually have the size of a shoebox, has enormous potential. If we want to realize better, more flexible and cost efficient nanosatellites in a shorter development time, a paradigm change is needed in terms of the construction and production of current satellite systems. 3D printing (additive manufacturing), with its enormous freedom of design, allows the realization of highly individualized and compact design solutions for nanosatellites.

At Fraunhofer EMI, design methods and concepts are employed and developed in order to implement application-specific nanosatellite structures. In this context, the automation of the design process with the integration of modern structural optimization algorithms guarantees a quick design adaption, the integration of functions in components, and the integral design to reduce the number of individual components. With the additive manufacturing technology of direct metal laser sintering, components can be produced in a resource efficient way from a broad range of different alloys including aluminum or titanium. At Fraunhofer EMI, we are constantly working on establishing additive manufacturing as a bridge between the real and digital worlds even in spacecraft technology.



Numerical modal analysis of the optical bench.

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The Rocket Lab Electron rocket during launch on November 11, 2018, deploying the payload – the first drag sail demonstrator.
© Rocket Lab

DEPLOYABLE DRAG SAIL FOR NANO-SATELLITES

In order to limit the number of objects left in orbit – so-called space debris – satellites have to be removed from orbit after the end of mission. International guidelines, which EMI also contributes to, stipulate a maximum de-orbiting time of 25 years. In higher orbits, the atmospheric drag is too low to ensure these de-orbiting times. In this case, a satellite requires a de-orbiting device for the maneuver.

At EMI, we are developing such a device for our nano-satellite ERNST. The de-orbit subsystem is a so-called drag sail, which increases the satellite's surface area and thus increases the atmospheric drag. For this purpose, an aluminum-coated membrane with a size of 2.5 square meters is deployed via tape spring booms. In the folded state, the deorbit system fits into a cube with an edge length of 10 centimeters. A sample demonstrator, which has been developed in cooperation with HPS GmbH, was launched onboard a Rocket Lab Electron rocket on November 18, 2018. Reliable results of this test in orbit are expected as of summer 2019.

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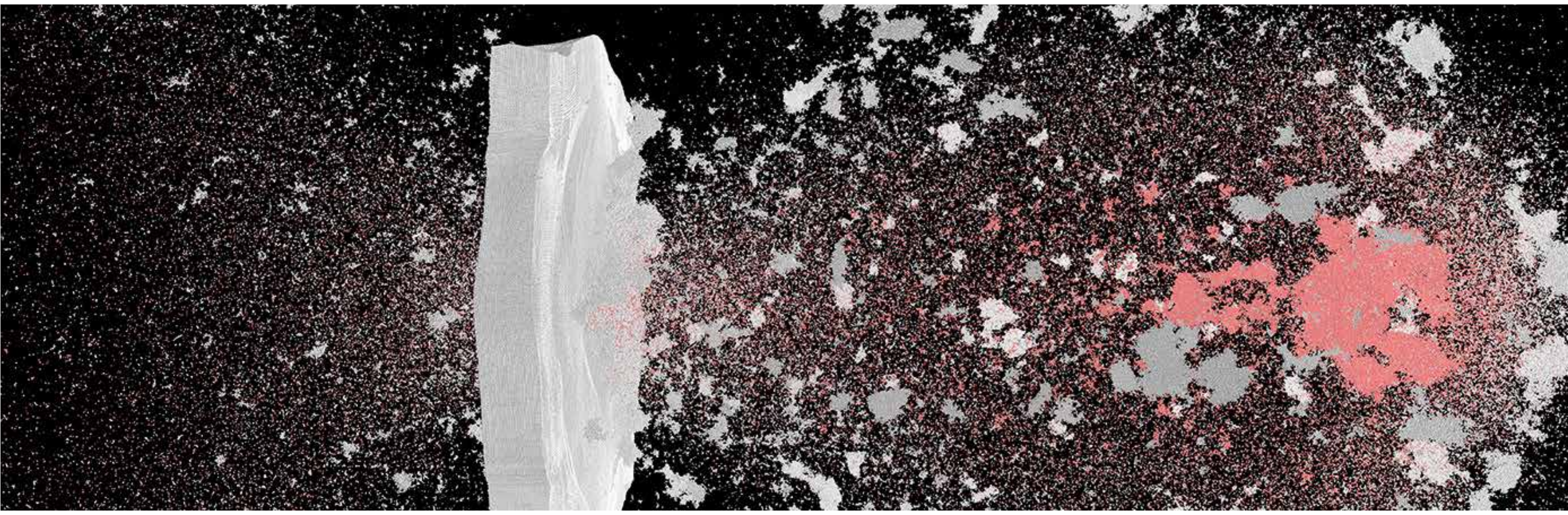
THE THREAT POSED BY SPACE DEBRIS

METHODS FOR THE DESCRIPTION OF FRAGMENTATION EVENTS IN ORBIT

Since the beginning of the space era in the 1950s, a large number of objects has accumulated in the Lower Earth Orbit (LEO) – for example rocket end stages or debris resulting from collisions. This debris orbits Earth with velocities between three and eight kilometers per second, depending on the orbit height. This so-called space debris presents a growing threat for active satellites. The collision of objects with an active satellite can lead to failure or even destruction of it. For a future evaluation, or more specifically, a realistic risk assessment of such collisions, a proper physical model for the material behavior of a solid during high velocity impact is essential. At Fraunhofer EMI, we develop such realistic models based on a particle method, and solve the dynamic equations that describe the physics using parallelized high-performance computer simulations. The gained knowledge can be used by customers, e.g. for the material optimization in the structural design of satellites. Furthermore, our computer experiments yield valuable insight into the optimization of satellite impact shielding and lead to a deeper understanding of material failure during high velocity impact. In this respect, the very expensive experimental trial-and-error-approach conventionally adopted in the development of new satellites can be substituted or at least complemented by a considerably more cost effective, tailored design which is optimized by computer simulations.



Simulation of a standard impact geometry with 7.7 million particles. Impact with a velocity of five kilometers per second.

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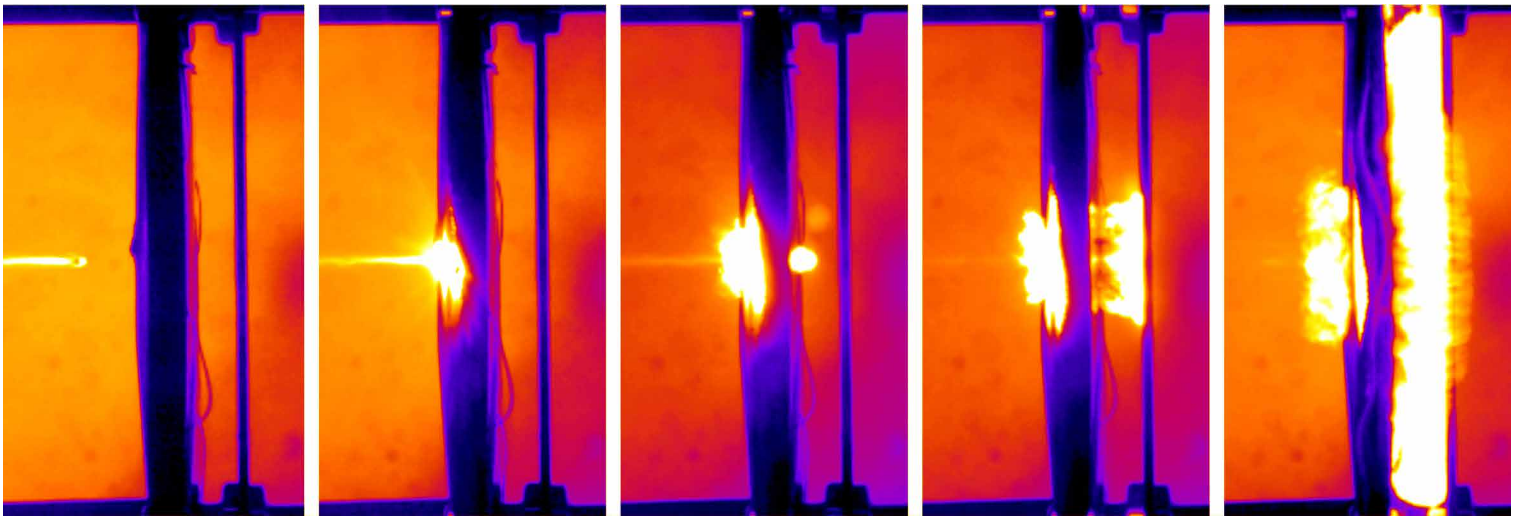

Image sequence of an impact test onto a protective shield of the Chinese space station TianGong (in pseudo colors).

IMPACT TESTS ONTO PROTECTIVE SHIELDS FOR THE PLANNED CHINESE SPACE STATION TIANGONG

The experimental simulation of the hypervelocity impact of space debris and micrometeoroids onto spacecraft systems is a special expertise of Fraunhofer EMI. Using two-stage light gas guns, objects with sizes ranging from micrometers to centimeters are accelerated to impact velocities of up to ten kilometers per second.

These experimental capacities, which have for example been employed in the development of the protective shield of the ISS European Columbus module, were again sought-after in 2018 for the protective shield of the planned Chinese space station TianGong. The background for this project is a cooperation between the European Space Agency ESA and the Chinese Academy of Space Technology CAST. For the Chinese scientists, we at EMI have experimentally analyzed their protective shield concept for the manned space station. The goal was to examine and to characterize the protective capability of the shield for various impact conditions. In fifteen experiments, the protective shields were tested. Based on the results, dedicated damage equations for the description of the protective behavior of the shields were then deduced.

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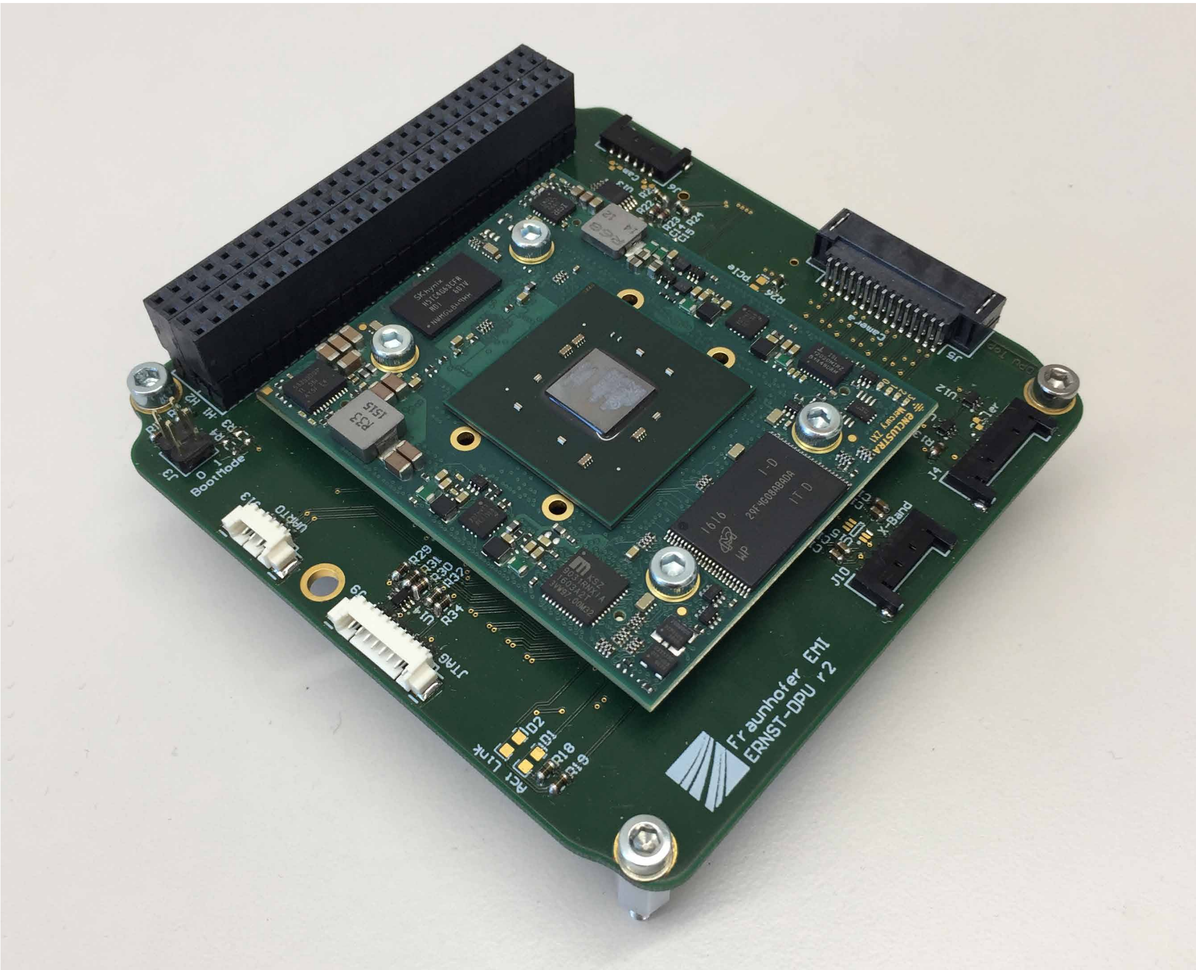
FPGA-BASED DATA PROCESSING UNIT

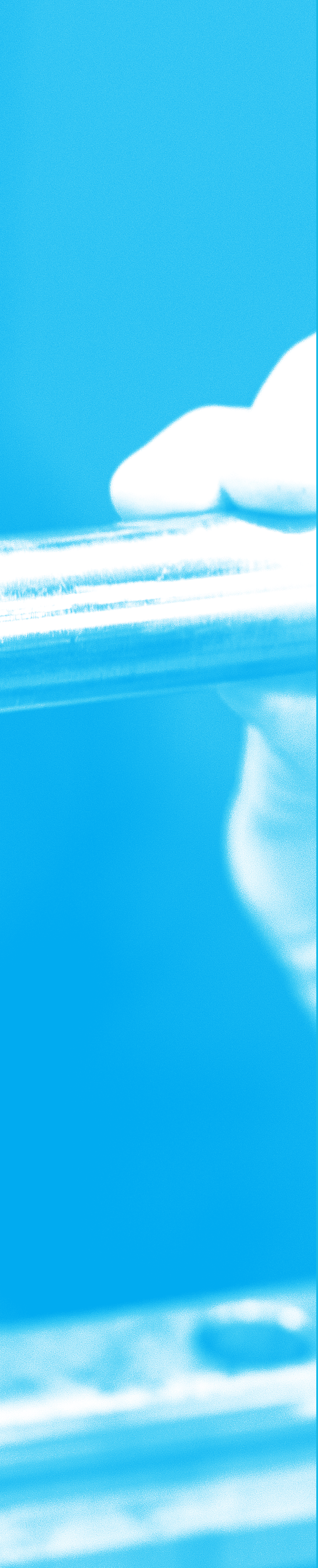
The data processing unit (DPU) for small satellites has been successfully ported to the latest generation of high-performance FPGAs (field programmable gate arrays). The DPU is thus prepared for future applications in artificial intelligence. The device will be put to use alongside EMI's satellite ERNST in several space missions of an industrial customer.



Data processing unit with FPGA technology.

BUSINESS UNIT AVIATION

Mechanical material characterization:
CFRP sample after high-rate tensile test.



BUSINESS UNIT AVIATION

Besides excellent aerodynamics and efficient engines, the implementation of a consequent lightweight design concept is the key to high performance and eco-efficiency of modern aircraft. The following article describes the research activities of Fraunhofer EMI in the context of sustainable, cutting-edge lightweight solutions, which are gaining in importance facing the increasing scarcity of natural resources.

In the wake of the crashes of two type Boeing 737 MAX airplanes in Indonesia and Ethiopia, the safety of commercial airplanes is under debate. At Fraunhofer EMI, we conduct research on further improving the high safety standards. Specifically, the researchers at EMI analyze everyday impact scenarios, such as hail or damage of CFRP structures caused by low velocity impact. The following contributions will provide an insight into this exciting and important field of research.

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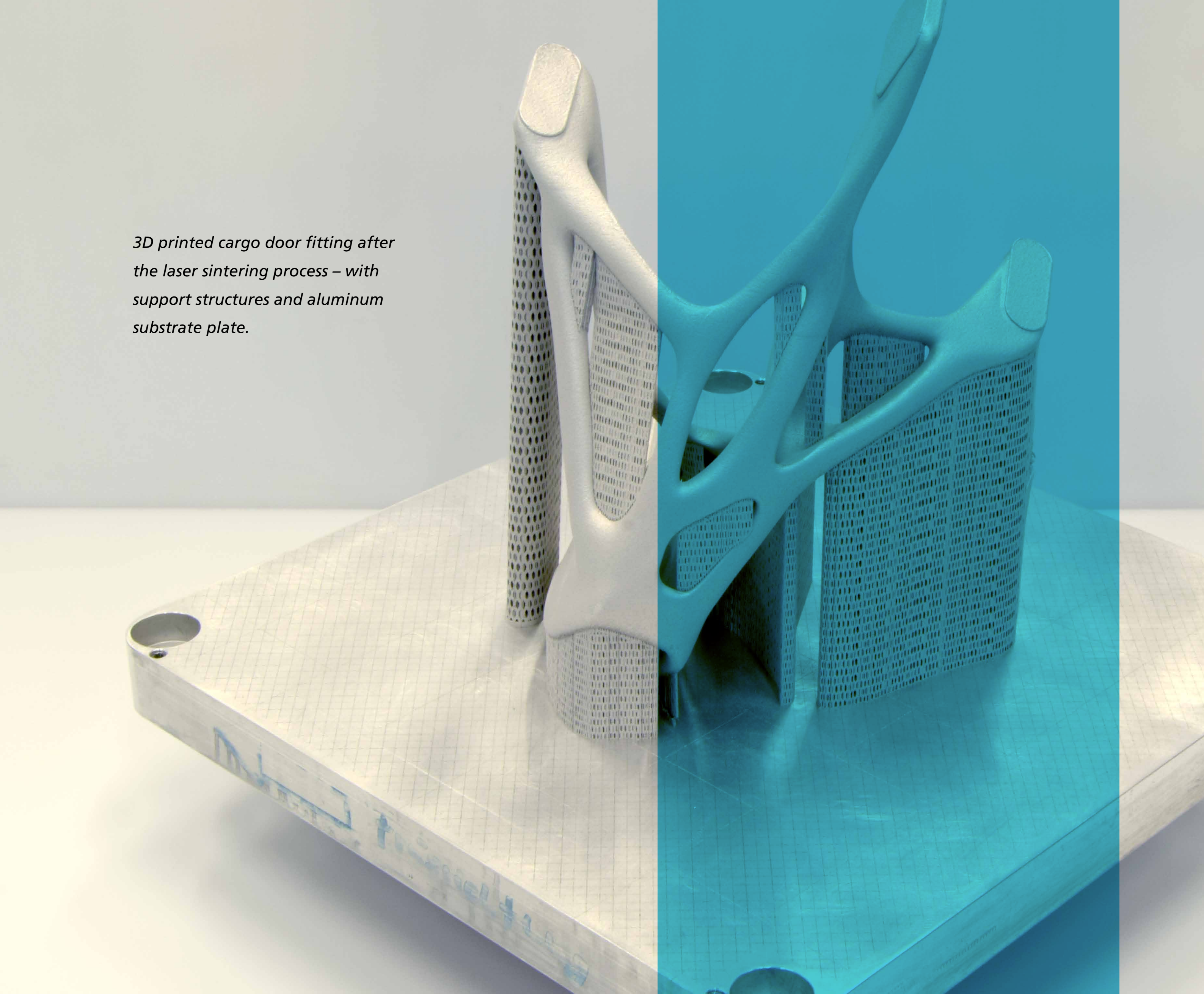

3D printed cargo door fitting after the laser sintering process – with support structures and aluminum substrate plate.

New fields of application and lightweight potentials of 3D printing of aluminum are in the focus of the Clean Sky 2 Joint Undertaking. The components have to be not only lightweight but also safe and sustainable. To obtain optimized and increasingly efficient systems as a solution, we employ intelligent design methods, lifecycle analyses, and simulation models.

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This project is funded by the European Union

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No. CS2-AIR-GAM-2018.

ADDITIVE MANUFACTURING FOR LIGHTWEIGHT, ROBUST AND SUSTAINABLE AIRCRAFT COMPONENTS

The sustainable use of resources and consistent or even increased safety are the main objectives in the eco-efficient, safe, and sustainable aviation of the future. In this regard, lightweight design and the use of high performance materials are potential key technologies, but at the same time result in high complexity of production processes and very high costs. However, 3D printing of light metals specifically has the potential to facilitate resource-efficient lightweight design. Only the amount of material that is really needed for the component is manufactured additively. In contrast to other technologies, no molds are needed, and no excess material has to be machined. Furthermore, this technology provides engineers with a considerably greater freedom of design when compared to conventional manufacturing processes with their geometrical restrictions. As a result, systems that are potentially lighter and more effective can be developed.

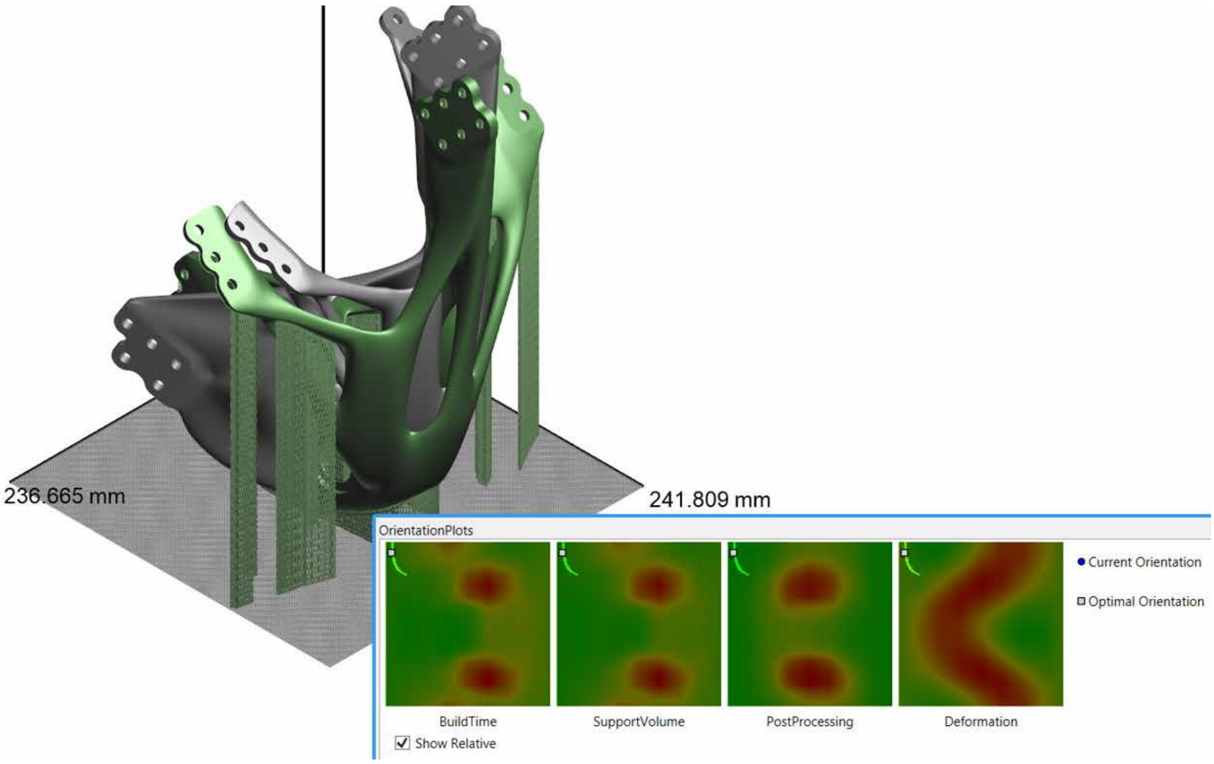
Design guidelines and lifecycle analyses for 3D printing of aircraft cargo door fittings made from aluminum

In cooperation with partners from the aviation industry, the scientists at Fraunhofer EMI investigate the possible fields of application for the 3D printing of aircraft components made from aluminum. This research is funded by the European Union in the joint undertaking Clean Sky 2. The research team unlocks new lightweight potential by exploiting the geometrical freedom, and establishes design guidelines for the efficient, essentially virtual product development. In addition, the entire life cycle of aircraft components is considered, and energy and material flows occurring during the manufacturing

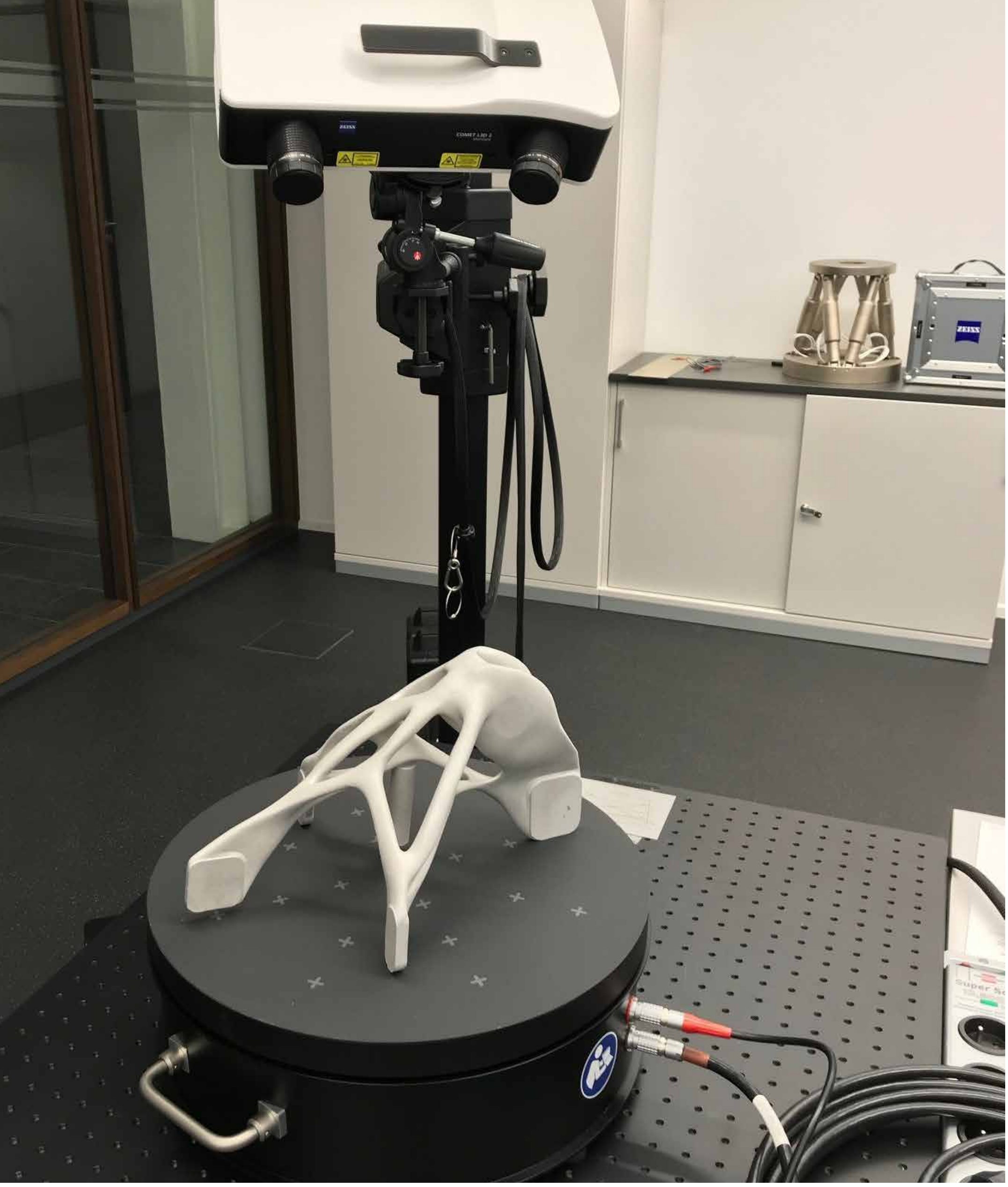
process are measured and analyzed. Thus, not only lightweight design and mechanical performance of the components are the main focus in the development of design guidelines, but also the sustainable use of resources in additive manufacturing and in the entire lifecycle.

Automated lightweight construction using intelligent design methods

New construction methods are needed in order to support engineers in exploiting the new freedom of design offered by additive manufacturing. Fraunhofer EMI is advancing simulation-based automated design models. In this context, the topology optimization method plays a decisive role. In the simulation, the load distribution in the component is determined and its geometry is optimized. The objective is to achieve a design solution with a more efficient load distribution and reduced weight employing an algorithmically automated process. At Fraunhofer EMI, we are working on the improvement of these methods for aircraft component production as well as on increasing the safety and robustness of the optimized lightweight solutions. In addition, the findings from the lifecycle analysis are integrated into the simulation models. In the end, not only lightweight design but also sustainability and component safety are important.



Development of design guidelines for the process using simulation methods.



High-resolution 3D scan of the 3D printed cargo door fitting for quality assessment.

Increased robustness and safety of optimized additively manufactured components

The freedom of design of additive manufacturing can be employed not only for lightweight design but also for attaining increased safety and robustness. At Fraunhofer EMI, we are working on designing topologically optimized components in a "fail safe" and structurally redundant manner. This means that components designed in this way can degrade gracefully when material failure occurs. For example, in the case of cracking or damage of the material, the load distribution is redirected in such a way that the safe operation is ensured and the affected component can be maintained or exchanged in time. In this way, redundant components can be avoided and safety factors significantly increased, and thus, systems that are more efficient can be developed.

DYNAMIC CRACK PROPAGATION

Taking into account the lightweight design concept, composite materials are increasingly used in primary and secondary structural components of modern airplanes such as the A 350 or the B 787. Composite materials are characterized by excellent in-plane properties but are susceptible to damage by loading in thickness direction due to their layered structure. A tool drop onto the wing of an airplane, hail damage, or the collision with a bird are typical examples of such loading scenarios.

During the design of aircraft structures, numerical simulation methods are increasingly used in order to guarantee the safety of aircraft structures under impact loading. The determination of strain rate dependent material properties is indispensable for predictive simulations but is often difficult. At Fraunhofer EMI, a novel experimental set-up for measuring fracture mechanical parameters under dynamic loading using the Hopkinson bar has been developed in cooperation with a customer. Thus, significant contributions to the safety of new generations of airplanes can be made.

The Hopkinson bar at Fraunhofer EMI.

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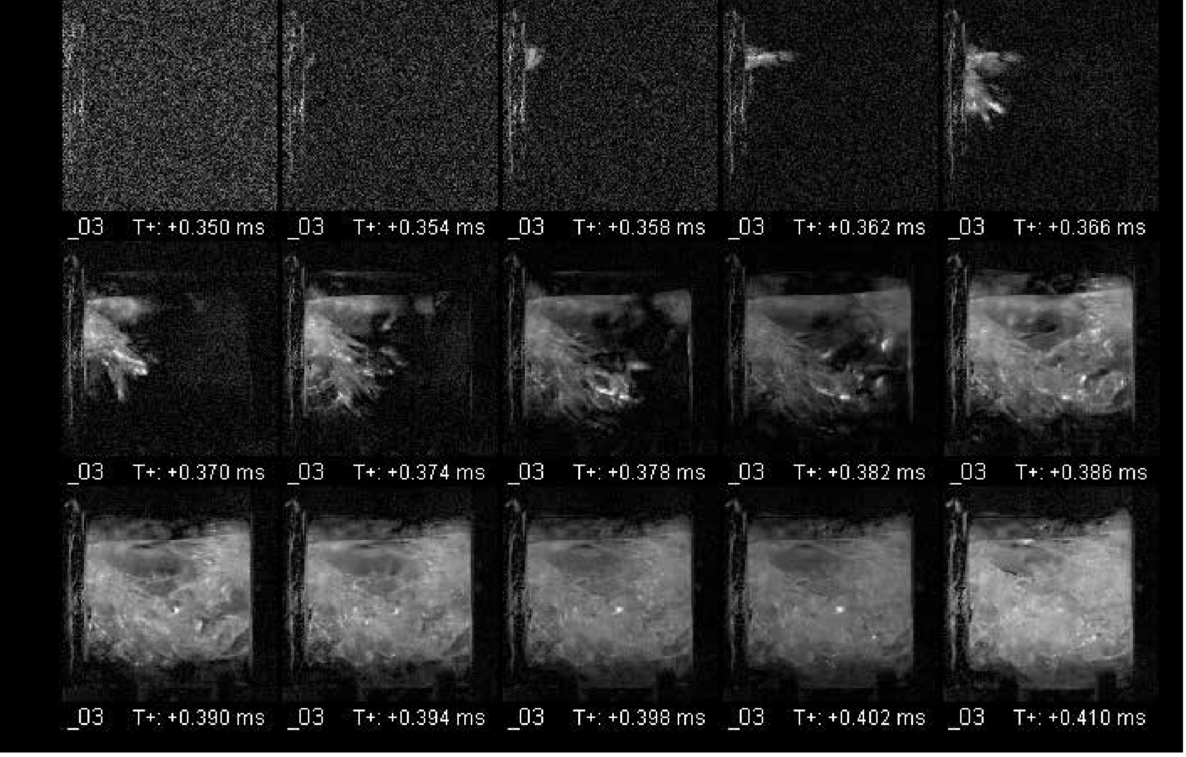

High-speed image of the crack propagation in an ice cylinder subjected to compressive loading in the split Hopkinson pressure bar.

SIMULATION OF ICE AND HAIL

Hail can lead to extensive damage on primary structures of aircrafts. The extent of damage on lightweight structures caused by hail is significantly determined by the properties of the ice impactor (hail stones) and the type of the used lightweight structure. In the framework of the EU project Clean Sky 2, Fraunhofer EMI has analyzed the modeling of ice impactors from an experimental and numerical perspective. Essential findings of the study show that the material behavior of ice depends on the loading velocity and the temperature. The major challenges were the tailored manufacturing of ice specimens and the conduction of test series under tempered conditions in advanced experimental setups, such as for example tests with the split Hopkinson bar and the high-speed accelerators for hailstorm scenarios. Another relevant observation was the significant scatter in material behavior and damage mechanisms. In the numerical modeling, this scatter could be depicted via a stochastic approach. In combination with a rate-dependent, brittle material model, the failure and the subsequent fragmentation of the ice impactors on impacted lightweight structures could successfully be reproduced.

For more information, visit
www.mdpi.com/1996-1944/12/8/1236

Clean Sky 2 | This project is funded by the European Union

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No. CS2-AIR-GAM-2018.

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ADMINISTRATON


ZAHLEN
&
FAKTEN

ADMINISTRATION

The past year at EMI has been characterized by intensive internal structuring. We will continue taking this path and continuously will keep optimizing our processes. The envisioned implementation of SAP in the entire Fraunhofer-Gesellschaft is a significant challenge. At the same time, we are facing the task to fill the keyword "New Work@Fraunhofer" with life and to advance the working environment at our institute. This is essential in order for us to remain attractive as an employer and improve our performance in increasingly complex and inter-institutional projects. The implementation of SAP as part of the agenda project Fraunhofer-Digital is gaining momentum, and it becomes increasingly clear that a comprehensive transformation of processes and structures will take place within Fraunhofer. In order to be able to implement this transformation successfully, we will have to incorporate the concept of "New Work" and purposeful human resources development.

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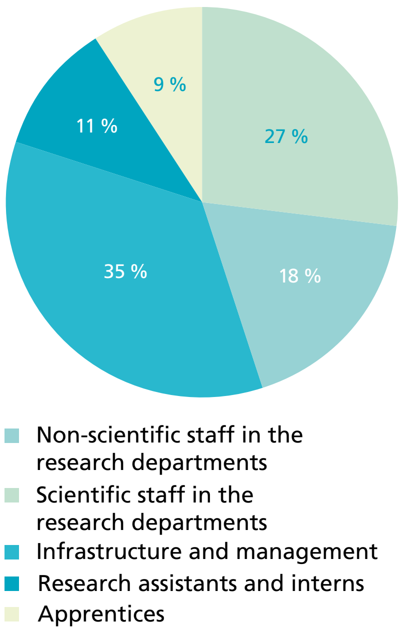
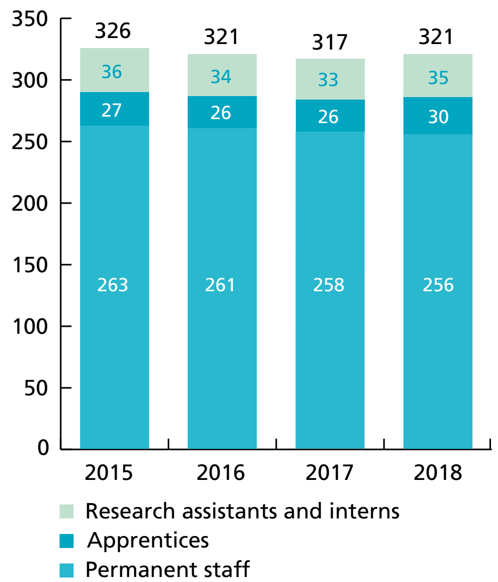
STAFF STRUCTURE

At the end of 2018, 321 people were employed at Fraunhofer EMI: 256 employees as permanent staff, 30 as apprentices and dual students, and 35 as research assistants and interns. 169 of the permanent staff were directly involved in research, and 87 worked in the fields of management and infrastructure. The proportion of permanent staff female employees increased to 27 percent. Ten of the 30 apprentices worked in precision mechanics, seven in electronics, and three in media design. The remaining ten worked at Fraunhofer EMI within the scope of their vocational training or their university studies at the Baden-Württemberg Cooperative State University (DHBW).

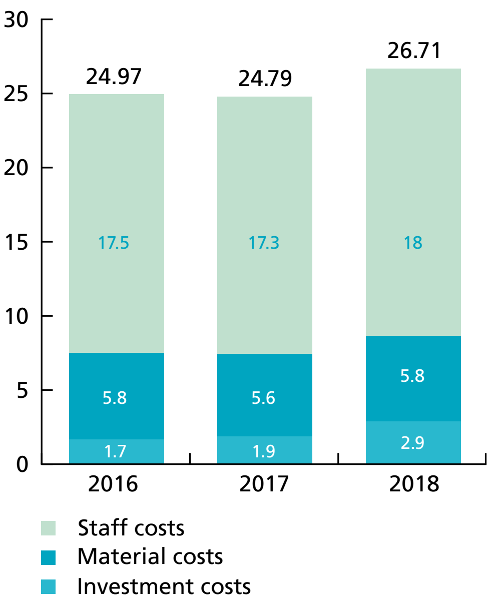




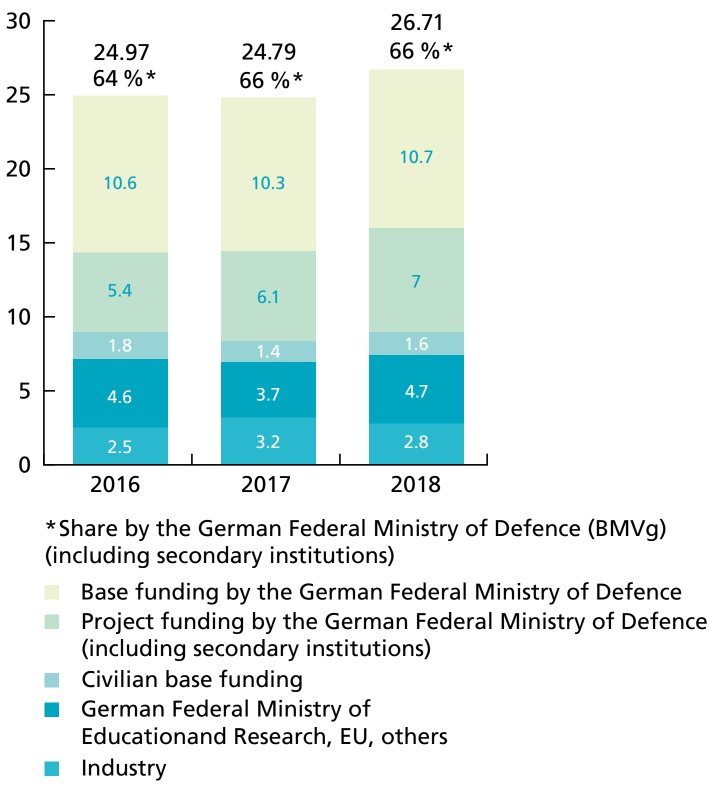
FINANCES

The total budget of Fraunhofer EMI increased to 26.71 million euros. 23.8 million euros of the total budget are allotted to the operating budget (staff costs and material costs) and 2.9 million euros to the investment budget. Fraunhofer EMI is being financed by external revenues from the industry, by public funding, and by institutional base funding by the German Federal Ministry of Defence (BMVg) and the German Federal Ministry of Education and Research (BMBF). 66 percent, the biggest share of the operating and investment budget, were financed by the German Federal Ministry of Defence in 2018. This year, the industrial revenues amounted to a very good result of 37.4 percent in total.

Finances of the overall budget in million euros



Finances overall budget in million euros



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The EMI advisory board at its meeting on July 20, 2018 in Freiburg.

ADVISORY BOARD

The advisory boards of the various Fraunhofer Institutes advise the directors of the institutes and the executive board of the Fraunhofer-Gesellschaft. The advisory board also enhances the institute's contacts to other organizations and to the industry.

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Dr. Rolf Wirtz
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The headquarters of the Fraunhofer-Gesellschaft in Munich.

FRAUNHOFER-GESELLSCHAFT

Research of practical utility lies at the heart of all activities pursued by the Fraunhofer-Gesellschaft. Founded in 1949, the research organization undertakes applied research that drives economic development and serves the wider benefit of society. Its services are solicited by customers and contractual partners in industry, the service sector and public administration.

At present, the Fraunhofer-Gesellschaft maintains 72 institutes and research units. The majority of the more than 26,600 staff are qualified scientists and engineers, who work with an annual research budget of 2.6 billion euros. Of this sum, 2.2 billion euros is generated through contract research. Around 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Around 30 percent is contributed by the German federal and state governments in the form of base funding, enabling the institutes to work ahead on solutions to problems that will not become acutely relevant to industry and society until five or ten years from now.

International collaborations with excellent research partners and innovative companies around the world ensure direct access to regions of the greatest importance to present and future scientific progress and economic development.

With its clearly defined mission of application-oriented research and its focus on key technologies of relevance to the future, the Fraunhofer-Gesellschaft plays a prominent role in the German and European innovation process. Applied research has a knock-on effect that extends beyond the direct benefits perceived by the customer: Through their research and development work, the Fraunhofer Institutes help to reinforce the competitive strength of the economy in their local region, and throughout Germany and Europe. They do so by promoting innovation, strengthening the technological base, improving the acceptance of new technologies, and helping to train the urgently needed future generation of scientists and engineers.

As an employer, the Fraunhofer-Gesellschaft offers its staff the opportunity to develop the professional and personal skills that will allow them to take up positions of responsibility within their institute, at universities, in industry and in society. Students who choose to work on projects at the Fraunhofer Institutes have excellent prospects of starting and developing a career in industry by virtue of the practical training and experience they have acquired.

The Fraunhofer-Gesellschaft is a recognized non-profit organization that takes its name from Joseph von Fraunhofer (1787–1826), the illustrious Munich researcher, inventor and entrepreneur.

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Fraunhofer

For further information, visit www.fraunhofer.de/en

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