Federal Ministry
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Annual Report Military Scientific Research and Innovation 2025



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Annual Report
Military Scientific Research and Innovation 2025


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Defence Research and Innovation for the German Armed Forces



The security developments of recent years and the dynamics of technological innovations have been fundamentally changing the demands placed on the Bundeswehr. New capabilities must be developed, evaluated and made available in a much quicker fashion. At the same time, a lot of the technologies that are relevant for the security and defence sectors today emerge outside of traditional defence-related development processes.

Innovation starts with research

Innovation is more than the mere development of new technologies. It is a pathway leading from scientific knowledge to the introduction of new capabilities into the armed forces. And defence research is the foundation of it all – the scientific groundwork on which innovation is based.

Especially in the field of dual-use technologies, cooperation and networking are becoming increasingly important. Science, industry and the Bundeswehr must combine their respective strengths at an early stage, which will make it possible to more quickly identify technological developments, assess their potential and make them usable for the Bundeswehr. Universities and research institutions as well as established companies, start-ups and new actors in innovation financing all play a part in this.

Innovation depends on cooperation

Innovation arises where scientific knowledge, technological development, industrial implementation and military application interact. For this to be possible, it is crucial to involve the future users at an early stage. Only if research, development and military requirements are brought together from the very beginning can innovations be achieved that result in a lasting gain in capabilities.

This is why the Bundeswehr consistently develops its understanding of what innovation means. With the establishment of its Innovation Centre, the Bundeswehr is now capable of contributing to defence research in a very specific manner. The Centre bolsters the transfer of knowledge and technology, facilitates cooperation with new innovation partners and creates additional opportunities for technological developments to be identified at an early stage, tested and introduced into the armed forces, while also promoting the interaction between the research domains within military science.





Conducting research in defence technology, military medicine, military psychology, social science, military history and geoscience offers an array of different perspectives and competences, which, when brought together, open up new approaches to solving complex issues and strengthen the Bundeswehr‘s capacity for innovation.

However, innovation is not a linear pathway. Lessons learned from experimentation, testing and in-service use lead to new research questions. As such, research and innovation are the building blocks of a continuous process of learning and improvement.

An annual report with aspirations

Also, for the first time, these developments have found their way into the title of this report. The Annual Report on Defence Research, as it was previously known, is now the Annual Report on Defence Research and Innovation, the new title illustrating a broader understanding of innovation – with research as its scientific core.

Innovation, however, can arise only out of the interaction of all of the actors who gather the scientific findings, develop them further and transform them into new capabilities for the Bundeswehr.

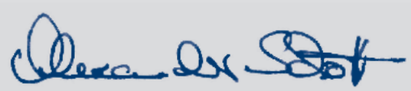
In its 2026 annual report, the Commission of Experts for Research and Innovation emphasizes the importance of strategically strengthened security-relevant research and efficient networking structures. The „High-Tech Agenda Germany“ similarly highlights security and defence research as a strategic field of research. These developments serve as a confirmation that we are on the right track.

This annual report illustrates what defence research is capable of and at the same time provides insight into its systematic further development. The articles show how scientific excellence, interdisciplinary cooperation and a modern understanding of innovation together contribute to a sustainable strengthening of the Bundeswehr‘s technological capacity for action.

Defence research creates the scientific foundations for the capabilities of tomorrow. The value of such research does not only lie in new findings as such, but also in how effectively these findings are transformed into innovations and ultimately find their way into the Bundeswehr. This is what we are working on together with our partners from science, industry and the armed forces.

I would like to thank all authors for their contributions to this annual report. And as for you, dear readers, I wish you an inspiring read!

With best regards



Alexander Schott





Foreword **4** **Defence Research and Innovation for the German Armed Force**

Part 1 **11** **Innovation projects and methods for the future and further development of the Bundeswehr**

12 Process Modelling for Military and Administrative Workflows

14 Predictive Analysis for In-Service-Support of Main Weapon Systems meets Bundeswehr Private Cloud

16 Multi-Domain Operations Command & Control (MDO C2) – Enabling Cross-Domain Operational Command and Control

18 GenAI-assisted Qualitative Data Analysis

20 Use of Computed Tomography for Acceptance Testing of Additively Manufactured Space Products: Possibilities and Limitations

22 Security in space – Dynamic operations and refuelling ensuring our capacity for action in orbit

24 KIOBS AI-supported Video Analysis Equipment Designed for Protecting Objects and Securing Restricted Areas of the German Armed Forces

Part 2 **26** **Defense Research and Technology**

28 Alternative Stabilisers for Gun Propellants

30 Ageing Effects on the Shock Sensitivity of Explosives Formulations

32 ERNST in Orbit – First Successes of the First Small Satellite Developed for the Bundeswehr

34 Anomalous Electromagnetic Propagation and its Impact on Radar System Performance

36 Ergonomic Design of a Standardized Ground Control Station for Loitering Munition

38 Visual Global Navigation Satellite System (GNSS)-free Navigationn

40 Integrated Broadband Front-end Solutions for Multifunctional Antenna Systems

42 Simulation of the Combustion of Multi-Material and Complex-Shaped Gun Propellants





44 Component-Based Object Recognition, Demonstrated by the Example of Military Vehicles

46 Visual Action – Determining Pilot Compensation through Eye Tracking

48 Simulation, Manufacturing and Experimental Validation of a Multi-layer Radar Absorbing Material

50 The Path to Automated Air-to-air Refuelling in the FARAO Project

52 OTTER Mission – Optical Traffic Tracking for Responsive Space

54 AI-based Camouflage Assessment with ABACUS

56 Influence of Geometric Dimensioning on the Unsteady Aerodynamics of Highly Contoured Aircraft Engine Intakes

58 Measurement of the Aacoustic Target Parameter of Underwater Objects Using Scaled Models

60 Software Vulnerability Analysis

62 Laser Weapons in the Context of Current Airborne Threats

Part 3 **64** **Military Medical Research and Military Psychology Research**

66 Internal Dosimetry – Measurement, Modelling and Assessment

68 Detection and Isolation of Francisella tularensis Using Recombinant Reporter Fusion Proteins

70 Novel Human Neuron Model for the Development of Antidotes Against Nerve Agents

72 Reliable Identification of Severe Lung Injuries After Chest Trauma – Photon-Counting CT Improves Diagnostic Imaging in Emergency Medicine

74 Immune Response as a Prognostic and Therapeutic Window – Cross-Species Biomarker Signatures after Severe Trauma

76 Preserving Operational Readiness Through Modern Dermatology: A Health Services Research Study of Psoriasis

78 Resilience in Three- and Six-Month Basic Military Training Programmes – a Model for National and Collective Defence

80 Parallels in Problematic Anger Between Military and Police Personnel Following Shootings: How Different Types of Deployment Affect the Mental Health of Emergency Respondersn

82 Effects of Rotating and Fixed Shift Patterns in Watchkeeping on Board





Part 4 **84** **Military History Research and Social Science Research**
86 The German Military in Colonial Operations, 1880–1918. A Continuum of Violence
88 What Can, and What Does, Military Chaplaincy Achieve? Pastoral Care and Religion in the German Armed Forces

Part 5 **90** **Geoscientific Research**
92 When Biology meets Cyber

Part 6 **94** **Bundeswehr-Related Research at the Bundeswehr Universities**
96 Wargames as Experiments
98 Hybrid Defence: Robust AI as an Innovation Driver
100 Additively Manufactured Reinforced Concrete for Structural Protection under Extreme Loads
102 Compatibility of Elastomers with Pyrolysis Oils

Part 7 **104** **Appendix**
106 Addresses and Contacts
112 Editorial Details





1

Innovation projects and methods for the future and further development of the Bundeswehr

The ability to innovate, and to make innovations available to the troops in a timely manner, is one of the guarantors of success when it comes to ensuring superiority of our armed forces and their deterrence capability. For this purpose, the Bundeswehr draws on its innovation management and its methods for future and further development that seamlessly work together to achieve this goal. The innovations and research projects described in the first chapter are quite diverse and reflect activities that stem from different methods and project phases. Their evolution is what they have in common – from the first idea on to multi-stage testing and further development to application and use within and by the troops.

The first research article illustrates how complex workflows are used to precisely assign responsibilities and resources by means of clearly structured models. Successful implementation has already been demonstrated in the Joint Support and Enabling Command and the Bundeswehr Joint Force Command, which shows that the “culture of change” is being taken seriously. The subsequent article focuses on an IT service that makes predictions as to the materiel readiness of weapon systems on the basis of usage data, machine learning and cloud infrastructure. Interim operation of the application began in 2025, and it has since undergone further development so as to be available to all users as a central data-driven service.

The “Multi Domain Operations Command & Control” study looks at cross-domain coordination and expedited decision-making with the aim to increase battlefield survivability. Seven different use cases are examined in the context of multi-domain operations command and control, with the focus on defence as a whole-of-government task. The CD&E project presented thereafter shows how generative AI can change qualitative data analysis in such a manner that informed military decisions can be made. The results also illustrate how services like these can be operated on controlled hardware to meet defence requirements.

On to an entirely different domain: DeltaOrbit GmbH is developing highly agile satellite systems that combine high thrust with high efficiency by means of cryogenic propulsion technology. The resulting multi-orbit agility is a completely new capability and significantly expands the operational range in the context of space operations. Then, DeltaVision GmbH, which also formed part of the DIANA Cohort 2025, presents the development of a fuelling infrastructure for space operations, the orbit transition demonstration of which is scheduled for 2026. The highly mobile refuellable prototype vehicle is a major contribution to European sovereignty in a contested orbit. Finally, we will take a look at an AI-based video analysis system which uses machine learning (ML) to relieve the user from routine tasks while also offering additional capabilities. In doing so, ML is taken from its research environment and brought to operational viability.

The innovations presented in this work underline the following: Innovation is an integral part of the strategic further development of the Bundeswehr and the basis for successfully meeting the evolving challenges of the 21st century and to ensure technological sovereignty of our armed forces.

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Process Modelling for Military and Administrative Workflows

Complex workflows require structured modelling, a clear assignment of responsibilities, and the identification of resources. To this end, the Bundeswehr Office for Defence Planning uses process discovery and optimisation methods. The results are documented digitally to enable architecture and software development. The goal is to create effective organisations with seamless internal workflows and external communication.

The increasing complexity of workflows across all Bundeswehr agencies necessitates a structured, transparent, and comprehensible design of processes – whether they are operational, administrative, or command-supporting. Without a clear assignment of responsibilities, resources, and interfaces, processes often become redundant or inefficient, which can lead to delays or errors during crises or in peak demand situations. Branch I 2 (3) "Systems Analyses" at the Bundeswehr Office for Defence Planning provides a proven tool for process modelling: the Best-Knowledge Method (Beste-Kenntnis-Methode, BKM).

Developed in 1997 by Dr Markus Gappmaier, BKM enables holistic modelling, optimisation, and renewal of business processes through visual, collaborative work using standardised cards (Fig. 1). It is employed to consolidate dispersed expertise, systematically analyse processes, and develop and optimise solutions together with all stakeholders. The Bundeswehr Office for Defence Planning uses BKM as a structured method to convert complex processes into clearly organised models, working closely with subject matter experts.

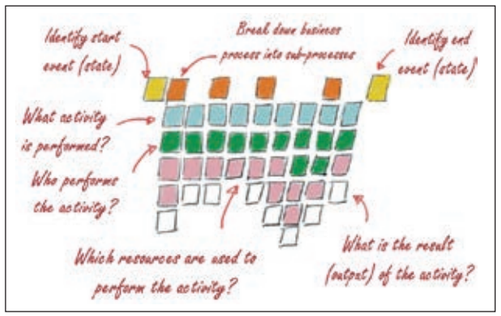


Fig. 1: Visualisation of the Best-Knowledge Method – a structured mapping of processes using standardised cards

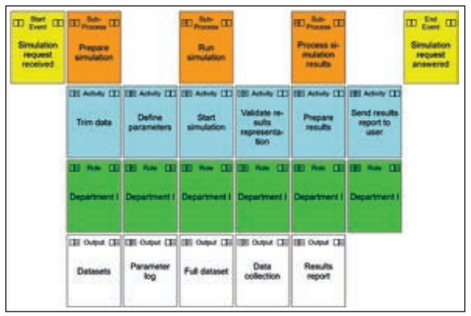


Fig. 2: An exemplary business process is mapped using the Best-Knowledge Method, illustrating subprocesses, activities, responsibilities, and outputs transparently within the process flow

Current-state processes (Fig. 2) and future target-state processes can both be mapped in order to visualise functional relationships, clearly define responsibilities, and identify potential for optimisation.

A prominent example of this is the application of BKM within the NATO Joint Support and Enabling Command (JSEC). During multiple workshops involving international participants, the core processes of "How JSEC operates" were modelled, documented, and optimised. The results were incorporated directly into the JSEC Enablement Coordination Directive and have since been evaluated during exercises.

The objective of the Best-Knowledge Method is to design organisations in a process-oriented manner, making them more agile, risk-aware, and responsive. For the German Armed Forces to operate efficiently and reliably in all situations, workflows must be clearly defined, comprehensible, and open to continuous improvement. The method is scalable and can be applied across all domains – from the internal operations of a Bundeswehr technical centre to the overarching operational processes of an operations command. It is a flexible instrument that can be adapted to specific organisations and their challenges. Further documentation is conducted in Business Process Model and Notation 2.0 (BPMN 2.0) – an internationally standardised format that is not only suitable for internal process communication but also enables direct access to architecture and software development. This makes processes usable across all levels – from leadership to execution (Fig. 3).

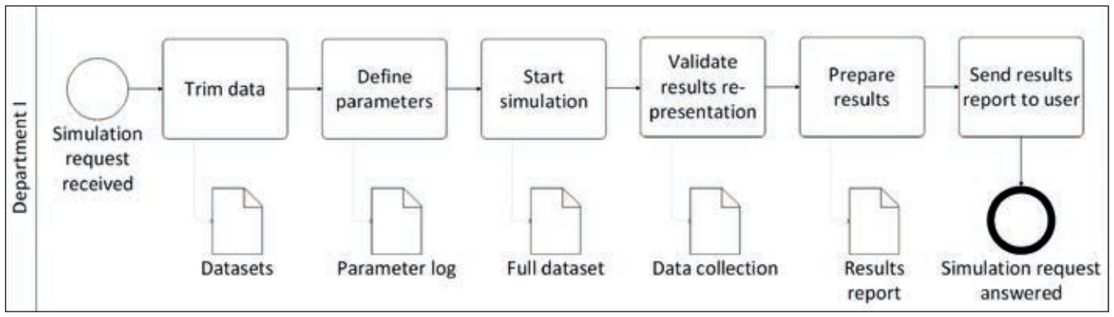


Fig. 3: An exemplary business process as a BPMN 2.0 model, transformed from a structured process representation previously developed using the Best-Knowledge Method

BKM and other methodological tools employed by the Bundeswehr Office for Defence Planning are not merely viewed as "modelling tools", but as "process of change": Through joint process discovery and discussion of issues, a shared understanding emerges that goes beyond mere documentation. This fosters transparency, promotes interaction between and within units and departments, and contributes to a culture of continuous improvement. Thus, BKM is more than a method – it is a tool for organisational transformation. It creates not only structure, but also understanding, accountability, and readiness for change. This is precisely what is necessary to make the German Armed Forces resilient in times of peace, crisis, and war.

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Predictive Analysis for In-Service-Support of Main Weapon Systems meets Bundeswehr Private Cloud

The Predictive Analysis Capability for In-Service-Support of Bundeswehr Main Weapon Systems is an IT service that uses simulation-based forecasting to determine the materiel readiness of weapon systems. Using usage data, machine learning and cloud infrastructure, it enables not only availability forecasts, but also "what-if" analyses as decision support for optimising operational readiness of material resources. Having been implemented temporarily on the Bundeswehr private cloud (Private Cloud Bw) since 2025, the Predictive Analysis Capability is being further developed by a cross-departmental team from the Bundeswehr Office for Defence Planning (PlgABw) and BWI. From October 2026, it will be available as a central, data-driven service to a broad user base.

Cold start capability, a key requirement for the Bundeswehr, demands a high level of operational readiness of material resources. However, availability has consistently fallen short of expectations for years – a situation that highlights the need for data-based forecasts for usage, maintenance and logistics. In 2018, therefore, the Federal Ministry of Defence (BMVg) commissioned the Bundeswehr Office for Defence Planning to develop such a capability. Three studies with industrial partners investigated the feasibility of simulation models for representative systems and came to the conclusion that it is possible to create weapon system-specific forecasts in separate simulations, providing the "blueprint" for subsequent projects.

On this basis, the project "Predictive Analysis Capability for In-Service-Support of Main Weapon Systems" was established. It combines simulation models for selected major equipment in a joint software demonstrator. The simulation quantifies the impact of usage profiles on failure behaviour down to the main assembly level and predicts future maintenance requirements over several years. Statistical methods and machine-learning are used to analyse usage patterns, calculate wear parameters and transfer them into the simulation (Fig. 1). By additionally allowing input parameters (required operating hours, changed maintenance intervals, available maintenance capacities) to be varied, "what-if" scenarios can also be tested by way of calculation.

A prime example is the TIGER attack helicopter: Despite its proven operational performance, it suffered from low availability. The Predictive Analysis Capability helped to identify the causes – in particular, the maintenance plan and maintenance capacity proved to be limiting factors. By simulating various change scenarios, the most effective package of measures could be selected. As changes only take effect with a time delay, prior simulation is crucial for making well-founded, cost-efficient decisions. The results were directly used in target agreements between the Bundeswehr and industry.

Building on this success, other major equipment projects such as the GTK Boxer, the Puma infantry fighting vehicle, the NH90 and the A400M recognised the value of this service and joined it.

Until 2024, the Predictive Analysis Capability operated within a closed IT environment at the Taufkirchen site. With the Bundeswehr's "Cloud First" strategy, the opportunity arose in 2024 to include it as a cloud-based service in the "Analytics & Simulation" cluster programme for 2026. A joint development team from the Office for Defence Planning and BWI was established and has since been working with purpose toward the launch of the cloud service. Initially, this service was implemented in the pCloudBw development environment, then it was transferred to the production environment accredited for processing information classified VS-NfD. During the interim period (until October 2026), the service is available to selected users. In target operation, the IT solution will be structured in three stages: data storage on the Big Data platform (Fig. 2), analysis on the Data Analytics platform (pCloudBw, Fig. 3), and simulation of operational readiness, if required. A central advantage is that data from different sources and formats will be stored in one place – this is unique compared to existing systems.

Today, the "Predictive Analysis for In-Service-Support of Main Weapon Systems" is an experimental, but already operational, IT service for simulation-based fleet analysis. It supplements the knowledge of weapon system experts with objective, data-driven and reproducible forecasts. In conjunction with BWI's private cloud strategy, the service will enable many project managers to purposefully control the use of their systems in future – and thus achieve a lasting improvement of the operational readiness of material resources.



Fig. 1: Operations Research (OR) – a method of future and further development

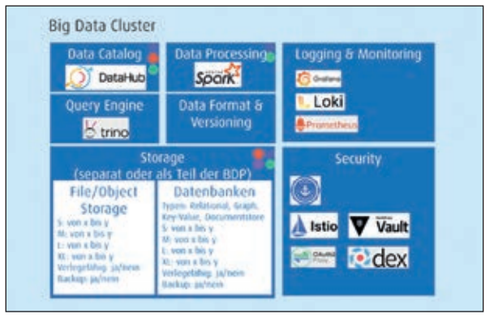


Fig. 2: Big Data Cluster – central data storage (Source: BWI GmbH)

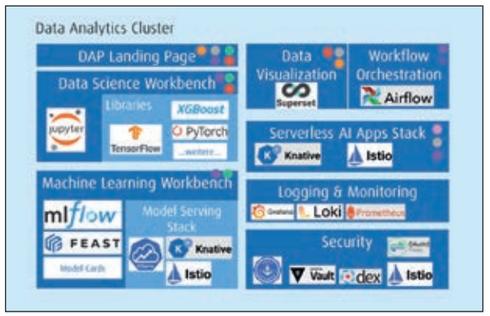


Fig. 3: State-of-the-art analytics workbench (Source: BWI GmbH)

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Multi-Domain Operations Command & Control (MDO C2) – Enabling Cross-Domain Operational Command and Control

In a data-centric warfare environment, MDO C2 is intended to facilitate cross-domain coordination of sensors and effectors — across the land, air, sea, cyber, and space domains, as well as across operational and functional dimensions — through harmonised, multinationally interoperable processes and procedures. This directly supports faster, more effective decision-making, which in turn supports enhanced battlefield survivability.

Modern warfare demands seamless coordination across all military domains: land, air, sea, cyber, and space. Multi-Domain Operations (MDO) are also an operational necessity, not just a tactical one, required to maintain superiority in an increasingly complex and networked battlespace.

MDO is fundamentally dependent on Command & Control (C2) processes and technologies. The availability of the required information in a resilient information and communications network ensures that decision-makers receive the right information — in the right form, at the right time, and in the right place — forming the essential foundation for a shared operational picture.

As the operational driver within the overarching CD&E (Concept Development & Experimentation) project on MDO, the MDO C2 subproject addresses the cross-domain planning and conduct of operations through different use cases. The subproject emphasises the need for plug-in capable furnishings and frames defence in the national and collective defence scenario as a whole-of-nation endeavour — requiring integrated civil-military coordination across all levels of government and society.



Fig. 1: MDO C2 in the context of data-centric warfare



Fig. 2: Experimentation of the Tactical Air Forces Integration Cell use case during Timber Express 2025

Assessing how we fight today — and experimenting with how we must fight under MDO in the future — forms the core framework for all activities within the MDO CD&E program.

The 2025 assessment of the actual state of the matter focused on Joint Fire C2 processes. In addition to evaluating the speed of operation and quality of situational awareness, the analysis examined both existing technical conditions and potential solutions to identified capability gaps.

The data collected through workshops and exercise participation (Timber Express / MFE ANDOJA) as well as dedicated experimentation conducted during the 20/25 iteration at the German Army's Combat Training Centre will serve as the comparative baseline for the target-state assessment planned for the 2026 annual tranche.

A key outcome of this endeavour was the development of the "Tactical Air Forces Integration Cell" use case, which operates as a cross-domain integrator. Commenting on the experimentally developed prototype of the cell, Lieutenant General Lutz Kohlhaus, Vice Chief of the German Air Force, said:

"Its mobility ensures the integration of tactical air force command and control with the Army's command posts at brigade and division levels during mobile operations. Furthermore, it enables the inclusion of the Space Command, Cyber and Information Domain, and the Navy in coastal areas [...] through the use of standardised IT services — including the Sitaware software — interoperability within the NATO framework is assured."

Building on this foundational capability, the next phase will involve expanding cross-domain, multinational integration — incorporating civilian stakeholders into the operational ecosystem.

In 2026, dispersed processes from different domains will be synchronised and aggregated into a unified, cross-domain Joint Fire C2 process. This concept will then be tested and analysed in subsequent exercises, including Timber Express and Spartan Arrow.

Overall, MDO C2 has demonstrated early successes within the context of data-centric warfare. To support iterative development, the task is to further integrate proven technical solutions to enhance operational processes — particularly through collaboration with industry partners and in compliance with stringent security and interoperability requirements.

In order to ensure that MDO C2 remains operationally viable and resilient, greater attention must be paid to organisational design and human factors, which need to be synchronised with technological and procedural developments in a more systematic way over the remaining timeframe of the project.



Fig. 3: Assessment of the current state of the Joint Fire C2 process during ANDOYA 2025



Fig. 4: Experimentation with the "Ground Observer 12" ground radar system in collaboration with units from 1 Air Defence Brigade, 7 Reconnaissance Battalion, and 8 Reconnaissance Battalion

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GenAI-assisted Qualitative Data Analysis

The Bundeswehr Office for Defence Planning is leading a national research initiative to explore how generative AI (GenAI) can transform qualitative data analysis to inform military decision-making. The study will also examine how such GenAI services can be employed in compliance with defence and information security requirements (Fig. 1).

The ability to systematically analyse large amounts of qualitative data, such as text, audio, and visual content, is essential for making informed decisions in any organisation. Traditionally, processing qualitative data relied heavily on manual analysis by experts. However, recent advances in generative artificial intelligence (GenAI) now enable the automated, context-aware analysis of complex qualitative datasets, unlocking insights from previously underutilised information sources.

In order to harness the potential of these technologies for the German Armed Forces, a national research project (Fig. 2) was initiated in cooperation with Airbus Defence and Space. The project aims to determine how GenAI can be effectively employed in different military scenarios to transform qualitative data into valuable insights for decision-makers.

The use cases investigated include:

- structuring and aggregating qualitative information,
- enabling context-aware semantic searches across extensive document archives,

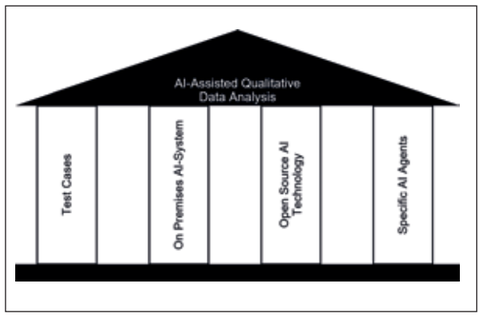


Fig. 1: Key aspects of the research project



Fig. 2: Project logo

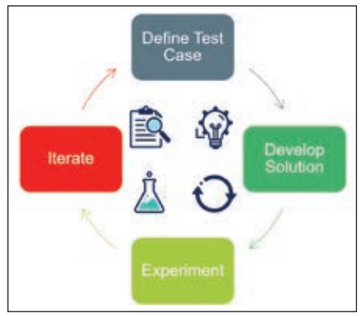


Fig. 3: Methodology of research project based on Gartner's GenAI pilot cycle

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- supporting enterprise architecture management,
- optimising and analysing business processes.

The approach in this project is based on Gartner's "GenAI Pilot Cycle" (Fig. 3). First, concrete military use cases are identified and specified. Subsequently, agent-based AI tools are developed and tested iteratively. These agents leverage the core capabilities of multimodal large language models (LLMs) to transform unstructured data into strategic and decision-relevant information.

To holistically analyse extensive document repositories and to handle complex tasks, an AI agent based on the DeepAgentFramework was implemented to overcome the limitations related to the context windows of traditional approaches. This agent overcomes the context-related limitations of conventional approaches and is equipped with special intra-model skills, tools like interfaces to databases or APIs, subagents and a cross-context, long-term memory, to solve complex problems (Fig. 4).

Furthermore, a multi-layered, multimodal AI agent was developed for the analysis of military processes in the context of Viewpoint C4 ("Standard Processes") of the NAFv4 framework. This agent uses generative AI capabilities to process visual, textual, and structured data simultaneously in order to generate Business Process Model and Notation (BPMN) compliant processes and answer analysis questions.

The project also demonstrates how GenAI capabilities can be operated in isolation using a container-based architecture that is based on open-source technologies (Fig. 5). This not only ensures compliance with strict security requirements but also makes the solution independent of licensing models and makes it scalable, flexible, and platform-independent.

Our objective is to substantially reduce the manual effort required for qualitative data processing while improving the accuracy, consistency, and reproducibility of the results. By doing so, we intend to leverage the transformative potential of generative AI to enable more agile, data-driven planning and decision-making within the German Armed Forces.

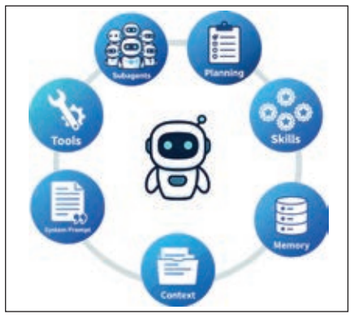


Fig. 4: Schematic representation of DeepAgent



Fig. 5: Open-source technology stack

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Use of Computed Tomography for Acceptance Testing of Additively Manufactured Space Products: Possibilities and Limitations

DeltaOrbit – the only German start-up involved in Phase 2 of NATO's Diana Accelerator – develops highly agile satellite systems that combine high thrust with high efficiency through cryogenic propulsion technology. This results in multi-orbit agility, representing a completely new capability that greatly expands the scope for space operations. Among the challenges to be taken on in this field are the realisation and testing of the highly-complex component designs required for such systems. To address this, DeltaOrbit relies on additive manufacturing and non-destructive micro-computed tomography (µCT).

In the emerging 'New Space' era, mobility is the key to achieving strategic sovereignty in space. To this end, Munich-based startup DeltaOrbit GmbH is developing an innovative propulsion solution in the form of a space transporter (Fig. 1) that uses cryogenic methalox propellants to combine high thrust with high efficiency.

The innovation lies in the possibility to store and reignite these high-energy propellants in orbit. This enables true multi-orbit agility, allowing satellites to perform complex manoeuvres, such as significantly changing their inclination or orbital altitude. Using a 'hub-and-spoke' model as a future organisational structure in space economy will enable payloads to be cost-effectively delivered to a parking orbit and distributed flexibly into target orbits, as shown in Figure 2. This also allows new strategies to be adopted in defence. Thanks to multi-orbit agility, satellites can be kept available in parking orbits and, in an emergency, transferred to operational orbits within hours.

In the long term, this architecture can be scaled up for lunar and interplanetary missions, opening up options for applications beyond Earth orbit. DeltaOrbit is thus addressing a critical capability gap, in line with the agenda of the European Space Agency (ESA) and the European Commission aiming for a sovereign European space infrastructure. Recognising the strategic importance, the German government's recently published National Space Safety and Security Strategy also explicitly requests 'multi-orbit agility'.

To address this subject, DeltaOrbit employs additive manufacturing, which enables the required complex component designs – such as the engine's spiral cooling channels – to be produced with high precision. Another challenge in this matter is that the strictest requirements apply to internal, inaccessible but functional structures; non-destructive micro-computed tomography (µCT) is a valuable option to overcome this issue. Its high resolution, made possible by the small focal spot, can identify particles, cracks, or blockages in controlled processes in order to assess hardware test readiness. Furthermore, dimensional accuracy can be evaluated. A simplified representation of the test setup is shown in Figure 3. A testing system of this kind is operated by WIWeB, for example.

In this investigation, we considered a nickel-based alloy combustion chamber manufactured by means of laser powder bed fusion. The powder that was used featured a standardised particle size distribution and had been applied at a layer thickness of approximately 40 µm. The CT scan was performed at a tube voltage of 260 kV, providing a voxel size of approximately 52 µm and enabling a detailed assessment of the internal geometry and measurement technology.

Although the 2D X-ray images obtained through µCT were successfully reconstructed into a 3D volume, they can only be used to a limited extent as a CAD model due to high scatter radiation, especially in areas of thick-walled component structures. Foreign bodies of 100 µm and above in size as well as the 1-mm-wide cooling channels could be represented precisely, enabling blockage analyses. Examples of foreign objects and debris are shown in Figure 4. Limitations were observed in terms of dimensional accuracy and roughness quantification. The latter could not be performed due to the material density and the component geometry. Additionally, scatter radiation affects image data in areas of high wall thickness and material accumulation, which complicates quantitative evaluation. Examples of this are shown in Figure 5.

Conclusion: µCT is an efficient method for detecting defects and higher-density material residues in such components, for example cooling channel blockages and contaminations, provided they are at least the size of the voxel size used. When material composition, component geometry and occurring scatter radiation (Fig. 5) are taken into account, µCT can be used as a complementary testing method prior to component testing. Massive structures require higher energy – like that provided by 450 kV tubes or linear accelerators – for macroscopic defects to be detectable. However, this comes at the expense of spatial resolution.

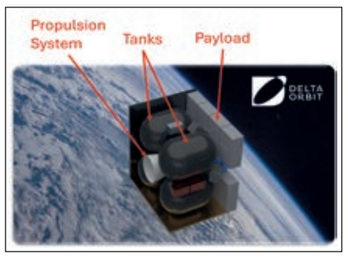


Fig. 1: The DeltaOrbit space transporter (conceptual visualisation of the Space Tug) with a chemical propulsion system



Fig. 2: Hub-and-spoke concept: efficient transport of payloads within space using a parking orbit as starting base

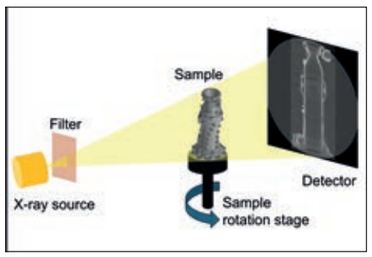


Fig. 3: Schematic diagram of the µCT test setup. The component to be tested is rotated step by step and x-rayed

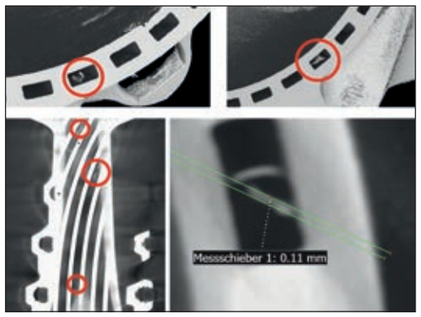


Fig. 4: Example µCT images showing foreign objects in the cooling channels

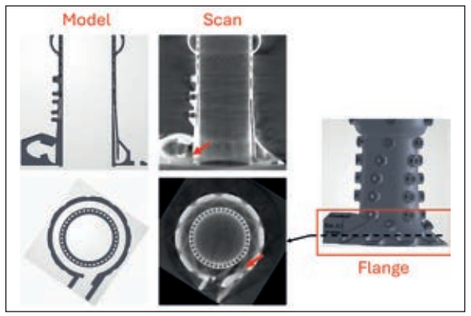


Fig. 5: Comparison between CAD model (left) and µCT scan (right): influence of scattered radiation in areas with thick walls (flange area). Examples of areas with poor image quality are indicated.

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Security in space – Dynamic operations and refuelling ensuring our capacity for action in orbit

deltaVision, an innovator in the NATO DIANA programme, is progressively developing technologies for dynamic space operations and a European in-orbit refuelling infrastructure. The 2027 OPTRA demonstration will pave the way for DOVE – a highly manoeuvrable, refuelling-capable spacecraft used for Earth observation, situational awareness in space, inspections, and electronic warfare. This approach will increase resilience and sovereignty.

Space has become a contested operational domain, in which static satellites are predictable and therefore vulnerable. To maintain their advantage and protect critical services, Germany and Europe must adopt Dynamic Space Operations (DSO) – a move made possible by manoeuvrable platforms capable of frequent repositioning, rapid reaction and extended operation thanks to in orbit refuelling infrastructure (Fig. 1).

Following this approach, deltaVision has prepared a practice-oriented, phased roadmap for developing in-orbit refuelling infrastructure (Fig. 2). Refuelling service vehicles, equipped with refuelling modules and utility interfaces, will deliver propellants to cooperative spacecraft. In parallel, drop depots will be introduced to allow refuelling service vehicles and mobile consumers to be refuelled in orbit, thus enabling repeated use and rapid turnarounds. On this basis, infrastructure can be scaled up to include additional logistics vehicles and longer-lifetime depots so as to provide assured access to propellants across multiple orbits. Together, these steps will make orbital refuelling a routine supply activity similar to replenishment at sea or aerial refuelling.

The OPTRA (Orbital Propellant Transfer) flight demonstration (Fig. 3) bridges the gap between components and operations. Supported by the DIANA framework, OPTRA uses deltaVision's proprietary fluidic coupler and propellant management technology to demonstrate repeated, leakage-free transfers in microgravity. OPTRA verifies the seals, flow control and safety functions required for routine refuelling. Thus, OPTRA is key for mitigating the risks associated with both short term servicing missions and future high mobility missions.

Building on this backbone, deltaVision is developing DOVE (Dynamic Operations Vehicle)—a universal, refuellable platform for dual use missions (Fig. 4 and 5). With a ΔV of ~4 km/s, compatibility with major European launch vehicles and Rideshare envelopes, and cooperative as well as non cooperative RPOD capabilities, DOVE will be able to

- shift rapidly between orbital planes and altitudes;
- carry payloads for Earth observation (electro optical or radar), SSA support, and inspection;
- assume tugging and servicing tasks;
- provide electronic warfare and other defence capabilities, particularly in short-range operations.

To sustain demanding missions, DOVE integrates high power generation with active thermal control and secure communications as well as phased array antennas for high data rates and robust command and control (C2). Multiple payload accommodation interfaces, a refuelling capability and a versatile utility interface (mechanical, fluidic, energy, data) support modular upgrades and interoperability.

DOVE will be able to conduct a diverse range of missions in peacetime as well as in the context of hybrid and declared military conflicts (Fig. 6). From the very beginning, versatility must be an integral part of its design as the DSO will continuously reshape the way the spacecraft will operate.

In short, OPTRA will provide the propellant infrastructure; the roadmap will establish the refuelling logistics; and DOVE will make manoeuvrability a repeatable capability.

Together, they will provide Europe with resilience, flexibility and sovereignty in space, ensuring that future missions will be defined by intent and design rather than by the fuel quantity remaining.

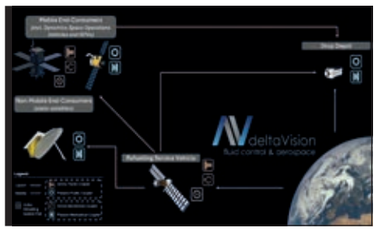


Fig. 1: deltaVision view of the fundamental layer of refuelling infrastructure and end consumers

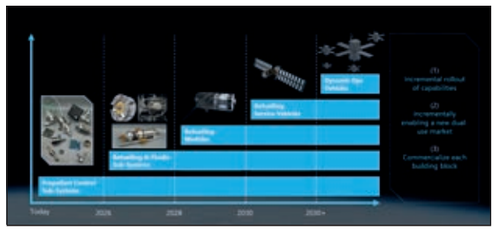


Fig. 2: Orbital refuelling infrastructure roadmap, moving from propellant control technologies towards Dynamic Space Operations



Fig. 3: OPTRA's in-orbit refuelling demonstrator set to launch in 2026

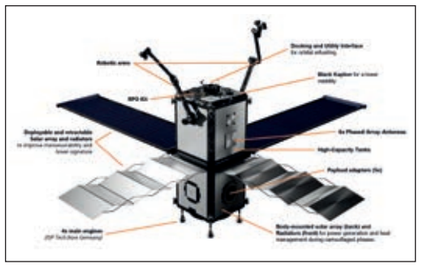


Fig. 4: DOVE's conceptual architecture

Features	Value
Launch Mass	1500 kg
Delta V	Up to 4 km/s (refuellable)
Host plethora of payload types	EO: Refuelling Modules; military payloads: optical; radar; EW; DEW; kinetic
Payload Service	2 kW; active cooling; high datarate
Orbital Services	> 5 years lifetime, reconfigurable
Manoeuvring capability	**Target performance**
LEO to GEO transit	1 x transfer w/o refuelling
Inclination	~15° possible (return)/ ~30° (single)
Rapid RAAN change	Comparable to Δi
On orbit manoeuvrability	Enables non-cooperative operations

Fig. 5: DOVE performance parameters

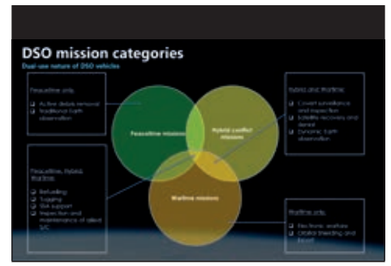


Fig. 6: DSO mission categories and versatility

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KIOBS AI-supported Video Analysis Equipment Designed for Protecting Objects and Securing Restricted Areas of the German Armed Forces

Object protection is becoming increasingly important, but suitable personnel are in short supply. Research results obtained by Fraunhofer IOSB in the field of deep learning processes are helping to free up operators from routine tasks. On behalf of the BAAINBw, Fraunhofer IOSB – assisted by WTD 91 – has developed key components of an object protection system designed to analyse and control video sensors.

The Video Analysis Systems department at Fraunhofer IOSB develops video analysis methods that allow persons and vehicles to be detected and tracked in challenging conditions, such as over long distances, in limited visibility and in adverse weather conditions. Analysing thermal infrared sensor data plays a particularly important role in this context (Fig. 1). Methods allowing individual and group behaviour to be detected are also part of the research area.

Based on this research, the KIOBS (German acronym meaning “AI-supported object protection system”) video analysis system was developed to provide AI-supported object protection and secure restricted areas of the German Armed Forces (Fig. 2). It supports observers performing surveillance activities by providing multiple high-performance sensor systems with cameras in the visual optical and thermal infrared ranges.

AI processes (specifically deep learning processes) simultaneously analyse, for example, eight Full HD video streams (visual optical (VIS) and thermal infrared (IR)) to detect defined security-relevant events. To this end, the cameras are actively controlled by dedicated software via automated, programmed camera movements corresponding to patrol routes. Again using software, the image data obtained is analysed for security-relevant events and processed and optimised for providing a better overview to the observer, and video sequences are stored in a database for later, repeated or further analysis (Fig. 3). The events to be detected are defined via geographical areas and relevant activities, such as unauthorised entry (of pedestrians and vehicles) or group behaviour patterns (Fig. 4). AI video analysis methods developed by Fraunhofer IOSB are used to detect these activities, analyse video signals in remote AI processors, and generate specific indications of activities.

Whenever such activities are detected, the geocoordinates of the event are determined based on the metadata from the pan, tilt and zoom sensor to thus allow the event to be geographically located and plotted on the situation display (Fig. 5). Notifications are recorded in a list which the operator works through to systematically evaluate all events. As a result, the KIOBS video analysis system enables operating personnel to automatically evaluate multiple video sensors in parallel and to capture relevant events in live video streams. This reduces the number of personnel needed and frees up staff from tedious routine tasks. Furthermore, additional aspects of interoperability are covered to enable the integration of the systems and the results generated by them into the Bundeswehr’s information infrastructure via STANAG-compliant interfaces.

Having been accepted in 2025, the five flexibly configurable series systems are currently being delivered to the German Armed Forces. In the future, the performance spectrum of the systems can be flexibly increased by adding further elements. Using drones as sensor carriers allows events to be clarified in an alarm situation even from behind cover and from the air. Alternatively, drones may also be used as tethered drones to permanently supplement a system’s sensor technology in poor visibility conditions or during mobile operations. Existing drone detection methods in addition permit threats from approaching drones to be detected and tracked. Furthermore, plans are in place to use KIOBS as a core component in the ‘Technical Object and Access Protection (TOZ)’ project.



Fig. 1: RBA 5-15/Hensoldt NightOwl high-performance sensors

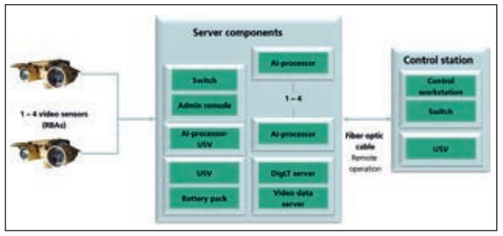


Fig. 2: Architecture of the KIOBS video analysis system for 1-4 high-performance sensors (IOSB part highlighted in grey)



Fig. 3: KIOBS work console



Fig. 4: Video board: Live video surveillance of VIS and IR video streams with specific surveillance areas being displayed



Fig. 5: KIOBS analysis software with sensor control and situation map



2

Defense Research and Technology

The year 2025 marks another important step in the development of the Bundeswehr's defence research and technology (R&T). The research and innovation system is more firmly established and now better geared to the dynamic security situation and the needs of the troops.

Institutional development

The establishment of the new Directorate-General for Innovation and Cyber, along with the integration of the branches for defence research and innovation management, helps in improving the intercommunication between researchers, requesting agencies and users, i.e. the soldiers. This "demand-to-result cycle" reduces the time required to get new technologies ready for use and makes it possible to avoid the "valley of death".

Cooperation landscape and international work sharing

The cooperation with national partners such as the Fraunhofer-Gesellschaft, the German Aerospace Centre (DLR) and the French-German Research Institute of Saint-Louis (ISL) continues to form the basis of innovation. At the same time, participation in EU and NATO programs is strengthened. In 2025, Germany again provided significant funds for joint projects under the European Defence Fund (EDF) in order to exploit synergies and use resources efficiently.

Technological priorities

In 2025, the focus was on the following technology areas:

- Air defence technologies: Defence against unmanned aerial systems and protection against guided missiles.
- Autonomous and interconnected platforms: Unmanned airborne and waterborne vehicles and logistics solutions using robotics.
- Electronic warfare technologies: Protection and enhancement of own capabilities.
- Artificial intelligence and machine learning: Autonomous systems, decision support and data analysis, in particular automated image analysis.
- Unmanned weapon systems: Teaming and swarms.
- Quantum technologies: Quantum communication and quantum sensor systems for secure communication and precise detection, as well as resilient communications networks.
- Space: Protection of space infrastructure.

Outlook and strategic orientation

Ongoing geopolitical tensions and global technological competition require resilience and flexibility. The Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support (BAAINBw), the Bundeswehr Office for Defence Planning and the Federal Ministry of Defence coordinate a broad portfolio of research programs in order to ensure that the Bundeswehr is equipped with the required capacities for analysis and evaluation. They promote projects that are characterized by their rapid scalability, which strengthens the ability to detect and respond to threats at an early stage – a process in which the armed forces are closely involved. The aim is to secure and expand the Bundeswehr's innovation power with lasting effect.

It is our hope that this report will provide you with an overview of the progress made and the ongoing technological innovations. The entire network made up of the ministry, research institutions, industry partners and international allies remains determined to sustainably secure and further expand the Bundeswehr's power to innovate.

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Alternative Stabilisers for Gun Propellants

As nitrocellulose undergoes autocatalytic degradation, classical nitrocellulose based gun propellants are not suitable for long term storage. Long term storage requires a small amount of stabiliser to be added since a stabiliser markedly slows the degradation processes of nitrocellulose. Organic molecules are evaluated for their suitability as gun propellant stabilisers.

Conventional stabilisers employed for gun propellants, such as Centralite I and II, diphenylamine, and Akardite II, have already been in use for an extended period of time. However, these substances, or their degradation products, pose significant health hazards. The main cause of this is that during storage measurable amounts of N-nitrosamines are formed, especially in propellant formulations that contain Centralite I or II and diphenylamine (Fig. 1). A substantial number of N-nitrosamines have been classified as carcinogenic, signifying that they are presumed to have a cancer-inducing effect.

Akardite II generates significantly lower amounts of N-nitrosamines compared to the other two compounds mentioned above. However, due to its high procurement cost, the potential impact of future REACH regulations on Akardite II synthesis, and the unfavourable supply situation (single-source problem in Europe), investigations into cheaper and/or better stabilisers are required.

The ISL has been engaged in searching for alternative stabilisers for double-base and multibase propellants for quite some time now. For the purpose of this study, derivatives from a variety of organic classes were examined and evaluated with regard to their potential use as gun propellant stabilisers.

Alternative stabilisers are required to meet the following criteria:

- no formation of N-nitrosamines
- very high efficiency that guarantees a long service life of the propellant
- chemical compatibility with plasticisers, nitrocellulose, and other propellant components
- REACH compliance

Potential stabilisers are subjected to a screening process that involves adding one weight-percent of each candidate to a double-base propellant formulation specifically prepared for this purpose. The formulation is then subjected to a hot-storage test conducted at a temperature of 90 °C for a duration of 18 days. Multiple samples undergo screening at the same time. The primary exclusion criterion is the weight-loss balance: the loss in weight must be less than three percent after the 18 days of hot storage at 90 °C.

Samples that have passed the screening process are then subjected to a more detailed investigation to satisfy NATO standard AOP48 (“Explosives - Nitrocellulose Based Propellants - Stability Test Procedures and Requirements Using Stabilizer Depletion”). This detailed analysis is performed to determine the degradation kinetics and detect the degradation products of the stabiliser used. For this purpose, ten test vials are filled with propellant and stored at 90 °C for 18 days. Every two days, a sample is withdrawn, weighed and visually inspected. In addition, HPLC (high-performance liquid chromatography) and NMR (nuclear magnetic resonance) analyses of the hot-stored samples are performed (Fig. 2 and Fig. 3).

The investigations conducted identified a large number of alternative stabilisers for double-base and multibase propellants. Their effectiveness is lower than that of Akardite II, the currently most effective stabiliser, but they can be used for short-term or medium-term applications, such as those required during crisis situations.

The work is financed via BMVg base funding, additional government funding, and third-party funding from the German defence industry.

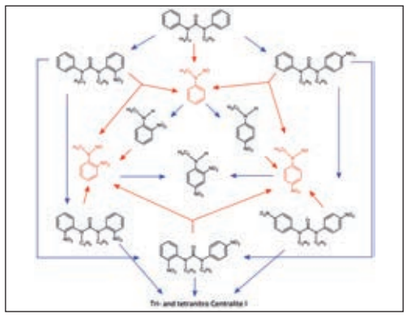


Fig. 1: Degradation scheme of Centralite I and formation of nitration products in Centralite I formulations. The structures highlighted in red are carcinogens



Fig. 2: Hot storage of a stabiliser candidate (1 wt-%) over 0 -18 days at 90 °C

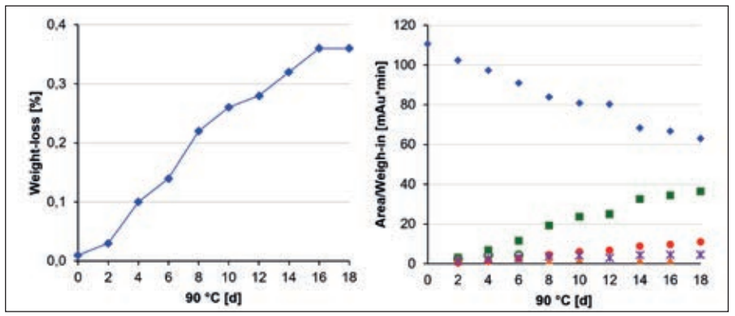


Fig. 3: Mass balance and HPLC analysis. Degradation kinetics of a stabiliser (blue) and detection of its degradation products

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Ageing Effects on the Shock Sensitivity of Explosives Formulations

Identifying the ageing mechanisms of energetic materials is a central part of this project. A combination of thermal ageing and mechanical loading is applied to a plastic bonded explosive in order to investigate the effects on its chemical and mechanical properties and to draw conclusions about its life cycle and shock sensitivity.

The project TVESIM (Thermal & Vibrational loading Effects on Structural Integrity of energetic Materials) is a French-German cooperation between ArianeGroup CRB in Vert-le-Petit, DGA-TT in Bourges, Fraunhofer ICT in Pfinztal, WTD91 in Meppen, and ISL in Saint-Louis. It was initiated after the success of the joint European IMA (Insensitive Munitions for Ageing) project with the common goal of France and Germany to continue working together in the field of ageing of energetic materials. The main objective is to examine how a combination of thermal ageing and mechanical loading, such as vibrations experienced by returning ammunition, affects the chemical and mechanical properties of various energetic materials. One main focus is on a new type of plastic-bonded high explosive (PBX). It is manufactured by ICT and then thermally aged for 180 days at +60 °C. Subsequently, mechanical loading is applied differently to three samples at WTD91: the loading is performed at temperatures of -20 °C, +20 °C, and +60 °C for six hours, respectively. Shock sensitivity analysis is performed at ISL using the projectile impact test (PIT). For this purpose, the sample is impacted by a standard-sized, flat-ended projectile using a powder gun. The projectile velocity and the shock transition time across the sample are measured using double flash X-ray radiography and short circuit gauges, respectively. There is a velocity threshold that, when exceeded, leads to a detonation of the sample rather then a deflagration. By varying the velocity, this threshold can be identified by a sharp decrease in the shock transition time. Typically, eight trials are performed on each sample, with the lowest projectile impact velocity that leads to a detonation, in combination with the highest velocity that leads to a deflagration but not detonation, characterising the sample's sensitivity to shock.

The initial comparison between pristine and unloaded samples is shown in Figure 1. In this context, unloaded means that only thermal ageing has been applied, and no additional mechanical loading has occurred. The transition from the non-detonation regime to the detonation regime occurs first for the pristine sample, i.e. at lower projectile velocities. Therefore, the non-aged PBX appears to be slightly more sensitive to shock. However, this difference is too small to be considered significant. In contrast, all samples that have undergone additional mechanical loading are more sensitive to shock, as they detonate at lower projectile velocities (Fig. 2 to 4). This effect is particularly pronounced for the sample loaded at +20 °C. Another noteworthy point is the extremely unusual manner in which the transition occurs for all three mechanically loaded samples. The irregularity within the transition zone is in strong contrast to the very typical PIT results of Figure 1. Therefore, the material properties are not well-defined within this, in addition, very wide transition zone. Consequently, the sensitivity results are so far unreliable. Considering the lowest projectile velocity in Figures 3 and 4, there is no certainty that the non-detonation regime has even been reached, and no further detonations occurred below 724 m/s and 754 m/s, respectively.

In summary, the PIT revealed an obvious trend of increased sensitivity following mechanical loading. However, further analysis is required to understand the reasons behind this. A future follow-up project will use micro-computed tomography to investigate the microstructure of the samples after mechanical loading. Further PITs are planned at an increased range of projectile velocities to obtain a more precise picture of the shock sensitivity and improve the statistics.

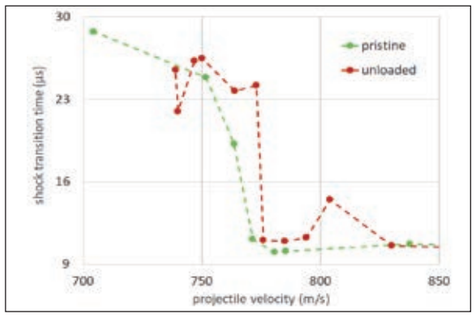


Fig. 1: PIT results for pristine and unloaded PBX. The transition from the deflagration regime to the detonation regime occurs at slightly higher projectile velocities for the latter. Thermally aged PBX is therefore slightly less sensitive to shock. The curve shapes of both transitions show clear steps in the shock transition time and thus correspond to expectations

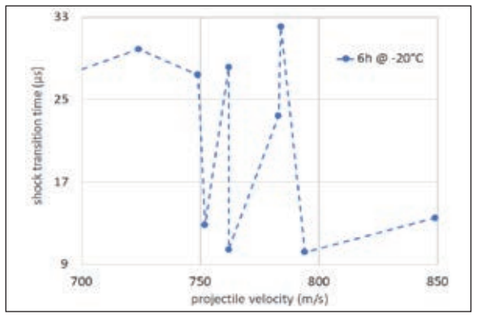


Fig. 2: PIT tests for PBX that was mechanically loaded at -20°C for 6 hours. The sensitivity to shock is increased compared to unloaded PBX. The transition zone is unusually irregular and significantly wider

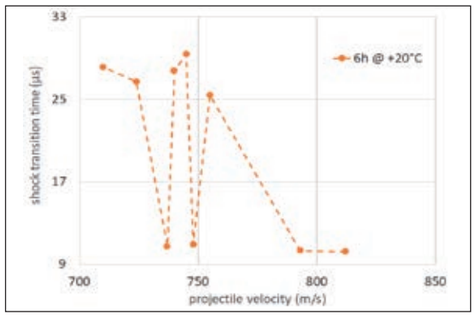


Fig. 3: PIT tests for PBX that was mechanically loaded at +20 °C for 6 hours yield the highest sensitivity to shock. The transition regime is again irregular and extremely broad

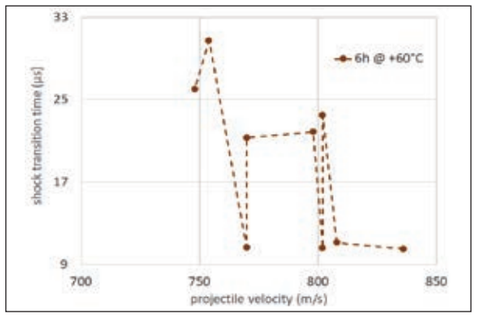


Fig. 4: PIT tests for PBX that was mechanically loaded at +60 °C for 6 hours. Unfortunately, as results from the lower velocity range are missing, it cannot be determined with certainty whether the shock sensitivity is even greater

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ERNST in Orbit – First Successes of the First Small Satellite Developed for the Bundeswehr

The launch of the ERNST satellite on August 16, 2024 marked the beginning of the use of small satellites for the Bundeswehr. Since then, the experimental satellite has not only demonstrated the agility of the satellite platform, but is also making an important contribution to future satellite-based early-warning systems by detecting missile launches and hypersonic missiles.

The space domain is essential for providing early-warning capabilities for the detection and tracking of ballistic missiles and hypersonic missiles. In a networked air defence system, satellites take on the task of target cueing for ground-based radar systems even before the threat enters their range. Infrared sensors on board satellites detect the exhaust plume of the engine and, if possible, the heated rocket body. From orbit, the trajectory of the missile is tracked from its launch in enemy territory in order to gain the crucial time needed to initiate successful defence measures. Satellite data required for the operation of the Patriot or Arrow 3 systems are provided by US satellites under a NATO cooperation arrangement. Up until now, Germany has had no own satellite data on the infrared signatures of missiles for early warning purposes.

ERNST has changed this situation and has already delivered valuable data within the first year and a half of its mission. The ERNST mission has two main objectives. Firstly, it demonstrates the potential of small satellites to rapidly test technologies and new areas of application with responsive, low-cost missions. Secondly, ERNST serves to investigate early-warning concepts by observing and tracking missiles. On both objectives, the mission has been highly successful so far.

The satellite platform adheres to the 12U CubeSat standard, with external dimensions of 24 × 24 × 36 cm³ and a mass of 20 kg. The spacecraft and its payload were developed according to the New Space approach, which relies on commercial components and a higher tolerance of risk in development. Under the motto ‘validate rather than certify’, this approach emphasises extensive testing. An example of this is the data processing unit (DPU), which is based on commercial FPGA chips whose performance clearly exceeds that of radiation-hardened space electronics. System robustness is achieved through hardware and software redundancy, as well as extensive laboratory testing.

This architecture has already been successfully used on numerous satellite missions, including those of the EMI spin-off constellr.

On ERNST, the DPU now performs not only its nominal tasks of data processing and transmission, but also a large part of the control functions of the on-board computer, a commercial CubeSat component. This change was implemented while ERNST was in orbit, illustrating the agility of the design, which enables performance optimisation and resilience of the experimental satellite in the event of any anomalies. A key objective for the remainder of the mission is to implement extensive automation of ERNST’s routine satellite operations.

ERNST orbits the Earth every ninety minutes at an altitude of now just under 500 km. In a forward-pointing mode, its nadir footprint of 96 km × 77 km is slewed by 30° along the flight direction, enabling the detection of objects above the Earth’s horizon and their tracking through orienting the satellite. This is a major advantage of low-Earth-orbit detection: Against the cold background of space, signatures of cooler or smaller objects also stand out clearly, whereas they would be harder to detect above the noise of the Earth’s background signal. When detection against the Earth’s background is required, ERNST switches between different spectral bands to ensure positive target identification. The mission thus provides important insights for designing early-warning satellites in low and geosynchronous orbits, the combined use of which in a future air and missile defence system will be needed to achieve the required performance and coverage. With the ongoing ERNST mission, the first step has been taken.



Fig. 1: Final integration of ERNST at Fraunhofer EMI in 2024



Fig. 2: Payload Stack of the Transporter-11 rideshare mission with ERNST located in the centre of the CubeSat deployer (left). Launch of Transporter-11 and start of the ERNST mission on August 16, 2024 (right) (Copyright: SpaceX)

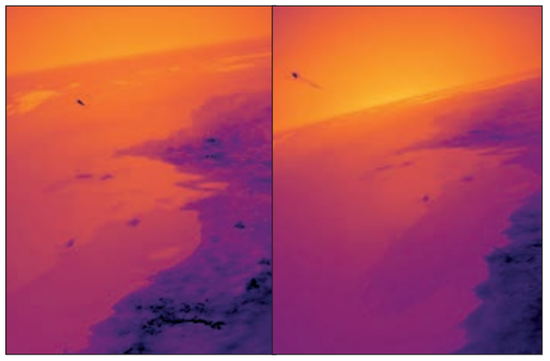


Fig. 3: Detection of a Falcon 9 launch (NASA TRACERS) from Vandenberg by ERNST. In the video excerpt, the ascent (left) and separation of the upper stage (right) can be seen in pseudo-colour as black objects in the upper half of the images

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Anomalous Electromagnetic Propagation and its Impact on Radar System Performance

The atmosphere affects the propagation of electromagnetic waves and hence the performance of radar systems. Temperature inversions and humidity gradients can cause anomalous propagation and ducting, thereby altering signatures and ranges. Fraunhofer FHR investigates these effects and develops in-house propagation models to provide reliable coverage forecasts.

Radar is of central importance to numerous military systems owing to its outstanding ability to detect, track and analyse objects over long ranges and in diverse environments. Our intuitive understanding of this technology is based on the assumption that radar waves propagate in straight lines. Only then can the range and bearing of a target be reliably determined from the transit time and the direction of arrival of the radar backscatter.

In particular over large bodies of water such as the sea, the assumption of straight line propagation often does not apply. Meteorological phenomena such as temperature inversions or rising water vapour can cause electromagnetic (EM) waves to refract away from or towards the Earth's surface. In extreme, yet not uncommon, cases so called ducts (refractive channels) can form, which considerably impact the visibility of opposing forces and one's own vulnerability. This non straight line propagation is termed anomalous propagation. An overview of the different modes of propagation is shown in Figure 1.

Within a duct, portions of the EM waves are guided along the Earth's surface beyond the horizon. As a result, targets beyond the geometric horizon become visible. At the same time, waves refracted into the duct no longer reach other areas that they would have reached under straight line propagation. This creates so called radar holes, in which target detection is severely impeded. The location and even the existence of these radar holes depend on the specific atmospheric conditions and are highly dynamic. Furthermore, assuming straight line propagation when propagation is in fact anomalous can lead to erroneous estimates of position and range. The consequences of anomalous propagation are illustrated in Figure 2.

In maritime operations in particular, anomalous propagation must be accounted for. It can mask as well as accentuate the signatures of one's own forces—and vice versa those of the adversary. Therefore, a sound understanding of anomalous propagation is essential in order to reduce one's own vulnerability and exploit the opponent's weaknesses.

Fraunhofer FHR is conducting intensive research into anomalous propagation. As part of this work, a novel ray tracing based simulation approach has been developed and integrated into a custom-made tool that predicts radar coverage based on atmospheric data. An example of a simulation result for a sample atmosphere is shown in Figure 3. In addition, Fraunhofer FHR carries out measurement campaigns to improve understanding of anomalous propagation and to validate simulations. Work is also underway on a method to infer information about the atmospheric state from clutter data, with the aim of minimising the need for difficult measurements during operations.

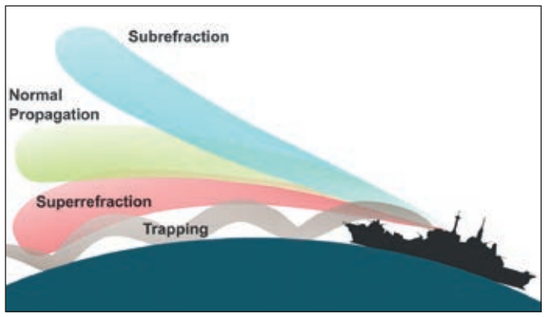


Fig. 1: Categories of atmospheric propagation of electromagnetic waves

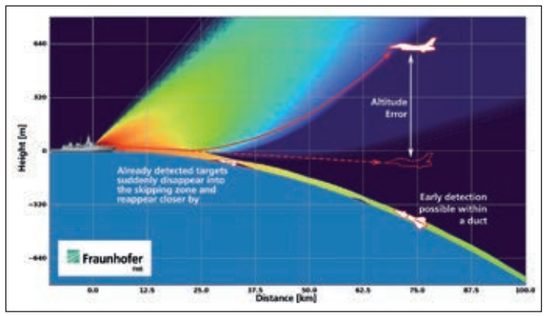


Fig. 2: Possible consequences of anomalous propagation

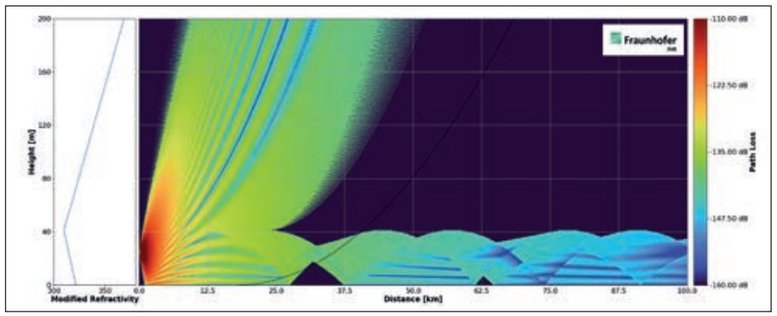


Fig. 3: Right: Simulated electromagnetic propagation in an atmosphere with the illustrative refractive-index profile shown on the left

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Ergonomic Design of a Standardised Ground Control Station for Loitering Munition

Loitering munition (LM) is a key future technology for security and defence. Fraunhofer FKIE is developing a mobile, modular and standardised ground control station that integrates ergonomic and technical requirements as well as novel risk analysis methods to enhance usability, prevent errors and improve the learnability of LM systems.

Loitering munition has been defined as a key technology for national and European security and defence. The research and technology needs for loitering munition are addressed in the “Future Technologies for Medium Range Loitering Munition” project of WTD 91. Fraunhofer FKIE was tasked to develop a concept for a standardised ground control station (GCS) for the control of loitering munition in order to enable a uniform and ergonomic human-machine interface across different systems from various manufacturers. In this context, humans are to remain the central and responsible actors in the deployment of loitering munition. Soldiers will be responsible for making critical decisions and act as a controlling authority in the sense of “meaningful human control”, ensuring that human norms and values are preserved and applicable legal regulations are complied with.

The design of a standardised GCS for loitering munition by Fraunhofer FKIE was carried out in an iterative process involving relevant stakeholders (Fig. 1). Based on design-defining requirements and parameters, a concept was selected and implemented. This concept comprises a highly

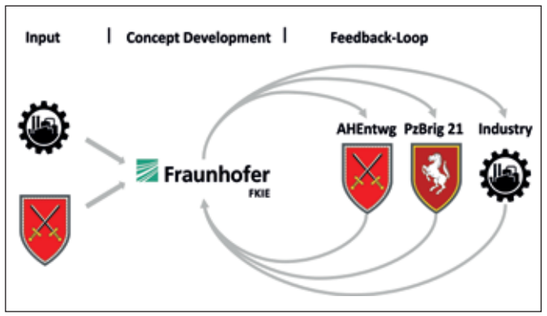


Fig. 1: Illustration of the methodology used to develop the standardised GCS

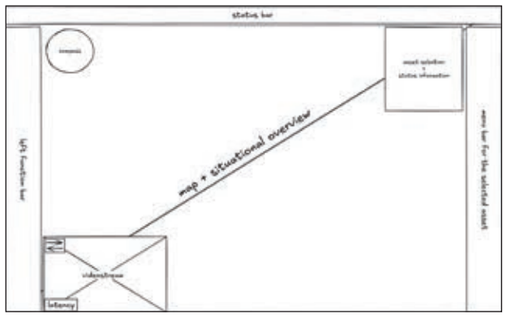


Fig. 2: Sample slide from the layout concept for the standardised GCS interface

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mobile and modular design of the standardised GCS. A tablet or handheld device was selected as the central interface for the standardised GCS. In addition, mission-specific functionalities can be realised through the option to integrate extended input and output interfaces (e.g., video goggles and controllers) as well as interfaces to the NATO Generic Vehicle Architecture and Battle Management System.

The core research task of the project, however, is the design and implementation of the user interface for the standardised GCS. In this context, a layout concept was developed in collaboration with the German industry (Fig. 2), which is intended to serve as a style guide for a harmonised user interface. A first prototype of the user interface has already been implemented (Fig. 3) and has been scientifically evaluated with soldiers of PzBrig 21 (German Armored Brigade 21). The results show that the concept offers a user-friendly and functional interface for soldiers, which, however, is to be further developed and adapted over the remaining two years of the project to meet the requirements of the soldiers and the LM systems.

In addition to taking a holistic approach to all of the identified requirements during the design phase, particular emphasis must be placed on system control reliability, as errors have the potential to cause significant damage. The control of loitering munition systems is complex and thus associated with an increased prevalence of potential causes of human error. From a methodological perspective, system reliability analyses primarily focus on technical aspects, however, as they are based on methods of technical risk analysis. The causes of human error cannot be analysed systematically and comprehensively using established risk analysis methods, so a complete identification of potential human error sources is not possible. Therefore, Fraunhofer FKIE has developed a structured method based on human factors hazard analysis that identifies potential causes of human error in weapon systems with regard to severe error states in relation to the system’s design parameters. The results of this analysis are used for the design of the standardised GCS.

The developed layout concept for a standardised GCS for loitering munition will be finalised by mid 2026 and published as a first version. Building on this, the harmonisation concept can be expanded in subsequent iterations, such as through standardised software interfaces and a uniform system architecture. The standardised GCS, particularly through its ergonomic design, is intended to improve learnability, usability, and reliability, thereby enabling shorter training times and safe system operation.



Fig. 3: Illustration of a possible handheld solution with the first implementation of the user interface

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Visual Global Navigation Satellite System (GNSS)-free Navigation

Global navigation satellite system (GNSS) interference caused by jamming and spoofing is increasingly jeopardising UAS navigation. Visual self-localisation can be used as an alternative. At Fraunhofer FKIE, a demonstrator for GNSS-denied navigation is being developed and tested for this purpose, combining camera-based methods with satellite images and digital surface models for robust position determination.

With the increasing use of unmanned aerial systems (UAS) in military conflicts, jamming (intentional interference with signals) and spoofing (broadcasting falsified signals to mislead receivers) of global navigation satellite systems (GNSS) have increased significantly worldwide. The aim is to deliberately disrupt the localisation and navigation of these systems. These attacks on GNSS affect not only UAS but also manned aircraft, maritime platforms and civilian land and air vehicles, impairing their GNSS-based navigation. In such situations, alternative self-localisation methods are required.

Instead of using GNSS, the self-positioning of a UAS can be carried out using optical sensors, such as daylight or infrared cameras. For this purpose, an onboard camera continuously records the Earth's surface, and the image sequences are then compared successively. Distinctive feature points are tracked in this process. By combining this with inertial sensor tracking, the own motion of the UAS can be estimated. However, the errors in these relative estimates accumulate over time, leading to a drift. Similarly, a loss of tracking can interrupt or terminate localisation.

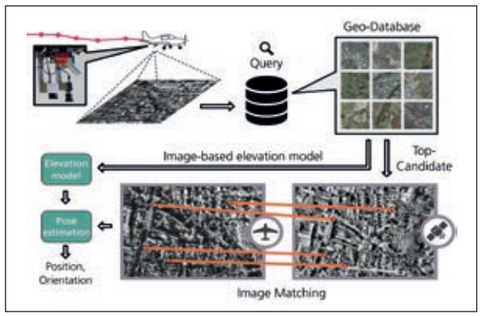


Fig. 1: Visual geolocation through the addition of remote sensing data



Fig. 2: Sensor payload for GNSS-free navigation, mounted on the 'Delphin' microlight aircraft

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Making localisation more robust or enabling relocation is possible by using remote sensing data such as satellite images and digital surface models. This data is typically widely available and offers comprehensive, often global coverage. First, the absolute references can be used to identify locations visually and roughly localise the UAS. Then, by incorporating digital surface models, precise position and orientation determinations are possible. In combination with relative estimation methods, this results in robust navigation that uses relative and absolute information (Fig. 1).

In light of emerging developments in the UAS sector, Fraunhofer FKIE has been continuously developing and evaluating a GNSS-free navigation demonstrator in the form of a sensor payload for several years (Fig. 2). For this purpose, an ultralight aircraft was used as a carrier platform for the payload, and a comprehensive data set on GNSS-free navigation was collected over several years and seasons. In addition to a daylight camera, the payload incorporates an inertial navigation system comprising an integrated inertial measurement unit and a barometric altimeter.

Based on the field data collected, extensive experiments on GNSS-free navigation were conducted and methods for visual (inertial) odometry (VO/VIO) and visual geolocation (VGL) were developed (Fig. 3). Depending on the quality of the available reference and sensor data, these methods typically achieve a positional accuracy in the range of a few metres and an orientation accuracy of less than 1° when combined. Additionally, the performance of the GNSS-free navigation methods was analysed with regard to their applicability in different seasons and theatres of operation. The timeliness of the reference data relative to the time the sensor data was recorded proved to be a decisive factor.

Furthermore, both relative and absolute visual localisation methods tend to be more accurate in urban and built-up areas than in forested or agricultural regions.

The demonstrator developed proved the feasibility of robust GNSS-free navigation under various environmental conditions. This capability will be further expanded and also examined in the context of small, agile platforms operating in extreme conditions.



Fig. 3: Example of a complete pose estimation using remote sensing data

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Integrated Broadband Front-end Solutions for Multifunctional Antenna Systems

Future military platforms will rely on multifunctional antennas for communication, radar, and Electronic Warfare (EW) under strict „Size, Weight and Power“ (SWaP) constraints. Millimetre- and submillimetre-wave bands offer high bandwidth, fine resolution, and low-observability propagation, but require highly integrated broadband RF front ends. An ultra-broadband metamorphic High Electron Mobility Transistor (mHEMT) receiver chip from Fraunhofer IAF demonstrates their feasibility.

Military operations are increasingly conducted in environments that are highly dynamic, distributed, and information-intensive. Mobile command elements, autonomous platforms, and sensor networks must exchange large volumes of data while minimising electromagnetic signatures and remaining operational under jamming, interception, or reactive electronic attack. The survivability of modern systems is largely determined by their ability to operate briefly, adaptively, and covertly across the electromagnetic spectrum. These constraints drive the transition to highly integrated radio-frequency (RF) architectures in which communication, radar sensing, and electronic warfare functions are consolidated within shared apertures and front ends.

At the same time, the available antenna space on airborne, unmanned, and ground-based platforms continues to shrink, while the number of functional requirements steadily increases. Ultra-broadband RF front ends therefore become a decisive enabler: large instantaneous bandwidths in the millimetre- and submillimetre-wave range allow short, high-capacity transmission and sensing bursts, enabling very fine range resolution, rapid scene updates, and a low probability of interception. Integrating radar and communication functions within the same hardware reduces system complexity, physical footprint, and electromagnetic exposure while enabling mission-adaptive use of spectral resources.

A key enabling technology for such concepts is the ultra-broadband receiver MMIC (Monolithic Microwave Integrated Circuit) recently demonstrated at Fraunhofer IAF. Fabricated using 35-nm InGaAs metamorphic HEMT technology, the MMIC integrates a low-noise amplifier (LNA), a local oscillator (LO) buffer, and an fundamental mixer (Fig. 1) on a single chip measuring only 1.25 × 1 mm² (Fig. 2). In contrast to conventional narrowband or multi-chip receiver solutions, this circuit operates continuously from 140 to 330 GHz, providing more than 190 GHz of instantaneous RF bandwidth within a single monolithic front end.

The MMIC architecture relies on a shared distributed-amplifier core used for both the LNA and the LO buffer, ensuring a flat gain response across an extreme bandwidth while preserving excellent noise performance. A resistive HEMT mixer enables efficient frequency conversion with moderate LO power requirements, which is especially critical for electronically steered arrays, distributed apertures, and mobile systems with limited LO distribution capability. Across the full measured band, the receiver achieves an average conversion gain of 16 dB and an average noise figure of only 6.8 dB, representing a new benchmark for ultra- wideband sub-millimeter-wave receivers at this level of integration (Fig. 3). Total power consumption is limited to 352 mW, fully compatible with stringent SWaP constraints. Simulations indicate equivalent performance up to 400 GHz, extending seamless operation across multiple waveguide bands without the need for hardware modifications.

The unique added value of this receiver MMIC lies in its unprecedented combination of high instantaneous bandwidth, low average noise figure, and full monolithic integration within a single compact chip. For the first time, a single-chip receiver simultaneously delivers >190 GHz bandwidth and sub-7 dB average noise figure, eliminating the need for band-specific receivers, switchable RF chains, or parallel front ends. This enables true frequency-agile operation, allowing communication, radar sensing, and electronic warfare functions to be dynamically allocated across a vast spectral range using identical hardware.

When combined with multifunctional antenna architectures, this MMIC forms the technological foundation for next-generation military platforms that demand extreme bandwidth, low observability, and rapid reconfigurability (Fig. 4). The resulting systems minimise hardware redundancy, streamline RF architectures, and enable mission-adaptive operation in the most demanding electromagnetic environments.

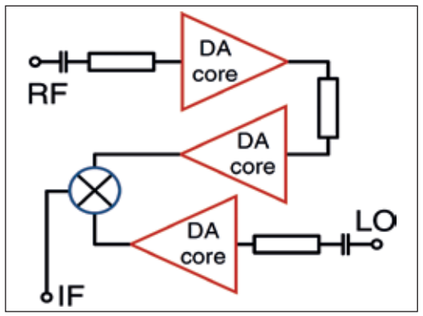


Fig. 1: Block diagram of the InGaAs-mHEMT wideband receiver MMIC including LNA, mixer, and local oscillator buffer amplifier

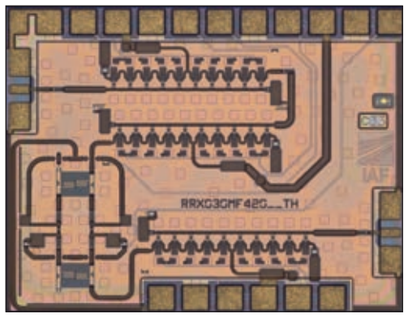


Fig. 2: Chip photo of the wideband receiver front end, processed with the 35-nm InGaAs mHEMT of Fraunhofer IAF. The chip has the dimensions 1.25 x 1 mm².

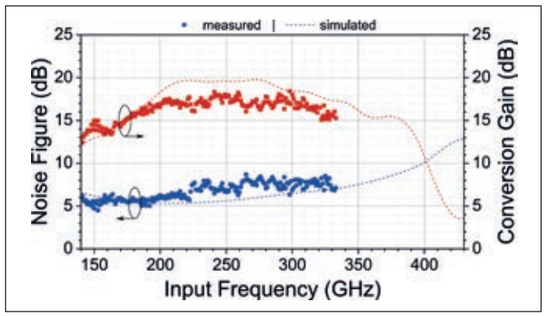


Fig. 3: Measured gain (red, right) and noise figure (blue, left) versus frequency for the realized wideband receiver



Fig. 4: Drone swarm and field camp scenario (AI generated)

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Simulation of the Combustion of Multi-Material and Complex-Shaped Gun Propellants

New manufacturing processes allow the geometry and material structure of gun propellants to be redesigned for the purpose of improved gun performance. The MMGPS algorithm was developed and implemented at Fraunhofer ICT to predict this performance and to, for the first time, describe the combustion of multi-material and complex-shaped gun propellants.

Even today, improving the performance of guns remains an important research objective that is of great military relevance for ensuring superiority in combat. The muzzle velocity of a projectile is determined by the shape of the pressure curve resulting from the combustion of a gun propellant. Increasing the muzzle velocity requires the area under the pressure-travel curve to be maximised. However, constraints such as the maximum permissible pressure and the need to keep the muzzle pressure as low as possible must be taken into account. As a consequence, a high pressure must be maintained for as long as possible (Fig. 1).

To describe the pressure evolution in a given system, it must be known how much propellant mass can be loaded into the ammunition and how much gas is produced in what time. The key parameters in this context are the bulk density of the propellant and the description of the pressure-dependent surface regression of the propellant grain.

Thus far, the bulk density of gun propellants has been determined experimentally in standardised bulk tests. Such tests

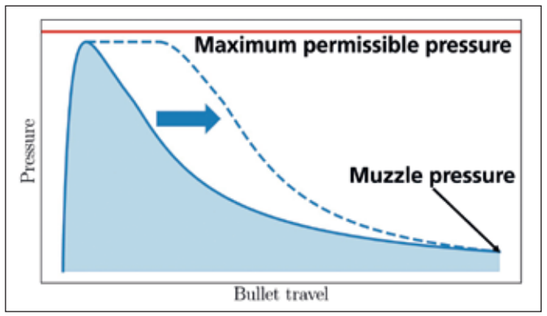


Fig. 1: Schematic representation of a conventional pressure curve (solid line) and an optimised pressure curve (dashed line) of a gun, taking the constraints of a maximum permissible pressure and the need to keep the muzzle pressure as low as possible into account. Due to the maximum permissible pressure, the pressure curve must be broadened to increase the area beneath it

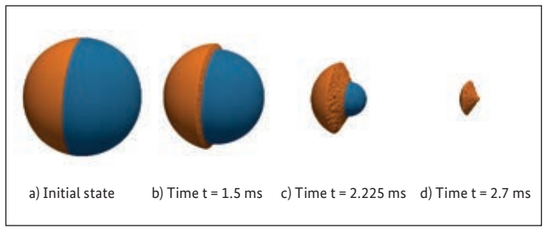


Fig. 2: A multi-material ball propellant consisting of two hemispheres as a material structure with different burning-rate coefficients, shown at different times during combustion simulation

are both time-consuming and costly and also neglect design-related and process-related factors such as the rear end of a penetrator protruding into the powder bed. For this reason, gun propellants produced via established processes generally use empirical values. Subsequently, the achievable loading density is then determined experimentally. However, empirical values do not exist for complex-shaped gun propellants prepared by means of modern manufacturing processes. Therefore, as presented in the 2024 annual report, Fraunhofer ICT for the first time used the discrete element method to simulate the bulk density of gun propellants.

Due to the use of well-established manufacturing processes, conventional gun propellant grains consist of a single formulation (chemical composition). This allows the surface regression of the gun propellant grain to be described independently of the pressure evolution in the system. Modern manufacturing processes, such as co-extrusion or 3D printing, permit the production of complex-shaped propellant grains consisting of several formulations, known as multi-material propellant grains. This allows the pressure curve to be optimised in a more versatile manner. However, new simulation methods able to describe surface regression are needed to exploit this potential. In multi-material propellant grains, several formulations may be present on the burning surface at the same time. In this case, surface regression can no longer be described separately from pressure evolution, as the different burning properties of the propellant formulations make it dependent on the pressure history.

To describe the combustion of multi-material and complex-shaped propellant grains, Fraunhofer ICT has developed and implemented the Multi-Material Gun Propellant Simulation (MMGPS) algorithm. This algorithm for the first time allows the combustion of multi-material and complex-shaped gun propellant grains to be described. Figure 2 shows an example of a multi-material ball propellant at various stages of combustion, with the blue formulation burning faster than the orange formulation.

Due to the different burning properties of the individual formulations, the pressure curve in a gun can be systematically optimised. Figure 3 shows a possible multi-material gun propellant grain and the corresponding schematic pressure curve. Once the maximum pressure has been reached, the blue, slower-burning formulation has been burned completely. The pressure then rises again due to the orange, faster-burning formulation now being exposed. This new increase in pressure enlarges the area under the pressure curve to thus increase the projectile's energy.

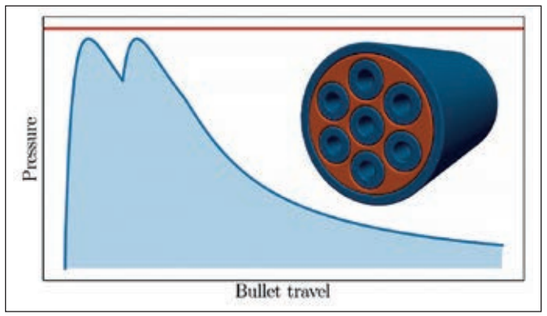


Fig. 3: Schematic representation of a pressure-travel curve and an example of a multi-material propellant grain

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Component-Based Object Recognition, Demonstrated by the Example of Military Vehicles

Component-based object recognition, as demonstrated by the example of military vehicles, identifies vehicles by detecting characteristic components such as a weaponry, sensory systems or drive components, the combination of which can then be assigned to a specific vehicle by means of a knowledge base. This approach can be transferred to other platforms, such as ships, without requiring a large amount of training data.

The identification of military platforms requires high levels robustness and comprehensibility. Operational imagery can vary greatly in terms of perspective, resolution, visibility conditions, camouflage, partial obstruction, or short-term modifications. Purely data-driven approaches often only provide a classification without transparent justification. In safety-critical applications, such black-box decisions are problematic because they are not verifiable.

Component-based object recognition therefore follows a hybrid approach that combines data-driven and knowledge-based methods. This approach is oriented towards the workflow of experienced image analysts: from recognisable, vehicle-specific components, conclusions are drawn about the vehicle as a whole.

Rather than evaluating only global image patterns, the method first identifies characteristic, discriminative components of military ground vehicles, such as armaments, sensor systems, protective features, and add-on elements, hatches, antennas, or specific structural features (Fig. 1). These components, which are directly interpretable by image analysts, together with a knowledge database, form the basis for verifying the model prediction.

To make the most of the information available in the images, the information regarding the components is combined with additional data-driven image classifiers in order to make robust decisions even under limited visibility.

Multiple sources of information are combined to provide reliable assessments even when the information is incomplete: identified components and their spatial arrangement, the detection confidence of individual components, quality indicators, and resolution indicators of the image material. These cues are jointly evaluated and weighted. Consequently, the method remains operational even under limited visibility, camouflage, or low image quality (Fig 2). If the information is incomplete, decision-making confidence will gradually and comprehensibly decrease instead of failing abruptly.

A central element is the underlying knowledge base of the Recceman® software. It systematically represents typical combinations of components and their assignment to vehicle classes. This allows for transparent reasoning: users can understand which detected components support a hypothesis and, if necessary, look up the underlying mappings. As an additional benefit, the system can generate a detailed description of the vehicles from the stream of components (e.g., external weapons, sensor packages, protective devices), supporting situational awareness analysis.

From a methodological perspective, the approach offers several advantages: by incorporating prior knowledge, the need for training data is reduced. Vehicles that the system has not been specifically trained on can also be identified if their characteristic components are detectable. Furthermore, modified objects can be integrated quickly by updating the knowledge base. This is a decisive advantage in dynamic operational contexts. In addition, combining of multiple independent sources of information increases robustness against disturbances and targeted manipulation attempts.

For ground vehicles, the method already achieves differentiated identification of around 150 vehicle categories. The concept is transferable across domains, provided that objects can be distinguished by their characteristic features. This transferability is currently being developed further in the maritime domain. Typical fields of application include drone and satellite image and mobile long-range reconnaissance, the automation of the Recceman® analysis software, and assistance systems that must explicitly inform users about relevant or vulnerable components.

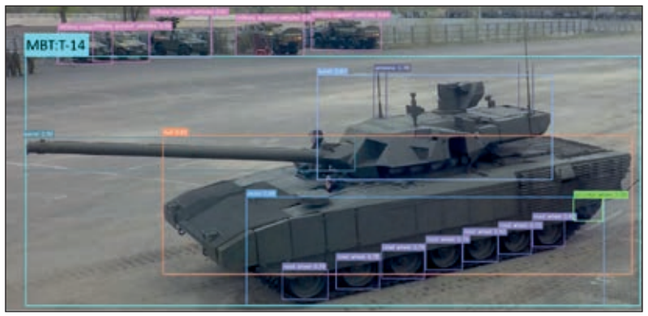


Fig. 1: Automatic identification of military ground vehicles based on their components

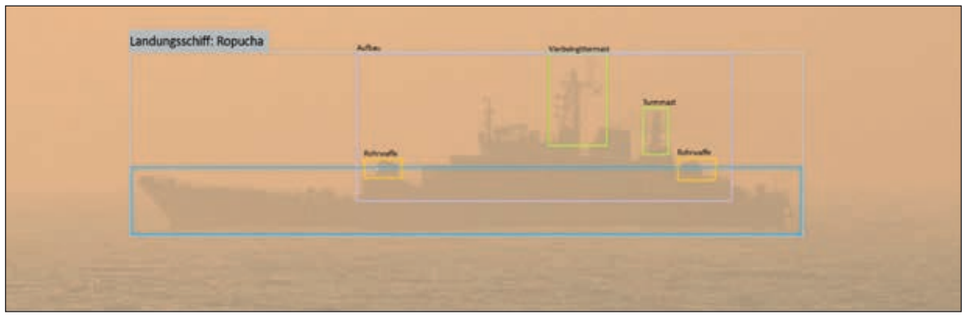


Fig. 2: Automatic identification of the Ropucha-class ship based on its components under challenging weather conditions

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Visual Action – Determining Pilot Compensation through Eye Tracking

The DLR Institute of Flight Systems developed the 'Visual Action' method, which uses eye tracking data to objectively quantify pilot compensation during helicopter manoeuvres. A simulator study demonstrates alignment with subjective pilot evaluations. The method has the potential to be used for workload monitoring and adaptive cockpit assistance in military helicopters.

As part of the EASINESS project, system development tools and innovative systems themselves were examined with the aim of expanding the tactical operational capability of military helicopters. In addition, methods were developed to assess the examined systems, among other things with regard to the pilot's workload.

During flight manoeuvres, helicopter pilots must always make additional mental and physical efforts – known as pilot compensation - to maintain a safe flight condition. The greater the compensation, the lower the handling quality assessment. Until now, pilot compensation has primarily been captured through control input activity or subjective pilot ratings. The Institute of Flight Systems at the German Aerospace Center (DLR) in Braunschweig has therefore developed the 'Visual Action' method, which uses eye tracking data to quantify pilot compensation objectively for the first time.

The method involves analysing the pilot's gaze movements in the cockpit. It counts how often the pilot deliberately shifts their gaze from one point of interest to another per second, filtering out small, involuntary eye movements. A mean gaze activity value is computed from the most demanding subphase of a given manoeuvre. Individual calibration for each pilot then allows for a cross-pilot comparison.

The underlying hypothesis states that when pilot compensation is low, more cognitive capacity is available for active gaze control and environmental scanning, resulting in an increase in visual action. Conversely, when compensation is high, attention narrows to a few visual reference points, resulting in a decrease in visual action and an inverse correlation between gaze activity and pilot compensation.

To validate this, test pilots performed four standardised flight test manoeuvres – hover, slalom, pirouette, and acceleration/deceleration – at the DLR Air Vehicle Simulator (AVES) in Braunschweig (Fig. 1), using flight controllers with different characteristics for each test. Gaze movements were recorded using an eye-tracking device (Fig. 2).

Analyis of the data revealed a strong correlation between the measured gaze activity and the pilot rating, with excellent conformance regardless of the respective manoeuvre. Furthermore, two clear threshold values can be derived that mark the transitions from minimal to moderate and from moderate to substantial pilot compensation.

This method is particularly relevant to defence research for military use. Military helicopter pilots regularly encounter extreme conditions – such as degraded visual environments (DVEs), shipboard landings and tactical low-level profiles – in which excessive compensation is safety-critical. This method has the potential to monitor workload, assess training, and provide adaptive cockpit assistance in military helicopters.

The 'Visual Action' method opens up new possibilities for a non-invasive, continuous assessment of pilot workload. Future work will investigate the transferability of the method to real helicopter flights and motion-based simulators and examine whether the approach can be generalised to other human-machine interfaces.



Fig. 1: The ACT/FHS replica cockpit at the DLR AVES research facility

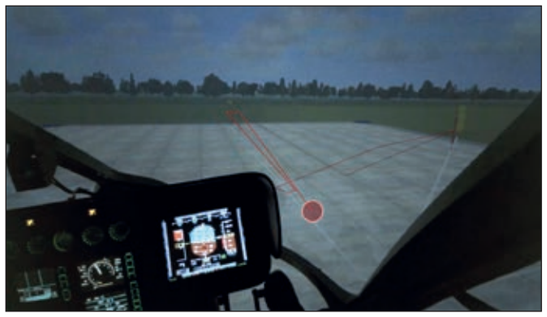


Fig. 2: Gaze movements of a helicopter pilot during a precision hover

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Simulation, Manufacturing and Experimental Validation of a Multi-layer Radar Absorbing Material

In a joint research project between the DLR institutes HR and BT, DLR-HR simulatively designed a multi-layer radar absorber, which was then manufactured by DLR-BT and characterised electromagnetically at DLR-HR. This work focuses on demonstrating the ability to digitally design complex radar absorbers, manufacture them within tight tolerances, and then validate them experimentally.

Radar-absorbing materials (RAM) are a group of functionalised materials that reduce the electromagnetic signature, or radar signature, of objects in the GHz range. Such materials consisting of several layers are referred to as multi-layer RAM. The Microwaves and Radar Institute (HR) and the Institute of Structures and Design (BT) have demonstrated their multidisciplinary capabilities in designing, manufacturing and experimentally validating such multi-layer RAM for aerospace applications.

Fillers with electrical or magnetic losses are required to absorb the incident electromagnetic energy. This study uses carbon nanotubes (CNTs), which cause high electrical losses even at low concentrations. First, layers of PEEK-CNT (a plastic composite material filled with carbon nanotubes) with different filler contents are manufactured and characterised electromagnetically to establish a correlation between CNT filler content and electromagnetic properties. Any combination of the measured layers can then be formed, and its absorption behaviour can be calculated analytically. The possible degrees of freedom are the filler content, the thickness of the individual layers and the total number or sequence of the layers. Subject to boundary conditions such as the maximum thickness of the overall structure, the minimum thickness of an individual layer that can be produced and the material tolerances, all combinations can be formed and calculated analytically. The absorption capability of each combination is then evaluated, and the optimum combination is selected to determine the final multi-layer setup.

Based on the thickness requirements, the individual layers of the multi-layer setup are pre-manufactured in the hot press (Fig. 1) using the respective high-temperature thermoplastic pellets (Fig. 2). In a second step, compliance with the tolerances is checked for the two layers made of (1) PEEK and (2) PEEK-CNT. Before bonding the individual layers in the press, the surfaces are plasma-activated to improve adhesion. The multi-layer plate is then trimmed and characterised electromagnetically.

This takes place in a free-space measurement setup, which is located in an anechoic chamber. The vertically installed sample is illuminated by an antenna that measures the reflection properties, thereby enabling conclusions to be drawn about the absorbance of the sample. To prevent the peripheral areas of the sample from distorting the measurement result, a lens is placed in front of the antenna to focus the energy on the centre of the sample.

The measurement results can then be processed and compared with the analytical results that were calculated in advance during the design stage (Fig. 3).

This workflow can be applied to other absorber designs in the future. The variety of manufacturing technologies at DLR-BT also allows the direct quantification of the influence of the manufacturing parameters on the electromagnetic properties. Current research focuses on challenges such as a mismatch in the coefficients of thermal expansion in hybrid joints. The solutions developed are always validated electromagnetically by DLR-HR. Combining the expertise of the two participating institutes will also enable future challenges to be overcome, for example those concerning the production and integration of such RAM technologies.

The core aspect of the work is to consider both the electromagnetic boundary conditions and the manufacturing-related framework together in order to obtain RAM structures that fulfil both their mechanical and radar-absorbing requirements.



Fig. 1: Rucks hot press at DLR-BT in Stuttgart

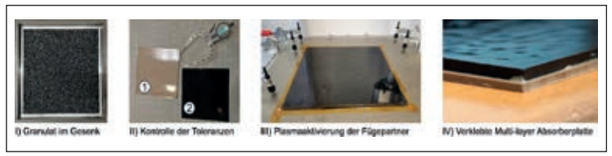


Fig. 2: The manufacturing steps for multi-layer RAM consisting of (1) PEEK and (2) PEEK-CNT

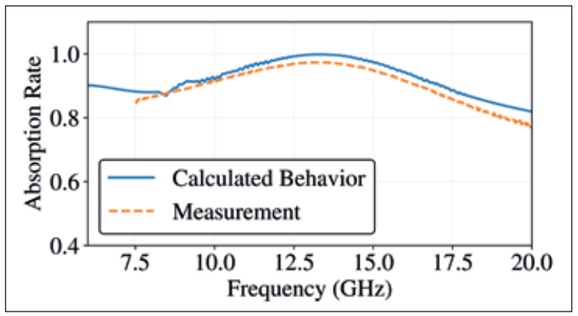


Fig. 3: Correlation of simulated and experimental results of the multi-layer RAM design

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The Path to Automated Air-to-air Refuelling in the FARAO Project

Air-to-air refuelling using the probe and drogue method remains a challenging manoeuvre for pilots. In the FARAO research project, assistance and automation systems as well as the required underlying technologies are developed and tested in simulators. The project is considering not only combat aircraft, but also transport aircraft, helicopters and unmanned aerial vehicles.

Air-to-air refuelling is an essential capability for air forces, enabling them to deliver effects over long distances on short notice. In the probe and drogue method, the receiving aircraft's crew must manually steer their air refuelling probe into a refuelling basket towed by a hose from the wing of a tanker aircraft. This procedure requires intensive training and places high demands on the crew. The 'Future Air-to-Air Refuelling Augmented, Assisted and Automated Operations (FARAO)' research project therefore aims to develop augmentation, assistance and automation systems that will reduce the crew workload and increase the probability of a successful coupling. Given the growing importance of unmanned systems within air forces, technology for fully automated air-to-air refuelling will also be indispensable in the future.

Initially, the project made significant contributions to advancing the air-to-air refuelling simulation at DLR. This involved implementing refuelling system failure cases, comprehensively improving helicopter simulation, and using HoloLens mixed reality glasses to provide a 3D visualisation of the hose and refuelling probe, thereby improving depth perception.

Subsequently, various visual assistance systems were designed and discussed with platform operators in workshops before being optimised and, finally, the most promising variants were implemented. Here too, the technical foundation is a pair of mixed reality glasses capable of displaying the relevant information clearly and quickly, depending on the stage of the refuelling process. This allows pilots to achieve a high level of situational awareness, whilst eliminating the need to look at the internal displays in the cockpit. An example of the assistance provided during the contact establishment phase is shown in Figure 1.

To enable the structured development of partially and fully automated systems, the relevant NATO standards were studied first and then a mission control system and a simplified development environment were set up (Fig. 2). Both form the basis for further work. Comprehensive control concepts, the necessary sensors and sensor models were then created to be able to rapidly evaluate the technical feasibility of various solutions. The next step was to investigate and optimise approach procedures, taking into account minimum safety distances, as shown in Figure 3.

In the field of basic automation technologies, it was demonstrated that an AI model trained using synthetic data from a virtual environment is capable of identifying the refuelling basket and recognising its position in real photos of air-to-air refuelling situations (Fig. 4). Furthermore, a solution that guides receivers to a tanker and determines the relative positions of both aircraft is being investigated using a GLASS (GLS approaches based on SBAS) system installed in a German Air Force A400M. This system uses SBAS satellite signals to broadcast a GLS (GBAS Landing System) glide path behind the tanker, which can then be picked up by any aircraft capable of receiving GLS-signals (Fig. 5).

A particularly noteworthy aspect of the FARAO project is the direct collaboration with the end user, namely the German Armed Forces and the pilots of the individual platforms. This enables concepts to be iterated quickly and research to be tailored to the requirements of the soldiers.

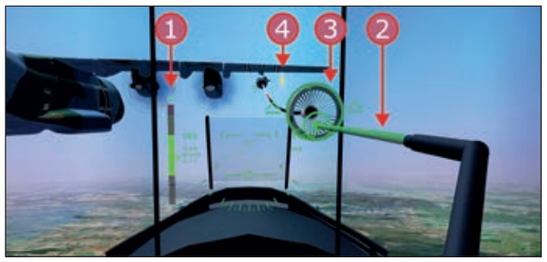


Fig. 1: Features of an assistance system in mixed reality: (1) OS scale; (2) pointer; (3) basket hologram with status and trend displays; (4) AR pod lights

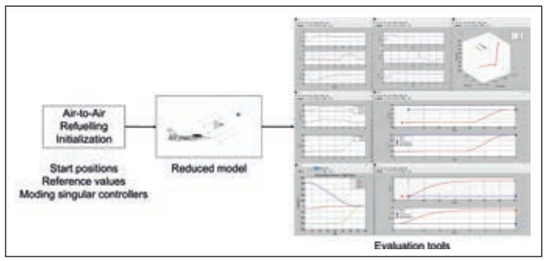


Fig. 2:Schematic of a development environment for partially and fully automated air-to-air refuelling systems

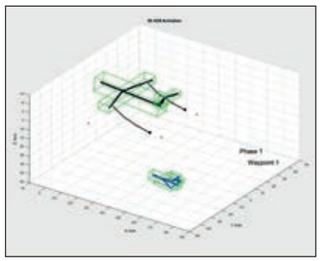


Fig. 3: Investigation of closing trajectories with collision boxes

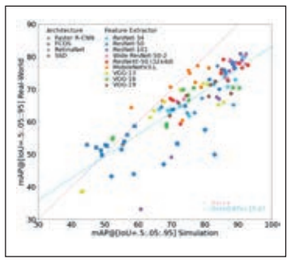


Fig. 4: Evaluation of 144 training models shows promising results for basket detection in the real world following synthetic training



Fig. 5: Planned installation of a GLASS (GLS approaches based on SBAS) station in an A400M

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OTTER Mission – Optical Traffic Tracking for Responsive Space

Geopolitical change calls for rapid adaptability in space technology research. The primary objectives of the OTTER small satellite mission, which were previously focused on the ground, are thus shifting into orbit: Once research into responsive space capability gaps in the satellite development process is complete, maritime domain awareness can be provided from space after the launch.

The Responsive Space Cluster Competence Centre (RSC³) at the German Aerospace Centre (DLR) is conducting a nanosatellite project called OTTER (Optical Traffic Tracking for Responsive Space), working closely with industry, users and research institutions. Nanosatellites, in particular so-called CubeSats, are roughly the size of a shoebox and weigh less than 10 kg. Thanks to their standardised form factor, they are often cheaper and faster to manufacture and launch into orbit than satellites weighing several tonnes.

In 2022, the OTTER mission aimed to conduct a market survey among satellite manufacturers to assess the feasibility of rapidly providing nanosatellites equipped with an AIS receiver and a camera as payload to contribute to maritime domain awareness by verifying the position of ships via AIS and optical imaging.

Initially, the main focus of the mission was to analyse and evaluate an accelerated satellite development process. When the industry was initially commissioned, it was a prerequisite that RSC³ would be able to accompany the development steps

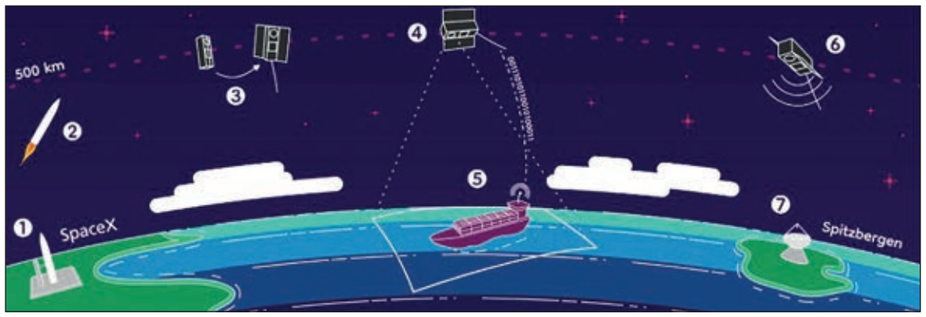


Fig. 1: The OTTER mission: (1) Launch with SpaceX; (2) deployment and release into a 500-km orbit; (3) deployment of the solar panels, antennas, and magnetometer. This is followed by images of ships and their signals (steps 4 and 5), and the downlink of data to the ground station and upload of the next commands (steps 6 and 7)

of the industry partners in the form of workshops, analysing possible capability gaps as well as the potential for improvement or acceleration. However, the target period of six months until launch could not be achieved due to regulatory, technical and resource-related issues. The two biggest factors causing delays were the postponements of the launcher and technical challenges. The numerous insights gained during development were successfully applied in the initial qualification of the RSC³ and in the establishment of its own research infrastructure.

During the period of delay until 2025, changes in the geopolitical situation altered the expectations for the mission: the satellite's ability to contribute to maritime domain awareness became more important than the opportunity to learn from development. Consequently, the OTTER mission's focus shifted from the ground to orbit and to operations. This made clear operating procedures, thoroughly tested, functioning hardware and a well-coordinated operations team all the more important. Less proven hardware, such as the UHF radio, was replaced with higher TRL hardware and extensive system validation tests were carried out to minimise the risk of failure in orbit. The rocket launch was also changed from a startup launcher (which had not yet flown in orbit at that time) to SpaceX in order to maximise the chances of success. The launch at the end of 2025 was successful, and the commissioning of the OTTER satellite in a 500 km sun-synchronous orbit has begun.

As part of Germany's participation in a multinational research and development (R&D) study, OTTER is set to contribute to the fusion of data from multiple sources, including those from other nations. The shared objective is to develop an independent maritime situational picture for future operational use based on findings validated through multinational trials.

OTTER operations therefore require precise position and orbit data, the processing of received cooperative AIS vessel information and the combination of this with data from optical earth observation sensors. Alongside maritime situational awareness, the OTTER mission aims to demonstrate the viability of a cloud-based mission control system. The concept of decentralised satellite operations, developed at RSC³, is to be tested in exercises at an international level. It will be possible to command OTTER in near real time from any location.



Fig. 2: Launch of the Falcon 9 rocket with the OTTER on board in November 2025 (source: SpaceX)

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AI-based Camouflage Assessment with ABACUS

The widespread use of uncrewed aerial and ground vehicles (UxVs) that use AI-supported sensor data analysis on the battlefield leads to continuous observer presence. This accelerates the sensor-to-shooter cycle and increases the pressure to constantly improve camouflage and deception techniques. Fraunhofer IOSB is researching AI methods for analysing camouflage quality and the probability of detection and offers an operational demonstrator called ABACUS.

Rapid advances in UxV technology and artificial intelligence (AI) are creating entirely new challenges for camouflage, signature management, and deception. The war in Ukraine demonstrates that numerous UxVs equipped with imaging sensors are being used for attack and reconnaissance purposes. When combined with powerful AI algorithms, this enables continuous observation on an unprecedented scale, posing significant risks to the concealment of soldiers, vehicles, and positions.

Modern AI-based object recognition methods are often freely available and easy to use. They can facilitate largely automated reconnaissance and detection. These systems are highly capable and can reliably recognize even well-camouflaged objects from long distances (Fig. 1). It is therefore of prime importance to develop suitable countermeasures and tools to verify the effectiveness of one's own camouflage measures against AI-supported reconnaissance.

To address this issue, Fraunhofer IOSB is researching AI-based methods for camouflage assessment in cooperation with WTD 52. Modern AI models for object recognition are trained using military image data and combined with so-called explainability methods. Object recognition provides automatic reconnaissance and enables an assessment of camouflage quality. The explainability methods deployed specify which parts of an object (e.g., extremities of personnel, running gear and armament of armored tracked vehicles) were most responsible for its detection and are particularly "conspicuous" to the AI (Fig. 2). This makes it possible to estimate both the risk of detection by AI methods and how camouflage measures can be improved specifically.

To simplify the use of both AI models and camouflage assessment, the ABACUS software demonstrator was developed (Fig. 3). ABACUS enables the loading of relevant image data, the evaluation of camouflage quality using various AI methods, and the detailed analysis of image regions that are decisive for detection. The ability to simulate camouflage directly in ABACUS allows for a fast, interactive process of testing different optimization measures without having to implement them in reality.

Results from complementary research projects on the assessment of camouflage measures in the context of AI indicate a significant threat ('detection') from sensor-equipped UxVs using AI-based image analysis. Field measurement campaigns have shown, for example, that ABACUS was able to reliably assign armored vehicles to the correct class even from long distances (Fig. 4).

Compared with classical observer experiments, ABACUS offers an efficient, less subjective alternative for the evaluation of the camouflage quality of an object. Furthermore, the explainability maps in ABACUS allows direct conclusions to be drawn about image areas of an object that need optimising with regard to camouflage. This process is becoming increasingly important as AI models can detect camouflaged objects with extreme precision, even at great distances. Figure 5 shows an example of an AI model's confidence in ABACUS, which detects two persons, one wearing camouflage clothing and the other not.

Currently, the camouflage assessment is being extended to include a camouflage-specific environmental assessment. The aim is to use UxV-captured imagery of the surrounding terrain, in particular, to estimate the suitability of different areas for camouflaging. This will enable us to make well-founded advance assessments as to which areas are suitable for positioning or movement, and thus offer the best possible protection against detection. Conversely, this ability can also be used to identify areas that an opponent would prefer to use for their own camouflage purposes.



Fig. 1: Even though the person is wearing a ghillie suit for camouflage, the AI reliably recognizes them (enlarged section)

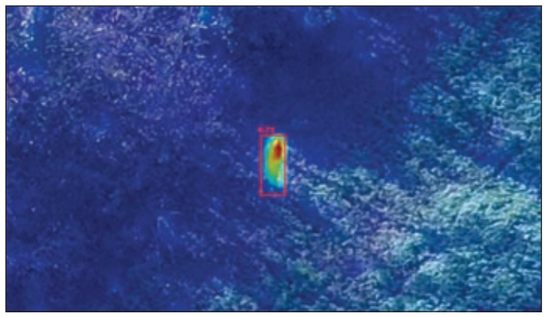


Fig. 2: Colors indicate which areas of the image matter to the AI when detecting a person at 60 metres: red marks the key regions, blue marks the irrelevant ones. The head and shoulders are the parts most visible to the AI and should therefore be camouflaged



Fig. 3: User interface of the ABACUS software for AI-based camouflage assessment



Fig. 4: Error-free classification of two armored vehicles by ABACUS in a UAV image (highly enlarged section). The AI model's confidence in its prediction is extremely high at 100 %

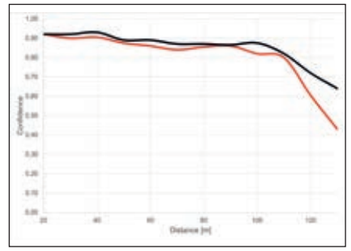


Fig. 5: Visualization of the model confidence (y-axis) relative to the distance (in metres, x-axis) in the camouflage assessment of a person without camouflage (black line) and a person with camouflage clothing (red line).

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Influence of Geometric Dimensioning on the Unsteady Aerodynamics of Highly Contoured Aircraft Engine Intakes

For aircraft with highly integrated propulsion systems, intake aerodynamics play a key role as they directly impact the operating behavior of the engine's compressor system. This scaling study investigates whether the unsteady intake aerodynamics of larger test items can be reproduced in smaller-scale experiments, which would enable significant savings in development time and cost.

Bent engine intakes are a necessary measure to ensure an aircraft's low observability characteristics. An S-shaped intake contour blocks the direct line of sight to the front compressor stage, thereby reducing radar reflections from the compressor. However, strongly curved intake ducts can generate secondary flow phenomena such as vortices and reverse flow, creating areas in which the intake air can no longer follow the duct geometry. Such areas of disturbed flow negatively affect compressor operability and efficiency and restrict the flight envelope within which stable propulsion operation is possible.

At the Institute of Jet Propulsion (IJP) at the Munich University of the Bundeswehr, such highly curved intakes are an essential component of numerical and experimental research. To this end, the Military Engine Inlet Research Duct (MEIRD), with a compact, highly curved intake geometry, was designed and manufactured to enable a wide range of investigations. The MEIRD is primarily intended for use in the IJP's engine test facility in conjunction with a Larzac 04 C5 engine (Figure 1), as built into in the Alpha Jet. Full-scale engine tests are time-consuming and costly. Therefore, test rigs featuring smaller, scaled versions of the MEIRD were developed. Investigations have shown that the time-averaged intake behavior can be accurately reproduced using scaled models, resulting in significant time and resource savings. However, the vortices and separations that develop in S-shaped intakes can also lead to strong temporal fluctuations in the inflow to the compressor. Such fluctuations may endanger flow stability inside the compressor, even when time-averaged values appear uncritical. The experiment presented here compares three test campaigns using MEIRD geometries of different sizes: the full-scale MEIRD as well as two scaled versions, MediMEIRD (Fig. 2) and MiniMEIRD (Fig. 3), with outlet diameters of 120 mm and 60 mm, respectively. The aim is to establish whether the unsteady intake-aerodynamic behavior is similar across all three sizes.

As shown in Figure 4, the three test platforms are fitted with high-frequency pressure transducers at four geometrically similar locations. Experiments are conducted for all three scales with similar flow velocities at the air intake opening of each configuration. The recorded signals are then analyzed using a fast Fourier transformation to compare the frequency content of the measured pressure fluctuations, and the signals from the different transducers are examined for mutual coherence. The resulting cross-power spectral density enables a phase shift computation between the measurement locations, which helps characterize the spatial and temporal propagation of pressure fluctuations within the intake duct. While the overall shape of the spectral distribution differs between the full-scale MEIRD and the scaled models, a characteristic flow phenomenon was identified for each size that propagates upstream from the rear end of the intake. This phenomenon's associated frequency changes with intake size. A more detailed characterization of this phenomenon, as well as the identification of factors influencing the change in frequency under scaling, are part of planned investigations.

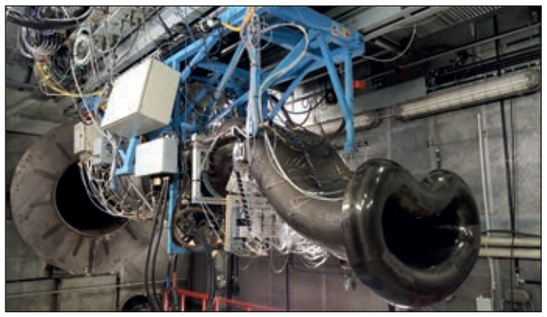


Fig. 1: Full-scale MEIRD test setup

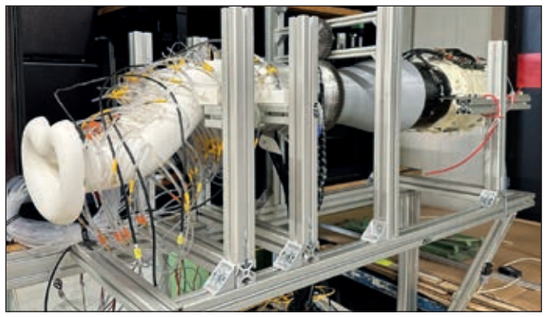


Fig. 2: Scaled MediMEIRD test setup with an outlet diameter of 120 mm

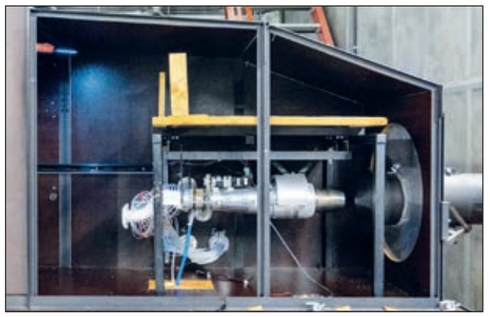


Fig. 3: Scaled MiniMEIRD test setup with an outlet diameter of 60 mm

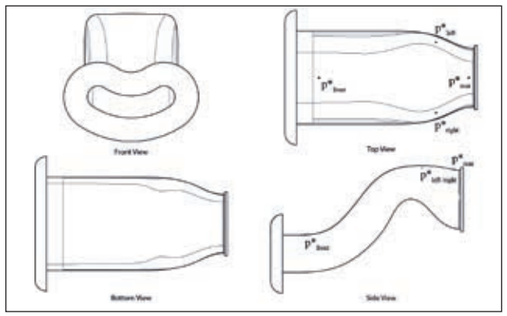


Fig. 4: MEIRD geometry with locations of the high-frequency pressure transducers

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Target Echo Strength Measurements of Underwater Objects with Scaled Models

The most important quantity for the detectability of underwater objects with active sonar is the Target Echo Strength (TES). The TES of an underwater object describes its spectral and directional reflectivity with respect to sound waves. In order to be able to determine the TES of medium-sized underwater objects, the TES measurement site of WTD 71 at Lake Plön was upgraded and used on first defined test objects.

The spectral and directional characteristics of an underwater object's TES form its unique signature, which can be used to detect and classify it by sonar. Knowledge of the TES of one's own and hostile objects is a decisive factor in Anti- Submarine Warfare (ASW). The TES of an underwater object can be determined by transmitting a sound signal towards it and analysing the reflected sound intensity.

In order to be able to determine the TES for medium sized bodies (1–5 m in length), a TES measurement facility was reinstalled at the test site of WTD 71 at Lake Plön, and predefined targets were investigated, as part of the international TESSMEx project (Target Echo Strength Scaled Model Experiments, with the Netherlands, the United Kingdom, Canada, Australia and Germany forming the participating nations). These targets are based on the computational models from the international workshops series on the calculation of TES BeTSSi I, II and IIb and were realized as physical models at a scale of 1:10. The TES of the 'M32' (Figure 2) and 'M32T' (truncated) models was measured at the newly reinstalled measurement facility in Plön and compared with the results of our numerical modelling. Both experimental and numerical results were submitted to the TESSMEx project as Germany's contribution.

The measurement facility, shown in Figure 1, has a fixed sound propagation range between the measuring house, which is built on stilts in the lake, and a barge that is anchored in the water at a distance of 220 m. One advantage of this long distance is that it allows for comparability with the conditions encountered in shallow sea; this property that cannot be provided by a simpler, more compact test setup (e.g. in a water tank).

The water depth at the test site is between 12 and 18 m. The target must be suspended halfway through the water column, below the barge. This means that the sound energy must be focused into a vertical beam with a width of a few metres at most. This demand results in a transducer requiring a minimum effective length of approximately 3 m, in order to achieve the necessary side lobe suppression at the target distance. Switching the transducer between transmit and receive modes allows the same advantageous beam pattern to be used also in receive mode, further suppressing background noise and reflections from the barge, the water surface, and the sea floor.

Among other targets, the TESSMEx target 'M32' (Figure 2) was suspended from the barge at half the water depth and slowly rotated in a controlled manner. This approach caused the target to constantly turn different aspects of its reflectivity towards the sonar head, enabling it to be scanned over a full rotation with respect to aspect angle. The following aspect angles were assigned to the target directions by definition: 0°: bow (front), 90°: port side (left), 180°: stern (rear) and 270°: starboard side (right).

Figure 3 shows the reflected impulse responses of the M32 target over the course of one revolution, derived from the reflections of the transmitted signal. In addition to the outer hull, some of its internal structures are also acoustically effective, as can clearly be seen in the reflections (e.g. the five strengthening frames of the hull at an aspect angle of 0°). These impulse responses can be used to determine the spectral reflectivity as a function of the aspect angle, shown in a frequency-aspect plot (FrAs-plot, Figure 4). The FrAs-plot allows us to assign certain frequencies to the properties of the target, or to identify broadband reflection behaviour (e.g. the reflection peaks of the shell at 90° and 270°). Near these aspect angles multiple reflections between the inner tube and the outer shell are also visible.

These measurements serve to gain knowledge and to validate and improve the numerical prediction methods in comparison (Figure 5) for the TES of objects. With the newly reinstalled TES measurement facility in Plön, the WTD 71 now has an important tool for determining the Target Echo Strength of scaled models and of AUVs/UUVs at its disposal again.

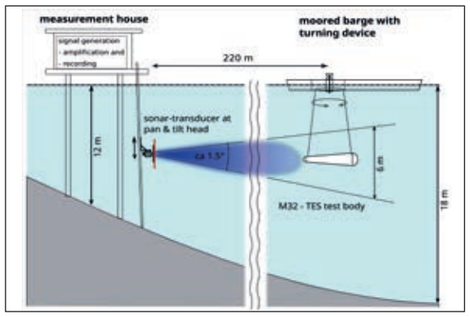


Fig. 1: The target strength measurement facility at Lake Plön. It consists of the measuring house (on the left) containing an adjustable sonar transducer, and a barge (on the right) anchored at a distance of 220 m, under which the rotatable test body is suspended.

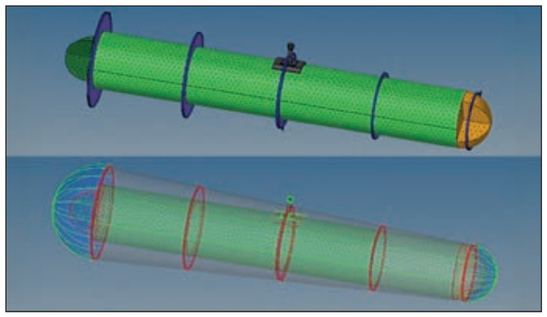


Fig. 2: The M32 test body, which consists of an inner steel tube (10 mm thickness) with strengthening frames (top) and a conical outer shell with hemispherical end caps (2 mm steel, bottom). It has a total length of 4.9 m and a maximum diameter of 1 m.

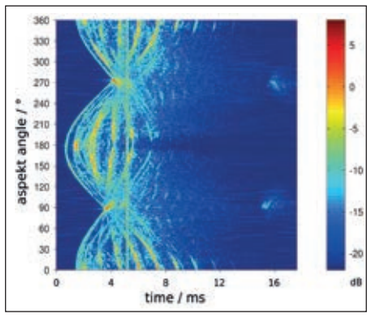


Fig. 3: : The impulse responses of the M32 body depend heavily on the aspect angle and exhibit time-resolved reflections from all the internal structures.

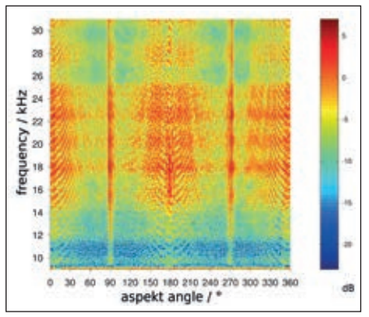


Fig. 4: The spectral reflectivity as a function of frequency and aspect angle, determined from the reflected signals, displayedin a so-called frequency-aspect (FrAs) plot.

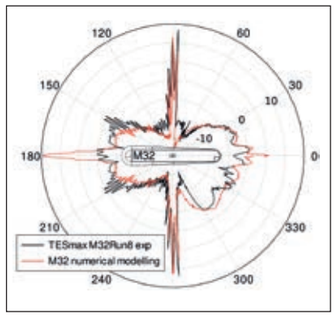


Fig. 5: A polar plot of the derived TES curve allows for the comparison of the acoustical effects with the results of the numerical modelling of M32.

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Software Vulnerability Analysis

The study “Software Vulnerability Analysis” was conducted by WTD 81 GF 210 in collaboration with HENSOLDT. The study involved surveying for tools and procedures suitable for software vulnerability analysis. A laboratory has been set up that can be used to examine most forms of software for vulnerabilities and malicious code. The focus was on practical feasibility.

Digitalisation is crucial for the future viability of the German Armed Forces. The networking of systems and the capabilities that can be achieved with software (software-defined defence, SDD) are becoming increasingly important. However, as software use increases, so does the risk of cyber attacks. A successful cyber attack could render capabilities gained through software useless, allow attackers to spy on data and, in extreme cases, take over systems. Thus, the protection of software against attacks is also gaining in importance.

The objective of the ’Software Vulnerability Analysis’ study was to identify tools and procedures that support the identification of vulnerabilities and malicious software. Conducted between 2013 and 2025, the study comprised five individual study measures, which were carried out by the company HENSOLDT (formerly ESG).

The topic was examined from the following perspectives:

- Dynamic analysis
- Static analysis of source code
- Static analysis of binary code

In dynamic analysis, the software to be analysed is executed either in its entirety or in part. Appropriate tools are then used to observe how the software interacts with its environment. Other analysis techniques include examining the inner workings of the software using a debugger, or intercepting interactions between programmes or system components (a process known as ‘hooking’, for example using the FRIDA tool). The study examined, among others, the WannaCry ransomware and demonstrated the functioning of the kill switch built into it (Fig. 1 and 2). Dynamic analysis also involves carrying out attacks against the software being analysed (a process known as penetration testing).

Static analysis involves using appropriate tools to scan the code for vulnerabilities or malicious content. Static analysis of source code is much easier than analysis of binary code. Tools such as Fortify™ and CodeSonar™ can be used to automatically scan large amounts of source codes within a short period of time. These tools have enormous potential for development through the use of artificial intelligence.

Binary code is a representation of a programme that can be executed directly by a processor (Fig. 3) Examples include EXE and DLL files in Windows™ operating systems. Binary code analysis is necessary when the source code of a software is unavailable, for example in the case of commercial software or malware. It is also imperative for the identification of vulnerabilities that only arise when the source code is translated into binary code, for example the overwriting of a return address due to a buffer overflow. Attackers can exploit this vulnerability to execute arbitrary malicious code. Fortunately, modern operating systems offer protection mechanisms against such attacks, such as Canaries, ASLR (Address Space Layout Randomisation) and DEP (Data Execution Prevention). However, these can be circumvented by techniques such as ROP (Return Oriented Programming).

Tools such as Ghidra (developed by the NSA) are used to analyse binary code. As part of the study, binary code analysis, among other things, was used to get to know the infection paths of malware. By combining binary code analysis with dynamic analysis, it was possible tocircumvent the security mechanisms of Android apps, such anti-tampering and anti-analysis features. The extraction of cryptographic secrets was also examined.

There is significant potential for improvement through the use of artificial intelligence. At the DARPA (Defense Advanced Research Projects Agency) Cyber Grand Challenge in 2016, systems that automatically scan binary code for vulnerabilities, eliminate them with patches, and even develop attacks on the identified vulnerabilities were demonstrated (Fig. 4). One such system (MechaPhish) was reconstructed and examined as part of the study.



Fig. 1: Laboratory computer infected with the ransomware WannaCry

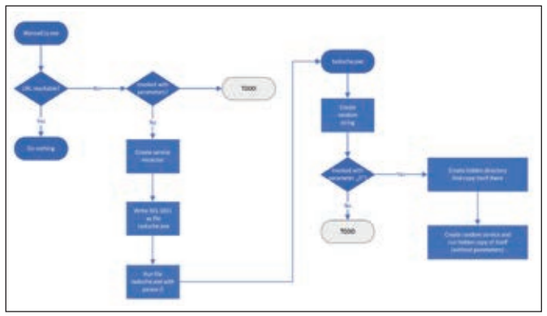


Fig. 2: First steps of an infection with the ransomware WannaCry

```
                    undefined8 __stdcall main(void)
undefined8            RAX:8          <RETURN>
                    main

00101139 55              PUSH    RBP
0010113a 48 89 e5        MOV     RBP,RSP
0010113d 48 8d 05        LEA     RAX,[s_Hello_World!_00102004]
         c0 0e 00 00
00101144 48 89 c7        MOV     RDI=>s_Hello_World!_00102004,RAX
00101147 e8 e4 fe        CALL    <EXTERNAL>::puts
         ff ff
0010114c b8 00 00        MOV     EAX,0x0
         00 00
00101151 5d              POP     RBP
00101152 c3              RET
```

Fig. 3: Binary code of a “hello word” program



Fig. 4: DARPA Cyber Grand Challenge

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Laser Weapons in the Context of Current Airborne Threats

Thanks to their unique system properties, laser weapons are key to countering new types of military threat, particularly when it comes to effectively engaging small unmanned aircraft systems (sUAS). At the Bundeswehr Technical Center for Weapons and Ammunition (WTD 91) in Meppen, the entire process from target acquisition to downing sUAS was successfully tested using the LWD 2024 laser weapon demonstrator developed by MBDA Deutschland GmbH.

Building on previous research and technological work, MBDA's LWD2024 laser weapon demonstrator was tested in several field campaigns on the laser test range of the WTD 91.

The main objective was to demonstrate the entire engagement chain – from detection and reliable, robust target tracking to the precise downing of highly agile targets – under realistic conditions.

The modular system is constructed on a 10-foot container base (Fig. 1) and, in its current configuration, operates with a laser power in the single-digit kilowatt range. The primary goal of this development stage is to demonstrate the system's ability to precisely and stably track targets as a prerequisite for an effective engagement (Fig. 2). The system architecture is also designed in such a way that more powerful laser sources can be integrated without the need for a fundamental redesign. This will significantly increase the range and effectiveness of the system in the future.

During field tests, it was demonstrated that dynamic targets several kilometers away can be reliably detected and tracked (Fig. 3). This is achieved through a special multi-stage tracking chain comprising radar-based detection, electro-optical coarse tracking, and active fine tracking. Active fine tracking uses an auxiliary laser to illuminate the target precisely, independent of daylight conditions, and enables highly stable guidance of the laser beam. This level of accuracy achieves a sufficiently high energy density at the target point as required for the rapid destruction of a UAV. Despite the laser power being deliberately limited in the demonstrator, effective ranges of more than one kilometer were achieved. Full performance demonstration was achieved through the successful engagement of several real drone targets (Fig. 4) at varying distances and with changing flight profiles.

The engagement process is clearly defined: after the initial target is acquired using radar sensors, the target data is transferred to the electro-optical system in the laser weapon turret. The electro-optical system then performs image-based coarse tracking, after which active fine tracking enables high-precision laser beam tracking. Once the target has been acquired stably, the exact target point is set and the high-power laser is activated. The operator is involved in this process at all times and can define the target point, for example a particularly vulnerable spot on the sUAS, as required by the mission. Also during firing, the robust tracking algorithm ensures that the laser beam remains aimed precisely at this point until the target is successfully engaged. This process usually takes only a few seconds and can be observed in real time on the remote control station monitors.

The demonstrator itself requires a footprint of approximately 2.5 × 2.5 meters and incorporates all the necessary subsystems, including the power supply and cooling system, in addition to the laser weapon turret. Test campaigns were conducted at the test and trial facility for high-energy lasers at the WTD 91, which is a fully instrumented laser test range spanning over more than two kilometers (Fig. 5). This facility enables the WTD 91 to evaluate, from agency-side, a wide range of issues relevant to high-energy laser radiation in practice, as well as to analyze the operational possibilities of and threats from laser weapons in a real-world environment.

This test environment was crucial for conducting the tests in full, safely and under realistic conditions. A significant increase in laser power is planned for future development stages. This should increase the effective range and further reduce the target engagement time. From an operational point of view, this is particularly relevant in scenarios involving waves of attacks or coordinated drone swarms.



Fig. 1: LWD 2024 laser weapon demonstrator



Fig. 2: Target tracking using the LWD 2024



Fig. 3: Engagement of a sUAS rotor using the LWD 2024



Fig. 4: A drone that has been downed

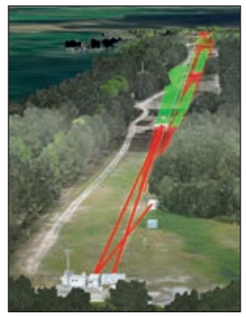


Fig. 5: 3D model of the test and trial facility for high-energy lasers at the WTD 91, to be used as a basis for planning laser trials



3

Military Medical Research and Military Psychology Research

As in previous years, the contributions for 2025 again show the broad spectrum of military medical and military psychological research aimed at protecting and restoring the health of the soldiers of the German Armed Forces.

For instance, contributions from institutes specialising in medical CBRN defence showcase the variety of topics covered. The Bundeswehr Institute of Radiobiology presents internal dosimetry, its measurement and modelling methods for post-radiation dose assessment, while the Bundeswehr Institute of Microbiology describes the specific detection of *Francisella tularensis* using single-chain antibodies. The Bundeswehr Institute of Pharmacology and Toxicology, meanwhile, reports on the development of a novel human neuron model that accelerates the search for antidotes against nerve agents.

The Bundeswehr Central Hospital in Koblenz describes a method for reliably identifying severe lung injuries following thoracic trauma. The Bundeswehr Hospital in Ulm reports on immune response biomarker signatures after severe trauma. Meanwhile, the dermatology department of the Bundeswehr Hospital in Berlin describes how modern psoriasis treatment concepts contribute to maintaining fitness for duty, and the Bundeswehr Institute for Preventive Medicine focuses on resilience in basic and advanced training as a model for national and collective defence. The Bundeswehr Psychotrauma Centre complements these topics with research into the impact of operational stress on the mental health of military and police personnel.

In their contribution, the military psychological researchers at the Naval Medical Institute report on a study of watch system design, conducted on a frigate during its UNIFIL deployment. The study aimed to determine the advantages and disadvantages of fixed and rotating watch schedules for crew performance and well-being, with the intention of formulating recommendations for their implementation.

Together, these contributions exemplify the important role of military medical and military psychological research in ensuring a modern, operationally ready Medical Service as part of a warfighting-capable Bundeswehr.

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Internal Dosimetry – Measurement, Modelling and Assessment

The Physical Dosimetry group at the Bundeswehr Institute of Radiobiology investigates methods for determining and assessing internal radiation exposure. It supports decision-making processes in medical CBRN protection by combining whole-body counting, Monte Carlo simulation and biokinetic modelling. These methods are validated through participation in national and international comparisons.

The current security situation highlights the growing relevance of nuclear and radiological threats. The Bundeswehr Institute of Radiobiology researches and establishes procedures to protect personnel before and after radiation exposure. In addition to external radiation exposure, the incorporation of radioactive substances into the body also poses a significant challenge. Therefore, reliable internal dosimetry is crucial for making decisions regarding medical treatments such as decorporation therapy, for assessing operational capability and for implementing radiation protection measures.

Internal contamination leads to complex, radionuclide- and organ-specific dose distributions. A combination of measurement technology, biokinetic modelling and dose simulation is required for reliable risk assessment. The Physical Dosimetry group is investigating methods for determining, modelling and assessing internal radiation exposure. The aim is to advance the scientific basis and methodological approaches to improve the reconstruction of individual doses under operational conditions.

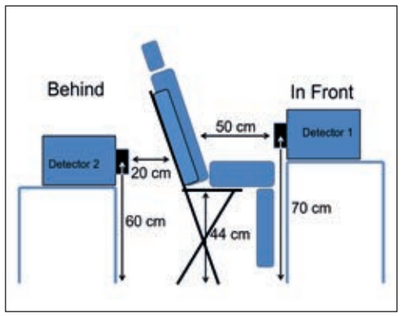


Fig. 1: Schematic setup for whole-body counting using mobile gamma spectrometers



Fig. 2: Whole-body counting calibration using a stylised brick phantom

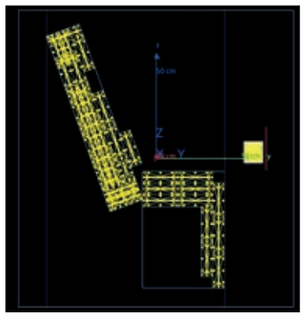


Fig. 3: Whole-body counting simulation using a stylised brick phantom

Whole-body counting involves detecting the radiation generated by incorporated radioactive substances in a shielded measurement geometry. Gamma spectrometers are used to identify and quantify gamma-emitting radionuclides. Body activity can be determined from the measured radiation using calibration procedures.

As few fixed whole-body counting facilities are available, a concept for improvised measurements based on mobile gamma spectrometers is being developed in collaboration with the MedCBRN Protection Task Force (Fig. 1 and 2). The aim is to enable the rapid medical triage of individuals with and without clinically significant internal contamination in operational settings. This will contribute to a rapid assessment of the situation during and after radiological incidents and improve medical command and control capability.

Numerical simulation methods based on Monte Carlo techniques allow us to analyse dependencies relating to measurement geometry, nuclide distribution and body constitution (Fig. 3). These methods are validated through international comparison measurements. In the ongoing EURADOS intercomparison, the institute's methodology is being tested using stylised brick-, voxel- and mesh-based paediatric phantoms.

The activity of incorporated radionuclides in the body changes over time due to physical decay processes as well as biological and chemical transport mechanisms. For medical assessment purposes, the initially incorporated activity must be calculated from the measured activity values in order to determine the effective committed dose for risk assessment. This requires the use of complex biokinetic models and dose simulations, which have been developed by ICRP and EURADOS.

The institute uses the latest recommendations and software tools, such as the OIR Data Viewer (Fig. 4) and CADORmed III (Fig. 5), to assess activity and dose. The proper application of these tools was demonstrated through participation in case study exercises with the Federal Office for Radiation Protection and in the ICIDOSE#2 laboratory comparison. These findings are incorporated into the development of operational assessment concepts.

This research enhances the Bundeswehr's capacity to swiftly identify and evaluate radiological hazards to personnel. The combination of measurement technology, simulation and biokinetic modelling specifically supports medical decision-making processes and the assessment of operational capability in radiological events. Continuous development of procedures and integration into national and international expert networks ensures long-term scientific expertise and capability development in medical radiation protection.



Fig. 4: The ICRP's Software tool for internal dosimetry, OIR Data Viewer

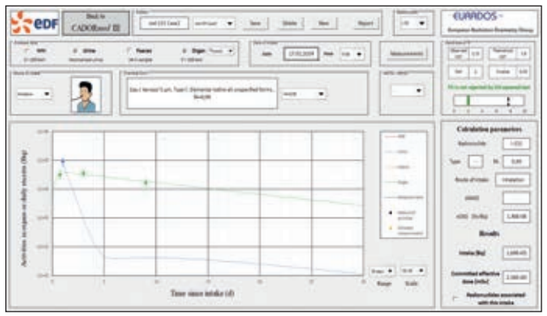


Fig. 5: EURADO's software tool for internal dosimetry, CADORmed III

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Detection and Isolation of *Francisella tularensis* Using Recombinant Reporter Fusion Proteins

Tularaemia is a re-emerging infectious disease in Germany. To improve the direct detection and isolation of *Francisella tularensis*, the bacterium that causes it, an antibody-based reporter fusion protein has been developed. Using this reporter, *Francisella tularensis* was successfully detected in clinical samples by fluorescence microscopy and isolated from infected ticks using reporter-loaded magnetic beads.

Tularaemia, also known as rabbit fever, is an infectious disease caused by the Gram-negative bacterium *Francisella (F.) tularensis*. In Europe, transmission often occurs through the bites of haematophagous vectors, such as ticks. However, infection can also result from direct contact with infected animals. In the 20th century, *F. tularensis* was investigated and weaponised as part of several nation's historical biological weapons programmes. The recent increase in naturally occurring infections, which can be severe or life-threatening, and the potential for misuse as an agent of biological warfare or bioterrorism explain the interest in improving diagnostic capabilities for *F. tularensis*.

Direct detection of *F. tularensis* by fluorescent microscopy could complement existing and routinely employed diagnostic procedures. To enable specific detection, a reporter fusion protein (here: reporter) was developed on the basis of an anti-*F. tularensis* antibody fragment (Fig. 1). The reporter consists of an antibody fragment that binds to *F. tularensis* and a signal component to visualise reporter-labelled cells on fluorescent microscopy. This detection of *F. tularensis* was highly specific (i.e., closely related bacteria were not labelled), as demonstrated in patient samples, including sputum, pus and lymph node tissues (Fig. 2).

In addition to microscopy, culturing *F. tularensis* remains an important diagnostic and investigative tool. To facilitate isolation, the reporter was bound to microscopic magnetic beads. These reporter-loaded magnetic beads can bind to *F. tularensis* cells in liquid samples, thereby enriching them. This enables *F. tularensis* cells to be separated from other microorganisms in samples with a high level of contamination, allowing direct cultivation of *F. tularensis* on non-selective agar plates. Advantages of this approach include the ability to rapidly and easily identify potential *F. tularensis* colonies directly on agar plates and the possibility of incubating the fastidious *F. tularensis* bacteria on non-selective growth media. This limits the negative impact that selective antibiotic substances can have on *F. tularensis* growth and possibly increases the chances of isolate recovery.

Tick homogenates (crushed ticks) were an ideal sample type to test this method, given the importance of ticks as tularaemia transmission vectors in Europe and the fact that the high level of contaminating microorganisms in these samples often makes the isolation of *F. tularensis* impossible. Ticks were collected in the Munich metropolitan area, mechanically lysed, and the samples were tested by polymerase chain reaction (PCR) for the presence of *F. tularensis* genetic material. The reporter-loaded magnetic beads were then used to attempt to isolate *F. tularensis* from PCR-positive, pooled tick samples (Fig. 3).

A total of more than 1000 ticks were collected. From eleven PCR-positive pooled samples, nine *F. tularensis* isolates were successfully recovered using reporter-loaded magnetic beads. This corresponds to an 81% recovery rate, which is a meaningful improvement on the isolation method previously used (Fig. 4). Furthermore, this approach enabled the identification of an unrecognised tularaemia focus in Munich shortly after a local patient case was reported.

The identification and analysis of biosecurity-relevant pathogens remains one of the core capabilities of the Bundeswehr Institute of Microbiology. The expertise gained regarding the magnetic bead-based enrichment of *F. tularensis* will serve not only to improve the investigation of tularaemia but also to inform the development of similar methods for the isolation of other highly relevant pathogens in military medicine.

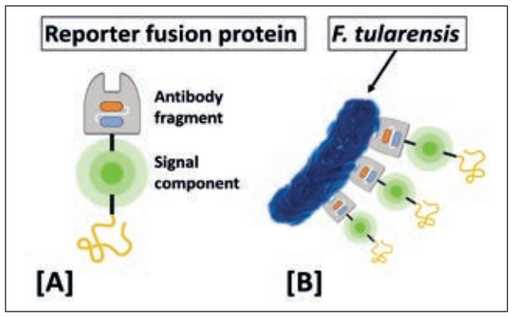


Fig. 1: [A] The reporter fusion protein (reporter) consists of a *F. tularensis*-binding antibody fragment and a signal component. [B] The antibody fragment binds to *F. tularensis* bacteria selectively, and the signal component enables detection by fluorescence microscopy

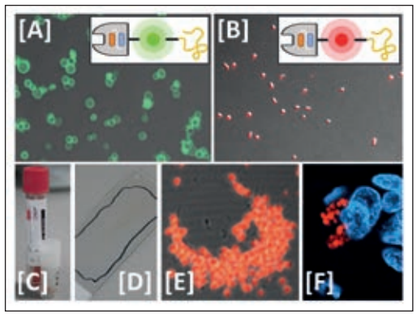


Fig. 2: [A,B] Green or red fluorescent *F. tularensis* bacteria after labelling with a green or red fluorescent reporter; [C-E] *F. tularensis*-positive samples were treated with the reporter directly on glass slides, revealing *F. tularensis* bacteria (red). [F] *F. tularensis* (red) in lymph node tissue

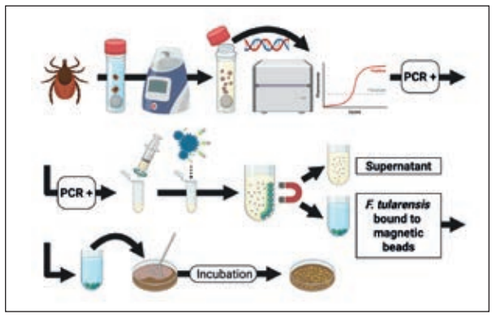


Fig. 3: Schematic overview of the enrichment of *F. tularensis* from mechanically lysed ticks using reporter-loaded magnetic beads, followed by culture-based isolation directly on non-selective agar plates; figure created with BioRender.com

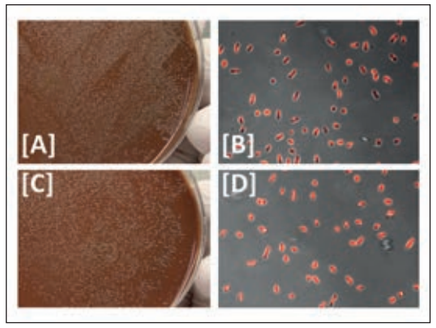


Fig. 4: [A,C] Two *F. tularensis* isolates on agar plates after enrichment from infected ticks using reporter-loaded magnetic beads; [B,D] Fluorescence microscopy images of the same two *F. tularensis* isolates after labelling with a red fluorescent reporter

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Novel Human Neuron Model for the Development of Antidotes Against Nerve Agents

During preclinical drug development, potential drug candidates are investigated and evaluated as antidotes for nerve agent poisoning. To this end, a human neuron model has been developed which realistically reproduces the neurotoxicity and mechanisms of action of the nerve agent VX, enabling targeted studies of antidote efficacy to be conducted.

Despite the Chemical Weapons Convention banning the production, storage and use of chemical warfare agents, nerve agents have been used repeatedly in conflicts. As global tensions increase, the threat posed by these weapons grows. Nerve agents are highly toxic and can be dispersed relatively easily. The approved antidotes (such as obidoxime and atropine) used for acute treatment are only partially effective. Furthermore, the long-term effects of nerve agent exposure, such as neuronal death, remain poorly understood. Therefore, new and more effective countermeasures must be developed. To this end, a novel human neuron model was developed which accurately reflects human physiology, allowing test results to be transferred to humans.

The neurons were generated from human induced pluripotent stem cells (hiPSCs), which were reprogrammed from adult skin fibroblasts. As pluripotent stem cells, they can develop into any cell type in the human body. This approach avoids the ethical concerns associated with the use of embryonic stem cells while closely following natural human developmental processes (Fig. 1).

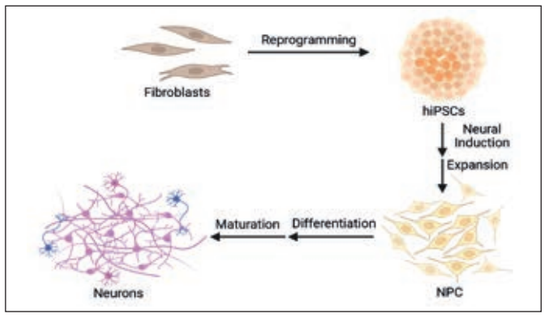


Fig. 1: Establishment of the human neuron model; dermal fibroblasts are reprogrammed into human induced pluripotent stem cells (hiPSCs), which then give rise to neural progenitor cells (NPC). These subsequently mature into fully developed neurons. Figure created with BioRender.com/vgcj048

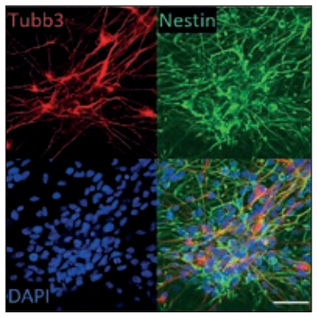


Fig. 2: Human neurons express neuronal markers such as β3-tubulin (Tubb3, red) and nestin (green); cell nuclei were stained blue with DAPI. The bottom right image shows the overlay of all channels. Scale bar = 50 µm. Modified from Schaefers et al. 2022

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Initially, the fibroblasts were transfected with non-viral plasmids — ring-shaped DNA sequences containing pluripotency factors required for reprogramming. These factors reverted the adult cells to an early, embryo-like developmental state; after 30 days, the resulting hiPSCs were ready for use. This approach minimises the risk of infection and prevents permanent genomic integration, thereby reducing risks such as tumour formation. In the next step, targeted inhibition of a specific signalling pathway over 21 days produced neuronal precursor cells. These cells differentiated within 7 days and matured into fully developed neurons over a further 21 days. Standardised culture conditions and protocols ensured high reproducibility and reliability, as confirmed by characteristic neuronal markers such as ß3-tubulin and nestin (Fig. 2).

To evaluate the neuron model's suitability for antidote testing, neurons were exposed to VX, a nerve agent, as a case study. Exposure to VX caused a time- and concentration-dependent reduction in cell growth and neurite length – the extensions responsible for signal transmission – as well as an increase in cells exhibiting altered shape and structure (Fig. 3). These effects demonstrate the neurotoxicity and cell death following exposure to a nerve agent. Additionally, an upregulation of genes linked to DNA damage/repair, neurotoxicity and cell death was observed (Fig. 4). High VX concentrations induced neuronal death, whereas lower doses induced initial signs of senescence, indicating premature cellular ageing.

The novel human neuron model successfully reproduced the inflammatory responses and cell death that occur as a result of nerve agent poisoning. Furthermore, it offered new insights into the mechanism by which these agents act. This model will be used in future studies for the targeted development of antidotes against nerve agents and related compounds.

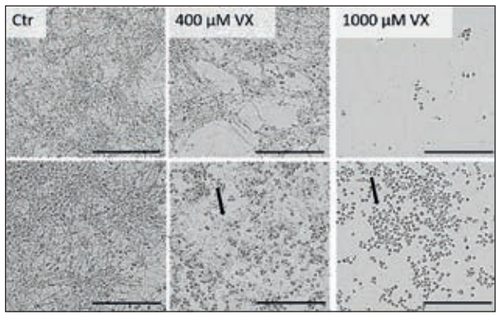


Fig. 3: Light microscopic images of neurons exposed to 400 and 1000 µM VX compared to solvent control (Ctr). VX exposure leads to reduced neurite length (top), morphological changes and cell death (bottom). Scale bar = 200 µm. Modified from Schaefers et al. 2024

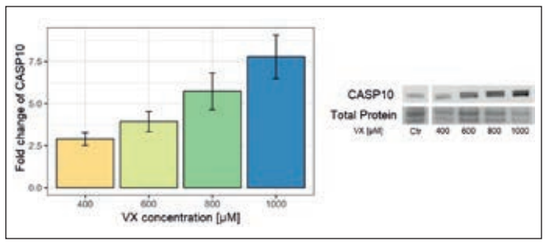


Fig. 4: Concentration-dependent upregulation of the cell death marker caspase 10 (CASP10) compared with the solvent control (Ctr); modified from Schaefers et al. 2024

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Reliable Identification of Severe Lung Injuries After Chest Trauma – Photon-Counting CT Improves Diagnostic Imaging in Emergency Medicine

The reliable identification of severe lung injuries after thoracic trauma can present radiologists with diagnostic challenges in conventional computed tomography (CT) diagnostics. In a retrospective study, we were able to demonstrate that photon-counting CT improves the discriminability of trauma-associated lung changes, highlighting its benefits for emergency and field medicine.

The Department of Radiology and Neuroradiology at the Bundeswehr Central Hospital in Koblenz was one of the first institutions worldwide to permanently integrate a photon-counting CT (PCCT) scanner into its clinical routine (Fig. 1). Aiming to utilise and explore the advantages of spectral CT imaging for emergency and field medicine, the hospital uses this device as the standard for initial diagnostic imaging in the context of polytrauma care in its trauma room.

Lung involvement is common in traumatic chest injuries and leads to an increase in density in the injured lung areas due to parenchymal haemorrhage. Accompanying trauma-associated lung collapse also results in increased lung density and is highly clinically relevant, yet has been difficult to differentiate using conventional diagnostic CT. Accurate identification is crucial in order to quickly and correctly assess the extent of the injury, initiate the necessary therapeutic measures and anticipate possible complications that may occur later on in the clinical course.



Fig. 1: A photon-counting CT scanner installed in the trauma room of the emergency department at the Bundeswehr Central Hospital in Koblenz

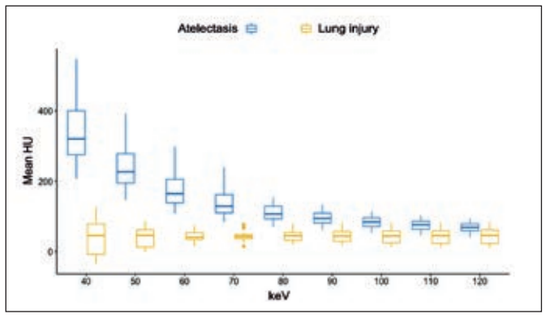


Fig. 2: Boxplots of the mean CT density (mean Hounsfield units, HU) of lung collapse (blue) and lung injury (yellow) at different energy levels (keV) of virtual monoenergetic reconstructions; as the energy level decreases, the density difference between lung injury and lung collapse increases

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A retrospective study was conducted at the Bundeswehr Central Hospital in Koblenz, combining the expertise of the Department of Radiology and Neuroradiology and the Department of General, Visceral and Thoracic Surgery. The aim of this study was to investigate the possibility of reliably distinguishing between injured and collapsed lung areas in polytrauma patients with trauma-induced increases in lung tissue density on whole-body PCCT by using PCCT-specific virtual monoenergetic image reconstructions (VMIs) of different energy levels.

Analyses of the objective image parameters of VMIs showed that the density of collapsed lung tissue was observed to increase with decreasing energy levels. However, the density values in injured lung areas remained constant regardless of energy level (Fig. 2). Consequently, image contrast between the two types of trauma-associated lung alteration increased in low-energy VMIs, providing a basis for reliable and rapid visual discrimination. Subjective differentiation was best at the lowest energy levels (40-50 keV), but when subjective image noise perception and image quality were also considered, VMIs at 60-70 keV were preferred in the subjective image analyses performed by three radiologists (Fig. 3).

The differing density behaviour of lung alterations associated with trauma is due to the differences in distribution of the iodine-containing contrast medium, which is routinely administered for whole-body PCCT examinations. Injured lung tissue receives less or no blood flow, whereas collapsed lung tissue continues to be perfused normally, resulting in comparatively higher radiodensity. Enhanced iodine contrast in low-energy VMIs improves visual differentiation and represents a significant advantage of PCCT over conventional CT.

In summary, this study demonstrates the advantages of spectral reconstruction in PCCT for emergency and field medicine. Encouragingly, our approach won the prize for best emergency imaging at the 2025 European Congress of Radiology (ECR) in Vienna (Fig. 4).

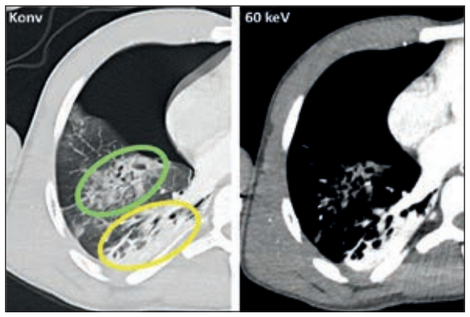


Fig. 3: Trauma-associated lung injury (green marker) and lung collapse (yellow marker); monoenergetic reconstructions at 60 keV of the photon-counting CT study show better visual discriminability than conventional reconstructions (Konv)



Fig. 4: Award for best emergency imaging at the European Congress of Radiology 2025

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Immune Response as a Prognostic and Therapeutic Window – Cross-Species Biomarker Signatures after Severe Trauma

Basic and translational research has identified highly conserved (i.e. shared across species) immune defence mechanisms after severe injury. Specific white blood cell subsets, inflammatory signalling molecules and trace elements in the blood form the basis of an interdisciplinary project to develop early prognostic markers and new treatment strategies for severe trauma.

Basic research has provided fundamental insights into how the immune system responds to severe injuries, in particular after traumatic spinal cord injury (TSCI, which can cause paralysis) and traumatic brain injury (TBI). A key finding is that both types of injury trigger immune responses that follow the same pattern in humans and animals. This makes it possible to transfer laboratory findings to clinical treatment. However, no reliable blood test currently exists that can predict early on whether a patient will recover from such an injury. This is precisely the gap this research aims to close (Fig. 1).

In a clinical study conducted over an extended period, researchers examined different subsets of monocytes – an important group of white blood cells belonging to the innate immune system – along with inflammatory signalling molecules (cytokines) and trace elements in the blood. The goal was to develop an early-warning system from the combination of many measurements. The most important finding: A specific, transiently appearing subset of monocytes (technically: CD14−/CD16+/IL-10+/CXCR4int) was significantly

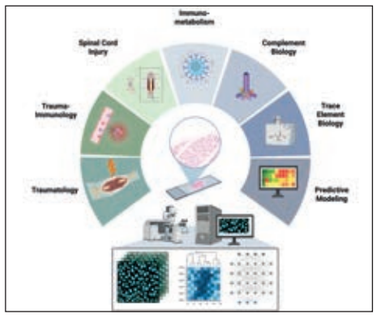


Fig. 1: Research framework of the interdisciplinary project; integration of trauma immunology, trace element and complement biology, and computer-assisted image analysis and machine learning. Created in BioRender

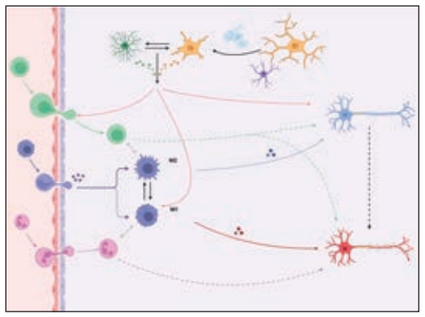


Abb: 2: Immune cells after spinal cord injury; monocytes (white blood cells) migrate into the injured area and develop into either repair-promoting (M2) or nerve-damaging (M1) scavenger cells. Which type predominates depends on the pattern of inflammatory signalling molecules. Created in BioRender

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more abundant in the first 24 hours after injury in patients who later recovered compared to those who did not. These cells are considered precursors of scavenger cells (macrophages) that create a repair-friendly environment at the injury site (Fig. 2). Because they can be easily detected in a blood sample, they are particularly attractive as a clinical predictor. A computational model combining several such parameters provides more accurate prognoses than individual values that only become informative days later. Additionally, the concentration of free zinc in the blood could distinguish recovery from non-recovery with an accuracy of over 83% as early as 24 hours, which suggests that metabolic and immune parameters together reflect healing potential (Fig. 3 and 4).

In a complementary animal model, the signalling molecule IL-4 was administered to steer the immune response towards tissue repair. The animals showed markedly improved motor function; at the cellular level, the balance of scavenger cells shifted from a pro-inflammatory type (M1) towards a regeneration-promoting type (M2). The fact that the same patterns appear in humans and animals is strong evidence for evolutionarily conserved mechanisms and thus for the possibility of targeting them therapeutically. Findings from animal experiments often do not translate directly to humans. Our approach of systematic comparison across different species addresses this problem by specifically identifying mechanisms that operate identically in humans and animals. This ensures that biomarkers developed in the laboratory are biologically meaningful in patients. The approach also strengthens the transferability of results and aligns with the 3R principles of replacement, reduction and refinement of animal experiments.

Building on these findings, an interdisciplinary research project has been launched. It aims to use conserved mechanisms after severe injury, including activation of the complement system (part of immune defence), changes in trace element levels and markers of nerve cell damage, as the foundation for prognostic signatures and therapeutic targets to enable earlier and more targeted care for service members following severe trauma.

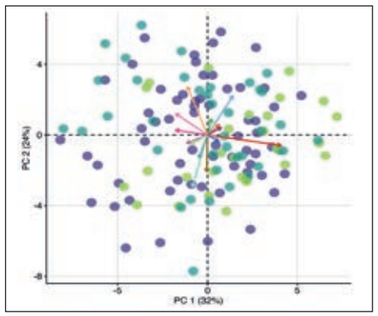


Fig. 3: Statistical analysis of monocyte subgroups; a specific cell cluster (Cluster 1, red arrow) accounts for the largest difference between patient groups and is the strongest predictor of neurological recovery after spinal cord injury

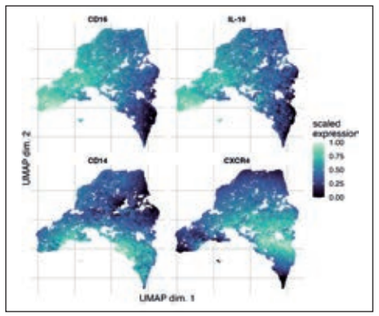


Fig. 4: Visualisation of monocyte subgroups after spinal cord injury using the UMAP method, a technique for displaying complex multi-dimensional data in an accessible way; Cluster 1 shows the characteristic pattern of repair-promoting precursor cells

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Preserving Operational Readiness Through Modern Dermatology: A Health Services Research Study of Psoriasis

A retrospective study at the Bundeswehr Hospital in Berlin examined the use of modern psoriasis therapies. Compared to conventional therapies, modern systemic therapies demonstrate superior efficacy, better safety profiles and higher treatment persistence. The results underscore the importance of military dermatological care in maintaining fitness for duty.

Psoriasis is a chronic inflammatory systemic disease with primarily dermatological manifestations (Fig. 1). In addition to visible skin changes, the disease is associated with systemic comorbidities, including joint involvement and metabolic syndrome, signs of which include obesity, high blood pressure and impaired glucose metabolism. A clinically proven increased risk of cardiovascular events has also been identified. Without effective treatment, this systemic stress can impair the general health and military fitness of soldiers. Particularly with regard to the functional integrity of the skin, intact skin function is essential to ensuring that affected personnel are not limited in their ability to wear uniforms and combat clothing under operational stress (Fig. 2). Early intervention by a specialist is therefore of great importance for long-term health maintenance.

For decades, the therapeutic arsenal had been limited to conventional systemic therapies, topical treatment with creams and ointments as well as UV therapies. Active substances such as methotrexate or ciclosporin have a wide-ranging effect on the immune system. While these long-established immunosuppressants are effective, they come with a considerable range of side effects that require regular, close laboratory monitoring. Such monitoring is particularly difficult to ensure during foreign deployments or longer training exercises. Another significant shortcoming of these treatment options was that complete or near-complete clearance of the skin was achieved only in the rarest of cases.

A decisive turning point in dermatological care came with the introduction of biologics, i.e. biotechnologically produced medicines (Fig. 3). This began with TNF-alpha inhibitors, which, for the first time, enabled significantly greater and more targeted improvements in skin condition. In recent years, the therapeutic landscape has undergone another fundamental change with the development of highly specific interleukin inhibitors (such as IL-17, IL-23 and IL-12/23). These modern drugs precisely intervene in the inflammatory cascade without broadly suppressing the immune system. This leads not only to superior efficacy, including complete skin clearance and resolution of joint symptoms, but also to a significantly improved safety profile and simplified handling in everyday military life.

The superiority of these modern systemic therapies was scientifically analysed in a retrospective study conducted at the Bundeswehr Hospital in Berlin. The study evaluated data from 77 soldiers who were treated at the Department of Dermatology, Venereology and Allergology at the Bundeswehr Hospital in Berlin (Fig. 4). A direct comparison between modern and conventional systemic therapies confirmed the clinical advantages: the use of modern interleukin inhibitors was associated with significantly greater treatment efficacy and higher treatment persistence. A key finding was the high safety profile of the drugs used, as no serious adverse events were reported during treatment with modern biologics. These results demonstrate that specialised dermatological care in the German Armed Forces is crucial for maintaining the health of soldiers. Early access to innovative systemic therapies can ensure long-term fitness for duty.



Fig. 1: AI-generated image of a soldier with psoriasis at the typical location on the extensor side of the arm



Fig. 2: AI-generated image of a soldier with scalp psoriasis



Fig. 3: AI-generated image of a biologic autoinjector

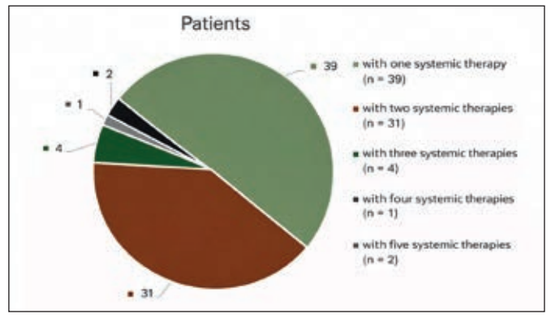


Fig. 4: Distribution of patients (n = 77) according to the number of systemic therapies used (n = 127)

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Resilience in Three- and Six-Month Basic Military Training Programmes – a Model for National and Collective Defence

Basic military training provides the foundation for coping with the demands and stresses that soldiers face. This makes it the ideal time to examine which resilience factors are relevant in a military context. This research project aims to identify the factors that influence stress and health perception as well as military performance during basic training and to evaluate their practical significance.

The life of a soldier is characterised by exceptional demands and stresses unlike those experienced in civilian professions. Deployment and combat, in particular, pose extreme physical and psychological challenges that require a high degree of resilience from service members.

Basic military training provides the foundation for coping with these exceptional demands (Fig. 1). It is therefore unsurprising that recruits perceive this initial training period as psychologically stressful (Fig. 2), with more than 20% leaving the Bundeswehr during the first six months of training.

Service members who are better able to cope with stress during training may exhibit qualities, beliefs or behaviours that will also help them to deal with professional demands later on in their careers. Basic training is thus an ideal opportunity to identify individual resilience factors which may affect the operational readiness and health of service members in the long term. In cooperation with the German Army and supported by the Department of Work, Organisational and Business Psychology at Helmut Schmidt University of the Bundeswehr in Hamburg, the Bundeswehr Institute of Preventive Medicine is conducting a preventive medical research project focused on basic training. Recruits as well as platoon and section leaders in training units complete standardised questionnaires in order to identify individual resilience factors that positively impact stress and health perception as well as military performance during the initial training phase (Fig. 3). The results will inform recommendations for adapting training in ways that strengthen these resilience factors and support recruits with shortcomings in these areas. The idea is to minimise adverse physical and psychological effects during the initial training phase and to strengthen qualities and behavioural patterns that will have a long-term positive impact on the health and performance of service members. Adapting basic training in this manner may also help to reduce the drop-out rate.

The initial results of a pilot study of 135 male recruits undergoing three months of basic military training suggest that resilience, mindfulness and self-efficacy may be relevant predictors. Recruits with higher levels of these three traits reported significantly lower stress levels at the end of their training and also rated their military performance more highly. Exploratory analyses revealed a positive development in self-efficacy over the course of training in contrast to resilience and mindfulness, which showed no such development. Therefore, potential adaptations to basic training should focus on promoting the two latter resources (Fig. 4).

In 2025, Army basic training was redesigned and extended to six months. At three different training locations, the Bundeswehr Institute of Preventive Medicine is currently investigating whether the findings from our pilot study also apply to this new, extended period of basic training.



Fig. 1: On the first day of basic training, new recruits still line up in civilian clothing

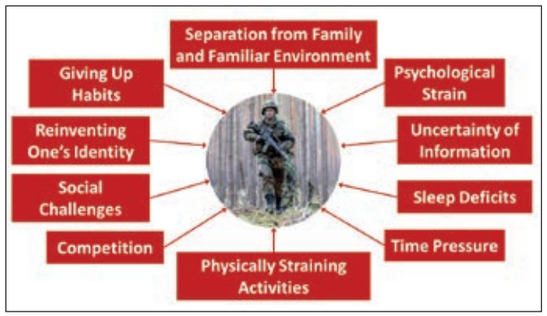


Fig. 2: Recruits are confronted with many stressors during basic training

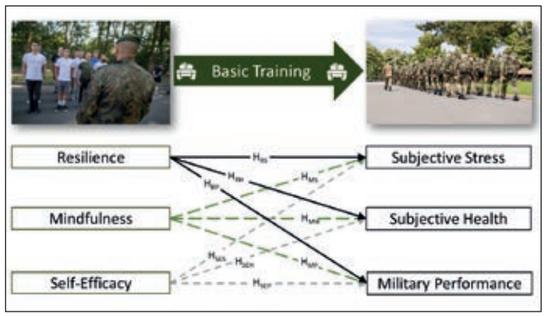


Fig. 3: Study design with hypotheses on how psychological factors (left) affect stress and health perception as well as military performance (right)



Fig. 4: During basic training, recruits learn basic military skills

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Parallels in Problematic Anger Between Military and Police Personnel Following Shootings: How Different Types of Deployment Affect the Mental Health of Emergency Responders

The CASH (Calamities, Anxiety, Stress & Hostility) project at the Psychotrauma Centre of the Bundeswehr Hospital Berlin investigates the impact of major incidents on civilian (Fig. 1 and 2) and military (Fig. 3) emergency responders. In both the military and civilian study groups, events involving the use or threat of firearms are associated with a significantly higher risk of experiencing chronic, problematic anger.

The CASH project aims to improve how emergency responders are prepared for and supported after operations and missions. To this end, the study included a large number of intentional and unintentional incidents of varying duration. The study includes various professional groups involved in emergency response and a control group. In addition to psychological consequences, numerous other variables are collected to provide the most comprehensive picture possible of stressors and their effects. The project is scheduled to run until December 2027, with further follow-up data to be collected until then.

Initial analyses show that the dominant emotion experienced by emergency responders during an incident significantly influences their subsequent psychological reactions. The emotional response patterns vary between professional groups depending on the specific type of incident. Whether these emotions subside within a reasonable timeframe or manifest in the long term depends on their intensity during the incident and other influencing factors. While adequate preparation for deployment and participation in conventional crisis intervention measures can have a preventive effect, taking on tasks outside one's professional competence, having experienced emotional neglect in childhood, and insufficient social support emerged as risk factors.

Both military and police personnel exhibit heightened levels of problematic anger after having had to defend themselves or others with firearms. Whether the service weapon was actually used or whether its use was imminent is of secondary importance. As the use of a service weapon presupposes a certain degree of aggressive readiness to act, anger is considered the primary emotion during such events. These findings are related to operations such as the evacuation from Afghanistan, the Breitscheidplatz terrorist attack in Berlin, a 34-hour hostage situation involving an intense exchange of gunfire, a mass shooting in Hamburg and the knife attack on a police officer in Mannheim's market square.

Such differences were not evident, however, in response to events not caused intentionally, such as the flood disaster in the Ahr Valley, a train derailment near Biberach and major traffic accidents. Similarly, no such effects could be demonstrated in intentionally caused events where the perpetrator no longer posed an immediate threat at the time of the intervention, such as the vehicle ramming attacks in Trier and Berlin. These findings suggest that the perceived threat level during the intervention is a key factor in the development of problematic anger.

Systematic analyses and processing of such deployments helps to improve deployment preparation and post-deployment support further. The goal is to more effectively prepare emergency responders for future wars, crises and disasters, while simultaneously reducing the negative psychological impact on both responders and the civilian population. A follow-up project aimed specifically at reducing problematic stress among emergency responders has already been approved. Due to the significant insights gained, the CASH project is set to expand across Europe after its completion. Against the backdrop of potential future national and collective defence scenarios, the findings will be used to further develop post-deployment support and psychosocial emergency care for responders and affected individuals.



Fig. 1: Breitscheidplatz (Berlin, Germany) after the terrorist attack; © PTZ/Photographer: Frank Eggen



Fig. 2: Funeral following the knife attack in Mannheim (Germany); © Stabsstelle Öffentlichkeitsarbeit Polizei Mannheim



Fig. 3: People in need of protection arrive in Tashkent (Uzbekistan) from Afghanistan during the evacuation operation. © Bundeswehr/Marc Tessensohn

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Effects of Rotating and Fixed Shift Patterns in Watchkeeping on Board

As there has been a lack of empirical data on the impact of permanent night work in watch system design, a study was conducted to determine the effects of rotating and fixed shift patterns on the performance, well-being and sleep of crew members aboard the frigate Brandenburg during its UNIFIL mission.

The majority of a ship's crew is divided into watches that take turns to operate the vessel, with their working and rest periods defined by a watch system. As work also needs to be done at night, when the human body is geared towards sleep and recovery, watchkeeping interferes with the body's natural circadian rhythm. This can affect the well-being, performance and ability to recover of watchkeepers. The design of watch systems aims to minimise these disruptions as much as possible, but the most effective way to achieve this is not yet fully understood.

One open question concerns continuous night work. Studies of night work on land suggest that it has a negative effect on sleep, well-being and health for most people, and that few can adjust to it in the long term. Therefore, rotating shifts are recommended, in which night, morning and evening shifts alternate. However, constant changes to working and rest periods also disrupt the natural sleep-wake cycle and are therefore widely considered suboptimal in the literature on watch system design for ships. Fixed working hours are

recommended instead. However, there have been no empirical studies that directly compare the effects of fixed and rotating shift patterns on a ship's crew.

The Naval Institute of Maritime Medicine therefore investigated the effects of fixed and rotating shift patterns on 49 crew members aboard the frigate Brandenburg (Fig. 1) during its UNIFIL mission. To this end, five periods at sea were observed. During the first and last of these, the crew worked in the usual rotating three-watch system, with working hours changing daily and crew members assigned to the night shift every three days. During the remaining three voyages, a fixed shift pattern was used, with one watch section per voyage continuously on night watch .

Study participants wore an actigraphy device to record their body movements, from which sleep behaviour could be inferred (Fig. 2). Every day at watch turnover, they also reported their subjective fatigue and performed a vigilance task that required swift reactions to sudden signals for performance measurement. Furthermore, at the beginning and end of each voyage, they provided saliva samples to determine cortisol levels as an indicator of stress.

The fixed watch system had a favourable effect on sleep. With constant daily working and rest hours, study participants spent less time awake after sleep onset than those in the rotating watch system (Fig. 3).

Fatigue, however, increased among night-watch crew members compared to all other crew members in the fixed watch system. These watchkeepers also had higher cortisol concentrations in their saliva than those in other watches. This suggests an increased strain due to permanent night work.

In the rotating watch system, the study participants were equally tired, regardless of their working hours on any given day. Performance in a vigilance task was better compared to the fixed watch system. Both the mean reaction time and the 10% slowest reaction times – an indicator of moments of inattention – were faster (Fig. 4).

Contrary to previous studies, the rotating three-watch system studied here is actually advantageous if poorer sleep continuity can be compensated for by sufficient sleep time, as was the case in this study. However, if sleep opportunities are scarce and must be used as efficiently as possible, fixed work and rest times are preferable.



Fig. 1: Frigate Brandenburg during its UNIFIL-Mission



Fig. 2: Study participant wearing an actigraphy device on his wrist

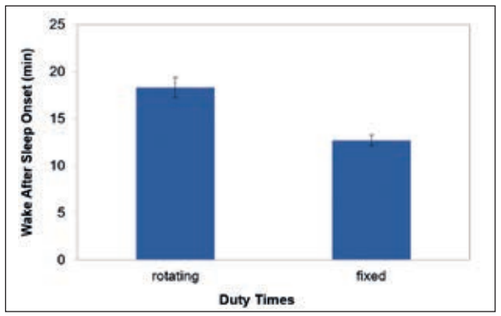


Fig. 3: Study participants spent more time awake after sleep onset under rotating shift patterns.

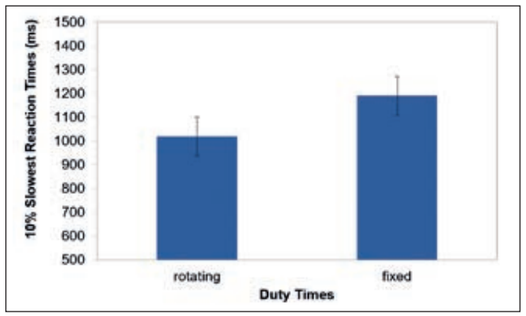


Fig. 4: Inattentive moments during the vigilance task were shorter in duration with a rotating watch system.



4

Military History Research and Social Science Research

The Bundeswehr Centre of Military History and Social Sciences (ZMSBw) conducts research in the fields of military history and the social sciences for the Federal Ministry of Defence (FMoD), and participates in public and academic discourse on the German military of the past, the present and the future.

Through its academic work, the Centre aspires to gain and communicate knowledge in the areas of military history and the social sciences, primarily for the FMoD and the Bundeswehr but also for parliament, the academic community and the general public.

The research carried out at the Centre predominantly concentrates on military history and the social sciences. Its main focus is on the past and the present of the Bundeswehr. The Centre's research is conducted according to established methods and standards from the disciplines of history and the social sciences and enjoys the freedom of academia and research as guaranteed by Germany's Basic Law.

Its research results provide an essential basis for history education in the Bundeswehr. The research therefore has an immediate impact on informed citizenship and the historical consciousness of Bundeswehr personnel, thereby contributing to Bundeswehr soldiers truly becoming citizens in uniform.

The Bundeswehr Centre of Military History and Social Sciences supports the FMoD in exercising its functional supervision of the Bundeswehr's museums and collections and, on behalf of the FMoD, is responsible for the professional control and supervision of all collections in the network of Bundeswehr museums.

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The German Military in Colonial Operations, 1880–1918. A Continuum of Violence

The project examines the role of the German military as an actor of state violence in colonial operations between 1880 and 1918. At its core is an analysis of the use of military practices of violence as a means of establishing and maintaining colonial order and rule. This encompasses combat operations as well as control and enforcement measures situated between military, policing, and administrative tasks.

European colonialism could, to a large extent, only be enforced through the use of organised military violence. The German military, too, served not only as a fighting force, but also as a central executive actor of coercive power in the colonies of the German Empire. Military operations were used to enforce colonial rule, secure political, economic, and administrative interests, and maintain colonial order in everyday practice. Military action often took place in settings where war and peace, military and policing tasks, the actual use of violence and the mere threat of its use blended into each other.

This project analyses the full spectrum of operational practices. The analysis is based on a broad concept of the term ‘operations’ that considers military action as the fulfilment of a governmental mandate and that is not limited to typical combat operations. In colonial contexts, military operations encompassed not only combat, but also military presence, deterrence, punitive action, policing measures and administrative security tasks. In these contexts, violence does not appear as an exception. Rather, it constitutes a defining structural element of colonial statehood.

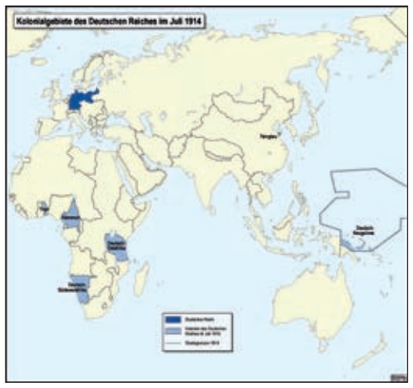


Fig. 1: The figure shows the global distribution of the German Empire’s colonial territories in July 1914 (Togo, Cameroon, German East Africa, German South West Africa, Tsingtao, German New Guinea); the legend distinguishes between the territory of the German Empire (blue), its colonial possessions (light blue), and contemporary state borders (dotted grey lines) (© Bundeswehr/ZMSBw)

The analysis of military violence as a dynamic process is at the centre of the project. It examines the various forms of violence, their organisational preconditions, their situational escalation, and the scope for action available to military actors. Particular attention is paid to transitions between different forms of violence and the ways in which the maintenance of order by military means was implemented in practice in colonial spaces. Analysing operational practice allows for getting a better read of military action in complex order and security situations. The project takes a comparative approach, including indigenous actors of violence alongside German ones in its analysis.

The research project is designed to run over several years and is structured around three consecutive workshops. The results will be published in an edited volume compiled in collaboration with the Institute for Diaspora Research and Genocide Studies at Ruhr University Bochum. Additionally, various transfer formats are planned to make the research findings accessible to a wider audience. These include, among others, the podcast “Schutz wovor?” (‘Protection from What?’), which examines the role of the Imperial Schutztruppe, or Protection Force, as a military and administrative actor of violence. A picture essay entitled „Bilder der Gewalt. Militärische Gewalt in den deutschen Kolonien“ (’Images of Violence. Military Violence in the German Colonies’) uses contemporary photographs to visualise colonial military violence as an everyday, symbolic, and structural practice.

The project offers a detailed analysis of military violence and the enforcement of order to provide a more nuanced reading of the operations of the German military beyond the simplistic dichotomy of ‘war’ and ‘peace’. It also sharpens the perception of structural dynamics of escalation. Finally, the project provides points of reference for history education and civic education within the Bundeswehr. The historical example of the German colonial period can be used to reflect on questions of the use of military violence beyond classic combat operations. At the same time, the research contributes to the objective societal and political evaluation of colonial military violence. The findings can be applied to training within the Bundeswehr and are also incorporated into university teaching. The course “Order, War, Annihilation? Military Violence in the German Colonial Empire”, which will be delivered at the University of Potsdam in the summer semester of 2026, is a case in point.



Fig. 2: Lecture by Dr. Jonas Kreienbaum at the ‘Understanding Colonial Military Violence’ workshop, ZMSBw Potsdam, 7 October 2025 (© Bundeswehr/Nimpsch)



Fig. 3: Recording session of a podcast entitled ‘Protection from What? The Imperial Schutztruppe and the Reality of Colonial Violence’, ZMSBw Potsdam, 3 December 2025 (© Bundeswehr/Nimpsch)

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What Can, and What Does, Military Chaplaincy Achieve? Pastoral Care and Religion in the German Armed Forces

Since antiquity, members of the clergy have accompanied the military on its missions. Still today, military chaplains are present wherever soldiers are deployed. For the first time in the history of the Bundeswehr, an extensive, systematic, and empirical study has been conducted on pastoral care, religion, and religiosity in the Bundeswehr. The result is a comprehensive, handbook-style reference work.

The Bundeswehr saw the creation of a military chaplain service that implemented the guaranteed 'right to pastoral care and undisturbed religious practice' (Section 36 of the German Legal Status of Military Personnel Act) in special ways. Compared to previous German, and many other, armed forces, the chaplain service was granted the utmost pastoral freedom, placing chaplains in a unique position within the Bundeswehr system. This ensures their independence from the military hierarchy and gives them a degree of latitude to cooperate trustfully at all echelons and in all areas of the Bundeswehr.

As both the Bundeswehr as an organisation and its personnel are changing, change can also be expected with regard to pastoral care and religion. This raises the question of how the Chaplain Service and its work is perceived within the Bundeswehr, what religious needs and interests soldiers express, and what experiences they have with military pastoral care and, beyond that, the Church.



Fig. 1: Was kann und was leistet Militärseelsorge? Seelsorge und Religion in den deutschen Streitkräften [What Can, and What Does, Military Chaplaincy Achieve? Pastoral Care and Religion in the German Armed Forces]. Edited by Petra-Angela Ahrens, Gerhard Kümmel, Sylvi Mauermeister, Hilke Rebenstorf, Markus Thurau and Meike Wanner, with contributions from Veronika Drews-Galle. Göttingen: Vandenhoeck-Ruprecht 2026; 487 pp. The book is available free of charge (in German) at www.vandenhoeck-ruprecht-verlage.com



Fig. 2: Joachim von Blumröder, Thomas Bretz-Rieck, Friedericke Erichsen-Wendt, Andreas Jensen, Roger Mielke, Sascha Zierold, Peter Zimmermann, Was kann und was leistet die Militärseelsorgestudie? [What Can, and What Does, the Military Chaplaincy Study Achieve?], Berlin, 2026; 72 pp. This first commentary volume (in German) presents the views of the Bundeswehr and the Churches on the research findings

The ZMSBw and the Social Science Institute of the Protestant Church in Germany (SI der EKD) were commissioned to carry out a joint project. The aim was for the two research institutes to contribute their scientific expertise and field knowledge in the areas of church sociology, religious sociology and military sociology to the working group in equal measure.

Due to the complexity of the research interests, the group opted for a multi-stage empirical approach. First, as part of a preliminary study, different focus groups were formed, and qualitative group interviews were conducted with soldiers of all ranks, military chaplains and their assistants as well as family members of soldiers. Secondly, based on the breadth of perspectives gained, a questionnaire for a representative survey tailored to current challenges was developed (initial sample: 25,000; response rate: 30%).

The project ran for several years, culminating in the publication of the research results in the form of an edited volume (Fig. 1 and 2). The volume shows that the Chaplain Service is held in high esteem in the Bundeswehr. This is largely because, despite their special status, chaplains are firmly integrated into the daily lives of soldiers, allowing a special relationship of trust to develop – both during routine duty at home and during deployments abroad. 91% of all respondents, including non-religious individuals and/or those who have not used the services offered by the Chaplain Service, liked that chaplains were available on the ground (Fig. 3). This high level of acceptance is also reflected in the endorsement of the chaplains' absolute duty of secrecy (seal of confession), which almost all soldiers consider important (Fig. 4). Chaplains are perceived primarily as advisors and confidants, and only secondarily as representatives of their religious community.

The study also demonstrated that what is known as character guidance training, a Bundeswehr-specific form of ethical education which falls under the responsibility of the Chaplain Service, is a recognised and firmly established educational measure within the Bundeswehr. The vast majority of respondents value both the instructors and the seminars themselves. As military chaplaincy is an area of application of the Bundeswehr's command and control principle known as 'Innere Führung' (referred to as 'leadership development and civic education' in English), the study also examined the relationship between the two. It was found that soldiers' personal attitudes towards 'Innere Führung' are largely influenced by the perceived attitudes of their comrades and superiors.

Overall, the study shows that military chaplaincy is highly regarded irrespective of denominational affiliation. It fosters environments of trust within the armed forces and provides a space in which existential questions that arise from service in the German armed forces, particularly in stressful situations, can be addressed.

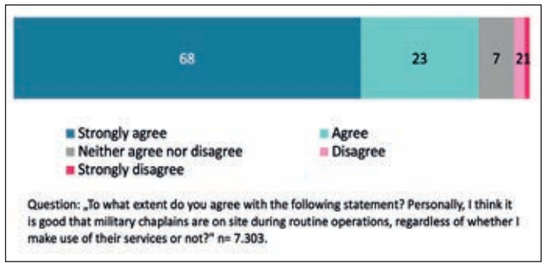


Fig. 3: Acceptance of military chaplaincy during routine duty in Germany (figures in per cent)

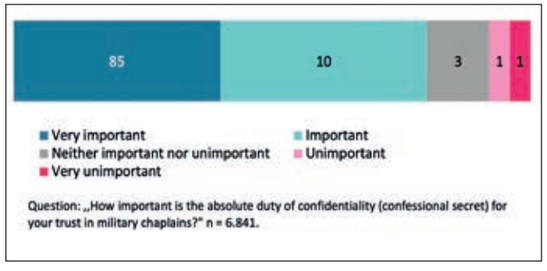


Fig. 4: Importance of the military chaplains' duty of secrecy (figures in per cent)



5

Geoscientific Research

Nothing drives, flies, shoots or hits without geoinformation: with this slogan the Bundeswehr Geoinformation Service seeks to attract new personnel. The mission of the Bundeswehr Geoinformation Service is to evaluate geoscientific data, develop them for further use and carry out independent projects with the aim of supporting the armed forces and the Bundeswehr as a whole in accomplishing their mission and averting damage to equipment and personnel. Geoscientific research is essential for ensuring a functioning geoinformation service in the Bundeswehr.

Geoscientific research focuses on geospatial factors. Geospatial factors are all natural or man-made features of the environment (such as climate, weather, terrain relief, bodies of water, vegetation and infrastructure) that may affect military capabilities and military operations. Across a total of 18 (geo)scientific fields of applied geoscientific research, the Bundeswehr Geoinformation Centre (BGIC) – the central agency within the Bundeswehr Geoinformation Service – is pursuing an interdisciplinary approach to work on multifaceted topics which affect the planning and conduct of military operations in a multitude of ways and across different timescales.

The Bundeswehr's refocusing on national and collective defence is leading to changes in the required services. Being able to meet the changed demand for reliable information necessitates adjustments to the structures of the Bundeswehr Geoinformation Service, to be implemented in 2026. In the process, the BGIC – as the institute responsible for geoscientific departmental research in the Bundeswehr – will be turned into a one-stop campus combining research and teaching in one department.

The long-term focus of geoscientific research currently lies on big data analytics and artificial intelligence in the geoinformation context, virtual and augmented reality, geoinformation data management, the quality of online services and further developments in positioning, navigation and timing (PNT). Several projects from these fields of application have been presented in the geoscientific research section of this publication in recent years. Teams working in the fields of atmospheric physics, geoinformatics and remote sensing are currently carrying out projects which have already seen the use of artificial intelligence methods. In biology, applied biological and ecological research and development benefit from the development of practice-related and user-friendly tools for the armed forces. Therefore, this year's publication will present a project that will take bird strike prevention by means of real-time radar monitoring to a new level thanks to the improvement of the VoVisWxBw software tool used for bird migration data visualisation.

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When Biology meets Cyber

The ageing VoVis expert system for bird migration data visualisation was reprogrammed in an agile and application-oriented manner by teams from the German Cyber and Information Domain Service Headquarters (Bundeswehr Centre for Digitalisation and Bundeswehr Geoinformation Centre). Within nine months, they created a future-proof, significantly improved modular software system for visualising bird migration and issuing weather warnings for the Bundeswehr (VoVisWxBw).

Defence research often requires a certain "start-up phase" in which the expert teams requesting a capability and the expert teams providing that capability through research get to know each other well enough to ensure that workflows run smoothly. In the case of the reengineering of the old expert system for bird migration data visualisation (VoVis), both teams were part of the German Cyber and Information Domain Service Headquarters (DEU CyberInfoDS HQ) – the Biology/Ecology Branch of the Bundeswehr Geoinformation Centre (BGIC) and the Situation Display/GeoInfo Systems Section of the Bundeswehr Centre for Digitalisation and Cyber and Information Domain Service Capability Development (BwC Digital). From the outset, there was a shared vision of the desired outcome: a future-proof, substantially improved software for bird migration data visualisation and weather warnings for the Bundeswehr (VoVisWxBw) which issues warnings to military pilots in the form of bird notices to airmen (BIRDTAMs) and which can be expanded on a modular basis.

In both civil and military aviation, collisions between aircraft and birds, known as bird strikes, occur many times a year. The risk of a bird strike is particularly high in military flight missions, which often involve low-level flight, because a very large number of birds are present at these altitudes. Therefore, a reliable assessment of bird migration represents an essential part of daily training and flight planning.

As part of flight-weather briefings, specialist staff from the Biology/Ecology Branch analyse current radar data which are graphically displayed via a visualisation software. Bird swarms are detected by identifying specific signatures which are compared with weather phenomena. If bird migration is identified as occurring at a certain level of intensity, the employees will then create a BIRDTAM. The radar data are updated every two minutes, which allows for, but also requires constant observation of the radar situation.

In the reprogramming effort, the challenge consisted in integrating a wide range of radar sources, complying with safety and security standards, creating specific output formats (BIRDTAMs) as well as increasing user-friendliness and enabling the future integration of automated, AI-generated detection methods. Within just nine months (from February to October 2025), the Situation Display/GeoInfo Systems Section (BwC Digital) succeeded – in close coordination with specialist users from the BGIC – in developing a sustainable, modular expert system for bird migration visualisation, called VoVisWxBw, on the basis of the SCRUM agile project management framework. The efficient processing of the project was due to the practice-oriented development approach pursued in the Cyber and Information Domain Service.

Throughout the entire development phase, BGIC experts could request changes and test every iteration directly in their day-to-day work. This allowed bugs and misunderstandings to be eliminated immediately and the programming to be corrected.

Another new and highly functional feature of VoVisWxBw is the ability to access historical radar data. Previous bird migration events can be analysed in detail and compared with the current situation. This facilitates the classification of current observations – but also the training with AI solutions in the future. Thus, VoVisWxBw is an essential tool for displaying bird migration data in near real time during operations. While the software does not replace aeronautical decision-making, it contributes to improving the information situation and supports the risk-conscious planning and conduct of military flight operations.

Conclusion: This project demonstrates the synergies created in the Cyber and Information Domain Service thanks to the integration and combination of expertise in natural sciences and modern IT skills. As a result of these synergies, solutions with a more specific orientation towards military applications can be found much more quickly for specific applications than would be possible with external industrial partners.



Fig. 1: An A400M standing on a runway at dusk. A dense flock of birds flies around it and in front of it (51 Tactical Air Wing, Air Traffic Services and Support Squadron Hohn, 2025)



Fig. 2: An aircraft mechanic cleaning a windshield during the post-flight check on a Eurofighter fighter jet at 73 Tactical Air Wing Steinhoff in Laage on 17 August 2023, following a bird strike

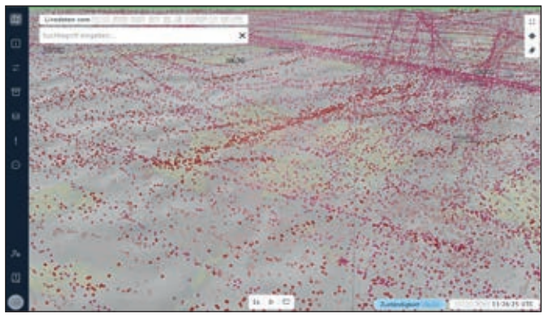
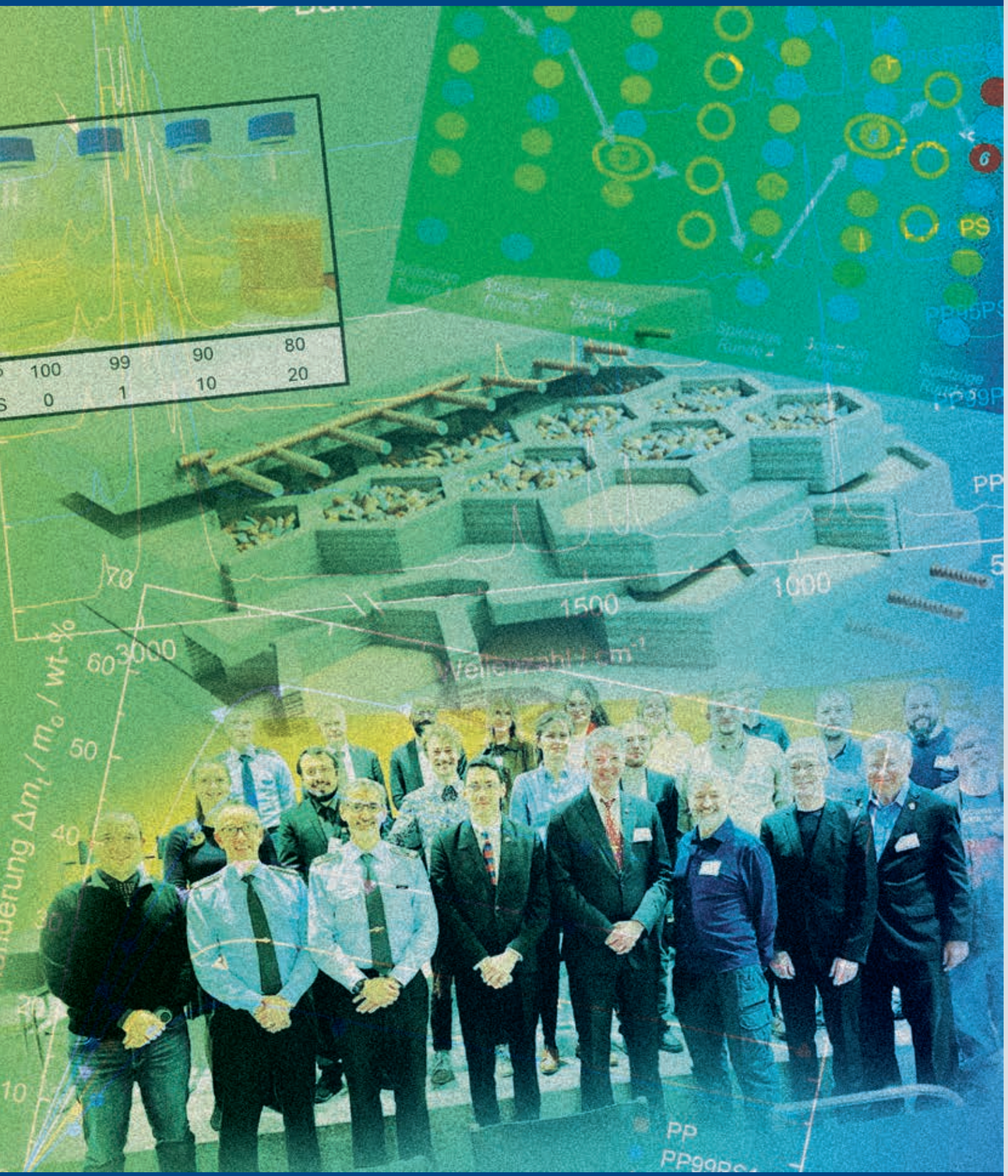


Fig. 3: The interface of the VoVisWxBw software displaying radar data points in a 3D view



6

Bundeswehr-Related Research at the Bundeswehr Universities

The two Bundeswehr universities (UniBw) in Munich and Hamburg conduct research across a broad spectrum of disciplines, ranging from basic research to experimental applied research and scientific implementation support. The universities' research also focuses on topics related to security and defence, in particular as part of interdisciplinary and transdisciplinary consortia as well as in cooperation with partners from science, industry and society. Innovations often arise out of the interplay between theoretical foundation, scientific analysis and practical application. With this in mind, the Bundeswehr universities are concerned with questions regarding engineering science and information technology as well as economics, social science and the humanities.

The so-called "Zeitenwende" necessitates a renewed focus on national and collective defence in the context of an increasingly complex global security situation, while at the same time the challenges posed by hybrid threats must be dealt with. These are considerations that factor into the research conducted at the two Bundeswehr universities. It is understood at these two universities that a broad interpretation is needed as to what kind of university research is relevant for security. Accordingly, it is generally accepted that a clear-cut distinction between purely civilian and dual-use research is no longer possible today. At the same time, the armed forces and many researchers at the Bundeswehr universities are increasingly interested in professional exchange and joint research and innovation work.

Since 2020, UniBw researchers have also conducted complementary research at the Bundeswehr Centre for Research on Digitalisation and Technology (dtec.bw), which is run by the two Bundeswehr universities and is currently funded by the European Union through NextGenerationEU. Ministerial responsibility for dtec.bw lies with the Director-General for Innovation and Cyber (IC). The large number of projects under way at dtec.bw, the cooperation with departmental research institutions and the armed forces that has developed and intensified, and the lessons learned and innovations developed show how valuable cooperation between science and practice can be.

The contributions to this annual report illustrate the broad spectrum of research conducted at the Bundeswehr universities as well as the prolific cooperation with other defence research institutions that has been going on for many years. In addition, they reflect the importance of promoting young scientists who are involved in research and who are thus given opportunities for qualification. Basic research grounded in theory and research on practical applicability in the field of innovative technologies and methods complement each other, as illustrated by the contributions to this year's annual report.

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Wargames as Experiments

In addition to being a useful tool for educational and analytical purposes, wargaming can be employed as an experimental research method. In the STRATEM project, strategic decision-making behaviour is systematically recorded and evaluated in a digital simulation environment. The aim is to make strategic competence, patterns of cooperation and decision-making logic empirically measurable under conditions of uncertainty.

At the core of this approach lies the systematic investigation of strategic decision-making behaviour in uncertain situations. STRATEM stands for “Strategiefähigkeit Analyse durch Tests und Experimentelle Messung”, meaning “strategic competence analysis through empirical measurement”. The STRATEM research project aims to not only describe individual and collective strategic competence in qualitative terms, but also to make it empirically measurable. At the heart of the project is the digital wargame “Entanglement”, which simulates complex, conflictual decision-making situations and systematically records actions, interactions and adaptive processes (Fig. 1 and 2).

Within this setting, decisions are not merely observed but quantitatively assessed. Moves, reaction times, resource allocations, cooperation patterns and escalatory decisions are documented and analysed as data points. Additionally, psychological indicators may be incorporated – as might physiological indicators too in future. This results in a controlled research design in which hypotheses on risk behaviour, willingness to cooperate, adaptability and strategic coherence can be systematically tested (Fig. 3).

The experimental perspective has been tested in various formats. In the wargame ”Ernstfall”, which was conducted in cooperation with the newspaper WELT and focused on escalation in the Baltic region, it became clear that institutional routines and coordination processes have a strong impact on response speed, even among highly experienced participants. Its benefit lay less in predicting future developments and more in analysing collective decision-making dynamics (Fig. 4).

This approach was also applied in the “Convergence” simulation, conducted with the Berlin Chamber of Commerce and Industry to examine operational capability in a security policy grey zone (Fig. 5). This exercise showed that situational awareness, coordination and institutional connectivity are essential for operational effectiveness, also in the economy.

Another example is the “Ostschild 2026” simulation, conducted in cooperation with the Friedrich-Ebert-Stiftung and focused on European defence industrial cooperation. The scenario explored the tensions between national industrial policy and collective European defence capabilities. The game dynamics illustrated how domestic political pressures and strategic uncertainty can affect long-term cooperation structures.

Finally, within the foresight process of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), the wargame “Entanglement 2035” addressed the issue of critical raw materials. Contrasting future scenarios, ranging from deeper European integration to fragmented trade regimes, were systematically explored from the perspective of varying geopolitical, economic and development policy interests.

These applications demonstrate that wargaming can serve as an experimental research method that extends beyond training and analyses. By deliberately varying factors, including resource distribution, institutional mandates and escalation mechanisms, and by systematically capturing variables, such as decision quality, cooperation levels and adaptability, it is possible to identify causal relationships.

Wargaming can therefore be used as an instrument of strategic social science research. As experiments, wargames act as a bridge between scientific methodology, practical application and the data-driven analysis of strategic decision-making.



Fig. 1: Participants at the first “German Wargaming Symposium” in collaboration with “Connections”



Fig. 2: First “German Wargaming Symposium” in 2025

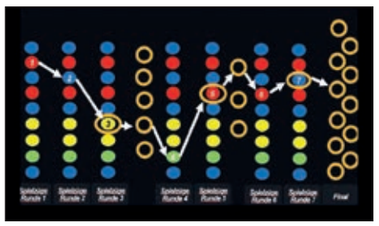


Fig. 3: Decision paths/strategic trajectories



Fig. 4: The wargame “Ernstfall” in collaboration with the newspaper WELT



Fig. 5: The wargame “Convergence”, in collaboration with the Berlin Chamber of Industry and Commerce

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Hybrid Defence: Robust AI as an Innovation Driver

The Chair of Hybrid Intelligence develops and validates robust AI systems for airborne reconnaissance, critical infrastructure monitoring and resilient navigation. These systems are consistently designed for real-world operating conditions that are resource-limited and safety-critical. The focus is on achieving resilient performance, operational integration and verifiable robustness.

The technological maturity of modern AI systems is shifting the focus of innovation from enhancing performance to ensuring robustness, validation and resilient integration under real-world operating conditions. The Chair of Hybrid Intelligence is addressing this issue by developing AI systems for airborne reconnaissance, critical infrastructure protection and robust navigation and sensor systems.

In the field of robust aerial thermal reconnaissance methods, the team demonstrated how unmanned aerial vehicles can be equipped with infrared sensors and a lightweight, optimised deep learning architecture specifically designed for this purpose. Based on thermographic images (Fig. 1), it is possible to conduct a precise classification of landmines. The architecture and model complexity were consistently designed for deployment in scenarios with limited resources, ensuring functionality even under real operational conditions. Additionally, substantial improvements have been made with regard to thermal personnel detection in complex terrain: Targeted preprocessing (Fig. 2) stabilises thermal features and addresses partial occlusions, vegetation structures and varying viewing angles. Evaluations at different flight altitudes demonstrated a very high classification performance, even with limited visibility. These results prove that resource-efficient AI models can run reliably and effectively in a realistic, disruptive operating environment.

The research group is also developing AI solutions for monitoring and analysing damage to critical infrastructure. The DualSightNet architecture has implemented a backbone for rail track monitoring that specifically combines local defect characteristics and global context information. This reliably detects both small-scale damage and large-scale disturbances on rail tracks (Fig. 3,4).

With regard to object recognition on rail tracks, misclassifications have been significantly reduced as a result of structured preprocessing and an adapted ResNet backbone (Fig. 5, 6). The key to this lies in the coordinated integration of architecture, data preparation and validation under realistic conditions.

In addition to airborne reconnaissance and critical infrastructure monitoring, a critical examination was conducted into existing GNSS spoofing detection approaches, which are currently particularly relevant in practice. Previous research has revealed significant validation gaps, as many methods are predominantly tested in simulated conditions. However, robust application systems require the systematic integration of real attack scenarios and various forms of deception – a topic that the research group will address in future projects.

The Chair's research is therefore making a tangible contribution to securing safety-critical navigation and sensor systems.

The research group's overall focus is on developing and validating robust AI systems that remain demonstrably effective under real, variable and safety-critical conditions.

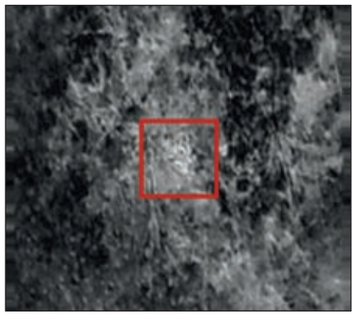


Fig. 1: A sample image of a landmine at a depth of 10 cm that was detected automatically using thermal data



Fig. 2: A sample image of a person that was detected automatically using thermal data

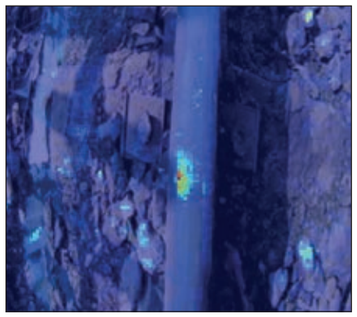


Fig. 3: A sample image showing how explainable AI can be used to detect rail shelling

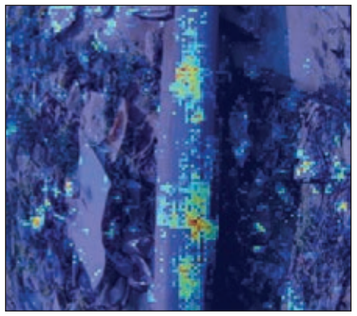


Fig. 4: This sample image illustrates the detection of rail flaking using explainable AI.

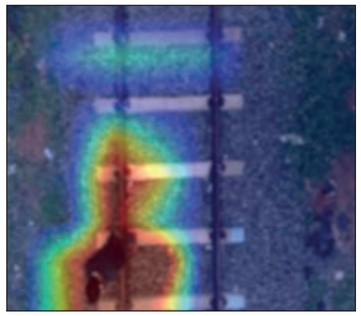


Fig. 5: This sample image illustrates the detection of a person on rail tracks using explainable AI.

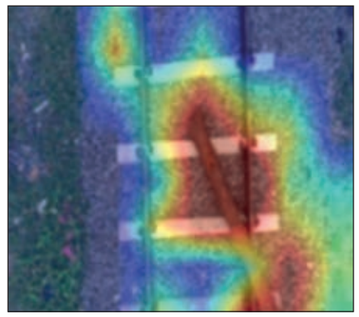


Fig. 6: Sample image illustrating the detection of an iron rod on rail tracks using explainable AI

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Additively Manufactured Reinforced Concrete for Structural Protection under Extreme Loads

By 3D printing reinforced concrete, it is possible to produce innovative, resource-efficient components with specifically adjustable properties. This article examines how additively manufactured, multi-layered, sand and gravel filled reinforced concrete slabs behave under extreme dynamic loads. In the process, it demonstrates the potential of this technology for protecting critical infrastructure.

Additive manufacturing processes are becoming increasingly prevalent in the construction industry. In particular, 3D printing reinforced concrete opens up new possibilities, as it enables complex geometries, load-adapted internal structures and high reproducibility to be achieved. For military and security-related applications, the behaviour of such components under extreme conditions is of particular interest. Figures 1 and 5 illustrate two different plate geometries produced by additive manufacturing. The cavity geometry can be designed to adapt the material distribution to the load, thereby contributing to controlled energy absorption.

As part of a research project at the University of the Bundeswehr Munich, an investigation was conducted into the failure behaviour of multi-layer 3D-printed reinforced concrete slabs with deliberately varied layer orientations. The aim was to analyse how the printing direction and internal layer structure influence failure behaviour following a contact detonation. To this end, several slabs were manufactured using an additive process, reinforced, and then subjected to highly dynamic experimental loading. By incorporating voids or using honeycomb-type internal structures, material consumption was reduced by up to 45 percent without a proportional decrease in mechanical performance. This demonstrates significant potential for improving resource efficiency compared to solid cross-sections. At the same time, digital design allows for the precise alignment of geometry, material distribution and anticipated loading conditions.

The experiments show that the internal structure and orientation of the printed layers significantly influence the damage pattern and residual load-bearing capacity. Certain layer configurations result in more favourable crack distributions and increased energy absorption. These results clearly demonstrate that, in addition to introducing new manufacturing approaches, 3D printing can also be used as a targeted tool to optimise the protective performance of reinforced concrete components.

From a technological perspective, combining digital process control with geometric freedom and material-efficient structuring is a significant innovation compared to conventional construction methods. As a result, components can be integrated into the design, weak points can be avoided, and load paths can be optimised. These capabilities open up new possibilities for modular and scalable protective systems, promoting a more sustainable and innovative approach to the design of future structures.

Findings from this research are being incorporated into the development of additively manufactured protective structures. These structures offer high resistance to extreme loads while reducing material consumption. This is particularly relevant for protecting soldiers and critical infrastructure.

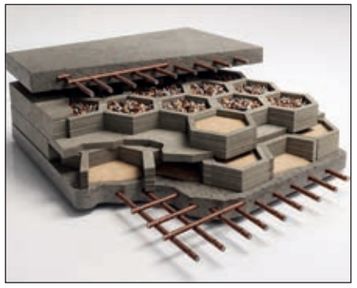


Fig. 1: Additive manufacturing of a concrete slab with a hexagonal internal cellular structure, filled with sand and gravel

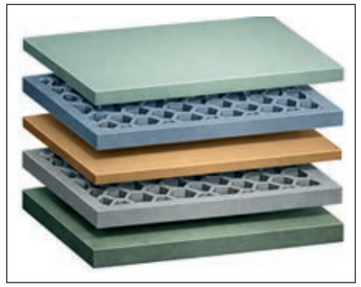


Fig. 2: Layered structure of a 30-cm-thick additively manufactured reinforced concrete element

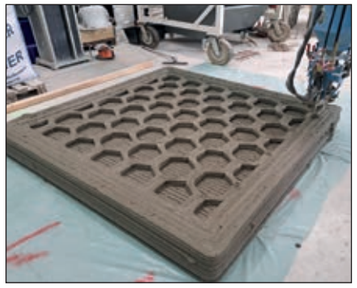


Fig. 3: Freshly printed honeycomb structure without infill

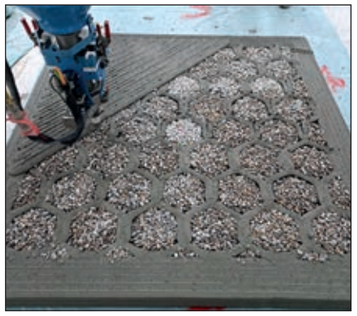


Fig. 4: Additive manufacturing of a concrete slab with hexagonal cellular structure and granular infill

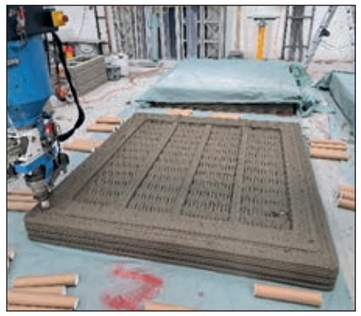


Fig. 5: Printing of a structured cavity geometry using sand and gravel filled cardboard tubes

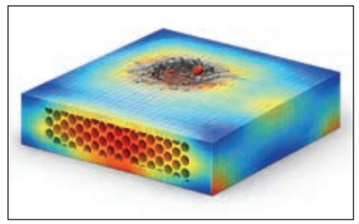


Fig. 6: Numerical FEM simulation of a concrete slab with structured cavity geometry under dynamic loading

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Compatibility of Elastomers with Pyrolysis Oils

With fossil resources depleting, alternative energy carriers must be developed to ensure a secure energy supply. Plastic waste pyrolysis is a promising way to produce liquid fuels. This study focuses on producing laboratory-scale pyrolysis oils and analysing their compatibility with the elastomer nitrile butadiene rubber (NBR).

In the military sector, it is of critical importance to ensure a secure supply of fuel, which is why it is so crucial to find alternative liquid energy carriers. In this context, pyrolysing plastics from packaging materials or end-of-life tyres is a promising method for producing liquid fuels with a high energy density. The aim of these studies is to enable fuel to be produced in decentralised field operations using small-scale systems and therefore ensure fuel supply for vehicles and electricity production in generators in the future.

The oils examined in this study are produced by laboratory-scale pyrolysis (Fig. 1) at high temperatures in an oxygen-free environment. Polypropylene (PP) is used as the feedstock (Fig. 2), with varying proportions of added polystyrene (PS). To ensure the safe application of pyrolysis oils in a military context, the physicochemical properties of the newly developed alternative liquid fuel types must be evaluated, as must the swelling behaviour of the elastomer parts. To this end, the pyrolysis oils are tested in accordance with the German diesel fuel standard DIN EN 590 and undergo a thorough

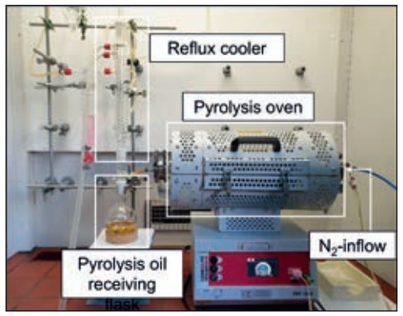


Fig. 1: A laboratory-scale pyrolysis setup consisting of a nitrogen inlet, a pyrolysis furnace, a condensation flask, and a reflux condenser for pyrolysing plastics

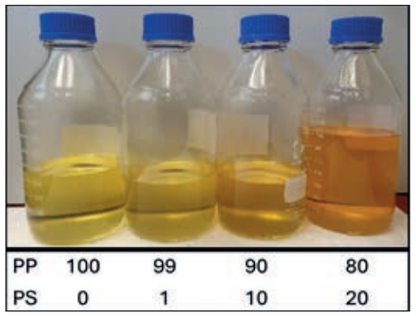


Fig. 2: Pyrolysis oils derived from polypropylene (PP) with varying proportions of polystyrene (PS)

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analysis using state-of-the-art techniques to assess their potential application as a fuel.

Sorption experiments were conducted to assess the swelling behaviour of the elastomer nitrile butadiene rubber (NBR), which is commonly used in hoses, seals and tank linings. To this end, tests were carried out to explore mass changes and the influence of swelling on the mechanical properties of NBR.

PP pyrolysis predominantly produces branched unsaturated hydrocarbons. Adding polystyrene to the feedstock also yields styrene and, to a lesser extent, other aromatic hydrocarbons during the pyrolysis process. Using sensitive instrumental analytical methods such as infrared spectroscopy, styrene can already be detected in small quantities (Fig. 3). Adding polystyrene to the starting material significantly affects the physicochemical properties of the pyrolysis oil, for example its density, viscosity and distillation profile. Consequently, the properties and composition of the pyrolysis oil progressively resemble those of fossil diesel fuel. To further evaluate potential applications, compatibility studies were conducted. During storage, pyrolysis oil produced from PP/PS mixtures diffuses into the elastomer, resulting in an increase in mass (Fig. 4). As the PS content of the feedstock increases, the mass change of the NBR increases accordingly. Therefore, it can be concluded that pyrolysis oils containing PS exhibit a significantly higher affinity to the elastomer. However, this mass increase correlates with a reduction in mechanical properties, particularly hardness. As the amount of PS increases, the diffusion behaviour and the mechanical properties of the material change significantly. This relationship emphasises the central importance of the detailed chemical composition of pyrolysis oils, as both physicochemical parameters and material compatibility strongly depend on the polymer composition of the feedstock.

This study demonstrates the fundamental relationship between the plastic feedstocks used and the properties of the resulting pyrolysis oils, particularly with regard to their compatibility with elastomers. Further investigations will be conducted to provide a comprehensive assessment of the potential use of plastic-based pyrolysis oils as liquid energy carriers. In terms of achieving independence from fossil fuels, this issue is particularly important. Furthermore, future research will include studies on other feedstocks and the potential influence of contaminant substances.

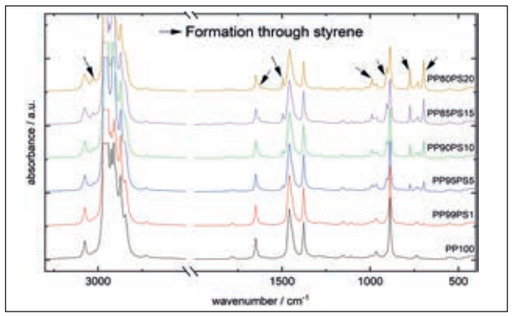


Fig. 3: FTIR spectra of pyrolysis oils derived from polypropylene and polystyrene in different proportions, with band assignments to structural elements

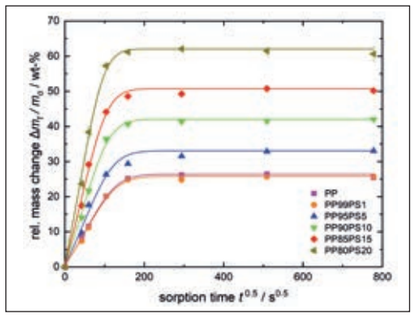
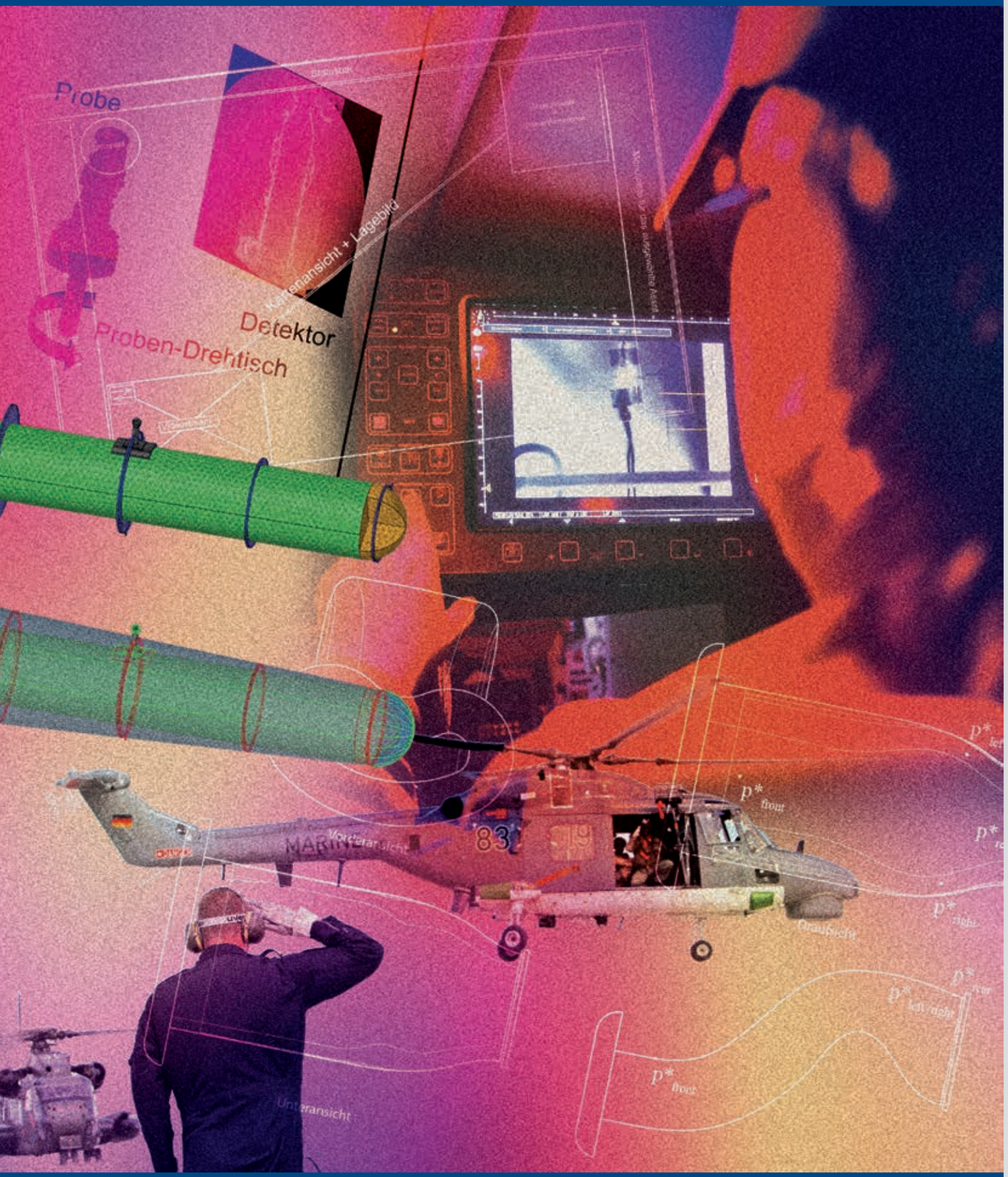


Fig. 4: Mass change of NBR after storage in pyrolysis oil derived from polypropylene and polystyrene, plotted against storage time


Probe
Detektor
Proben-Drehtisch
Kameransicht + Lagebild
MARINE
Vorderansicht
Draufsicht
Unteransicht

7



Appendix

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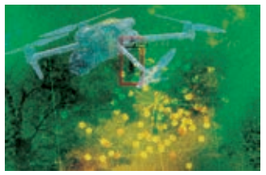
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