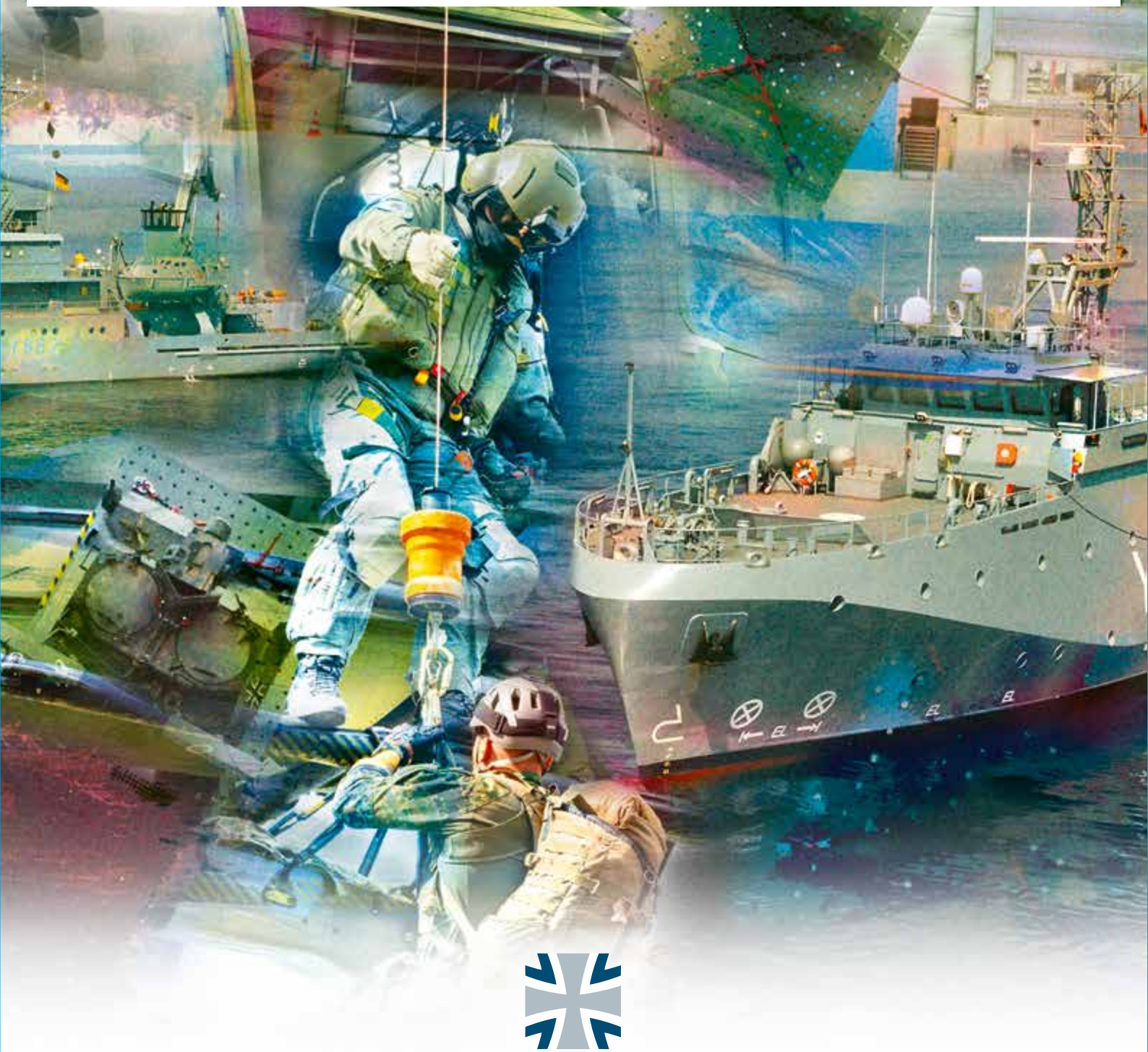
Federal Ministry
of Defence

Military Scientific Research Annual Report 2024

Defence Research and Innovation for the German Armed Forces



BUNDESWEHR

Federal Ministry
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Military Scientific Research
Annual Report 2024

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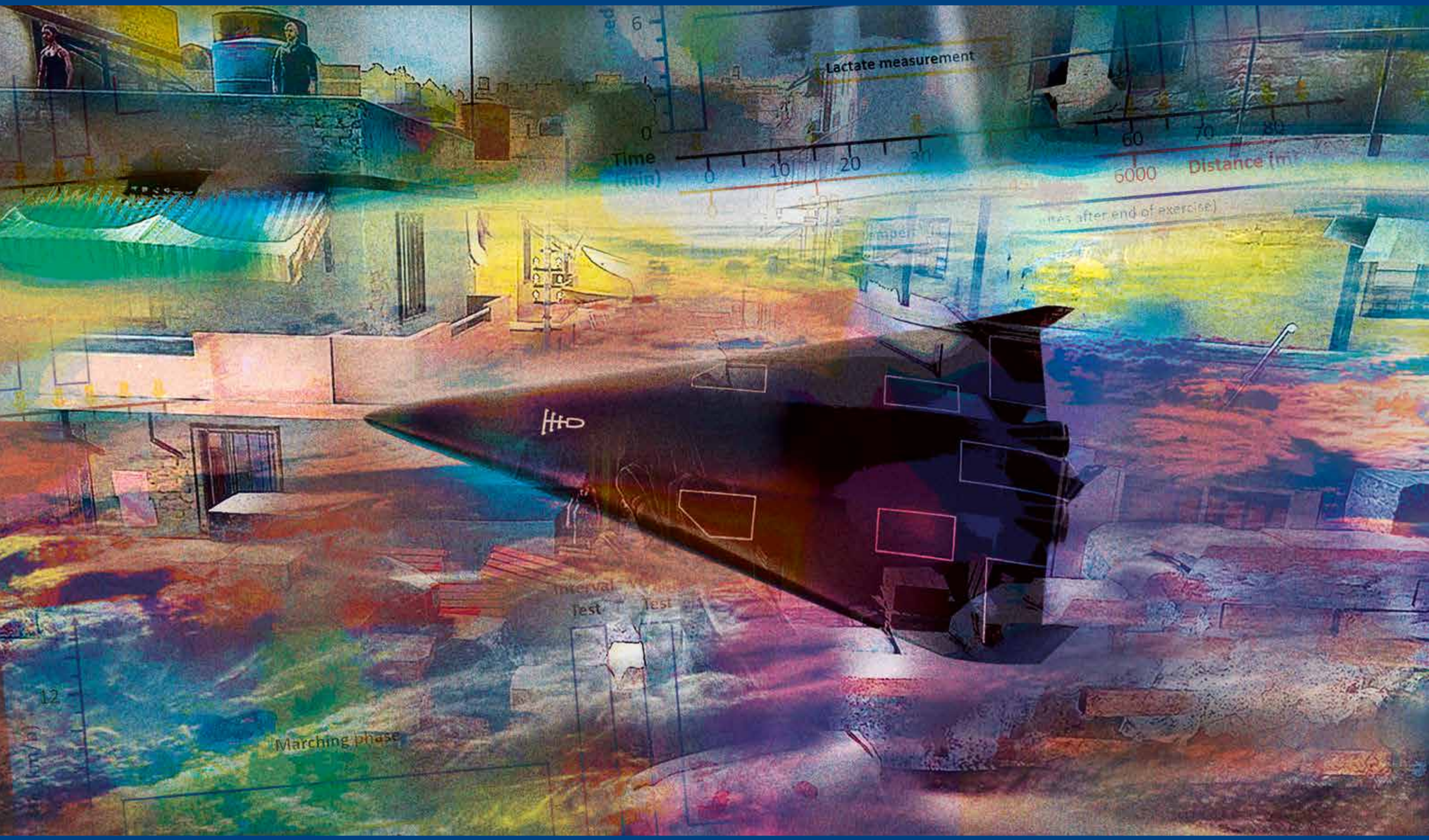
Defence Research and Innovation for the German Armed Forces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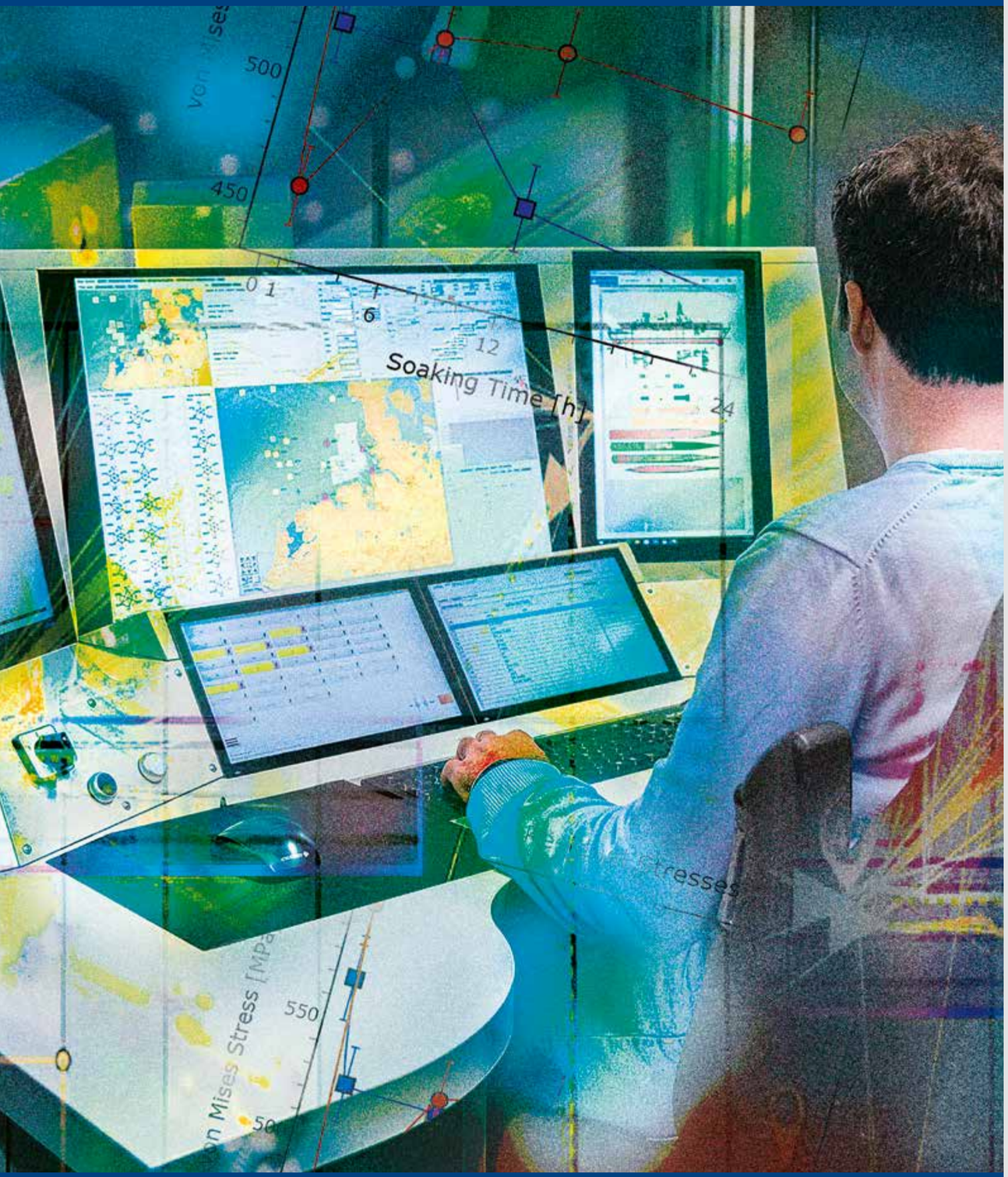


Chief Technology Officer & Director Science Innovation Staff
Alexander Schott

Federal Ministry of Defence

Defence Research and Innovation for the German Armed Forces

In the policy statement of the new Federal Government, Federal Chancellor Friedrich Merz declared on 14 May 2025: “This war and its outcome will not only determine the fate of Ukraine. The outcome of this war will determine whether law and justice continue to apply in Europe and throughout the world – or whether tyranny, military power and the law of force will prevail. What is at stake in Ukraine is nothing less than the peaceful order of our entire continent.”

In his speech, the Federal Chancellor therefore emphasises: “We ourselves must and will continue to strengthen our own defence capability and readiness. We want to be able to defend ourselves so that we don‘t have to defend ourselves. For decades, we have called this principle deterrence. There are few lessons learned from recent history that can be applied as accurately to the present as this, because this lesson is simple: Strength deters aggression, while weakness invites aggression.”

With its National Security and Defence Industry Strategy of 4 December 2024, the Federal Government responds to the security challenges of our time. It demands that rapid developments be met by technological leadership and swift adaptability in order to achieve lasting command and control superiority, effects superiority and force protection.

The following areas of defence research form the basis for this technological leadership and adaptability:
- defence research and technology,
- military medicine research and military psychology research,
- military history research and social sciences research, and the social sciences, and
- geoscientific research.

The annual report is designed to give you an insight into this departmental research and create a greater understanding of the Bundeswehr’s defence research as a whole.

The increased importance of innovation:

It is important to shorten existing innovation cycles and quickly transform research results and new technologies into innovations and thus into Bundeswehr capabilities.

The annual report is a reflection of this holistic approach to research and innovation. It is the first time that the subtitle of this report “Defence Research and Innovation for the German Armed Forces” has included the item “Innovation”, and a corresponding chapter has been added.

This is more than just a change in title. We are currently in the process of changing the approach and the mindset of the Bundeswehr. In order to

ensure rapid innovation cycles, it is necessary to continuously analyse the innovative activities of the area of responsibility of the Federal Ministry of Defence and reorganise them as required.

This has already occurred at the level of the Federal Ministry of Defence by pooling innovation management and defence research and technology. In future, a separate agency in this area of responsibility will act as the Bundeswehr innovation hub and cooperate with the established Digital Laboratory Network to coordinate Bundeswehr activities and, among other things, manage highly prioritised innovation campaigns for the Bundeswehr.

Civil-military interfaces in research and innovation:

From a strategic perspective and with a view to modern overall defence, close cooperation is required not only within the Federal Ministry of Defence and its area of responsibility, but also with other ministries, federal states, universities, civilian non-university research institutions, private companies, and international institutions. Long-standing civil-military research partnerships, such as with the German Aerospace Centre, the Fraunhofer Institute and various universities far beyond the two Bundeswehr universities, serve as a good example here.

In its 2025 annual report on Research, Innovation and Technological Performance in Germany, the Commission of Experts for Research and Innovation calls for an end to the strict separation of military and civilian research in Germany in view of changing threat levels. This applies in particular – but not exclusively – to fields such as drones, quantum technology or artificial intelligence, which are developing with enormous momentum.

In its 2025 position paper on science and security in times of global political upheaval, the German Science and Humanities Council states: “With Russia’s war of aggression against Ukraine and the USA’s transition of power, a significant change in German strategic culture and foreign policy culture is also imminent. In order to adequately grasp these security policy challenges and adequately prepare for and accompany the upcoming strategic change, the scientific field and the interaction of science and humanities with political, economic and social actors should be significantly expanded and further developed.”

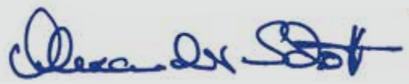
Achievements and exciting technological developments:

This report includes a wide range of articles from all fields of defence research. It is obviously not an exhaustive overview, and, as in previous years, the choice of topics presented has been carefully considered in order to protect our achievements. Nevertheless, I hope my team has once again succeeded in compiling an interesting report that will provide you with new insights.

This year, I would like to particularly highlight the articles “MILOS-D laser weapon system: High-precision and cost-effective effector for land-based and special operation forces”, “The PhagoFlow research project: Practicability test of bacteriophage therapy at the Bundeswehr Hospital Berlin”, and “Afghanistan, Iraq, Mali: Current representative study on Bundeswehr personnel with mission-related mental disorders”. They prove that defence research is at the cutting edge of science and demonstrate how new technology and discoveries will impact Bundeswehr capabilities.

I would personally like to thank all of the authors who contributed to this annual report. I trust that our readers will find it an enjoyable and enlightening read.

With best regards



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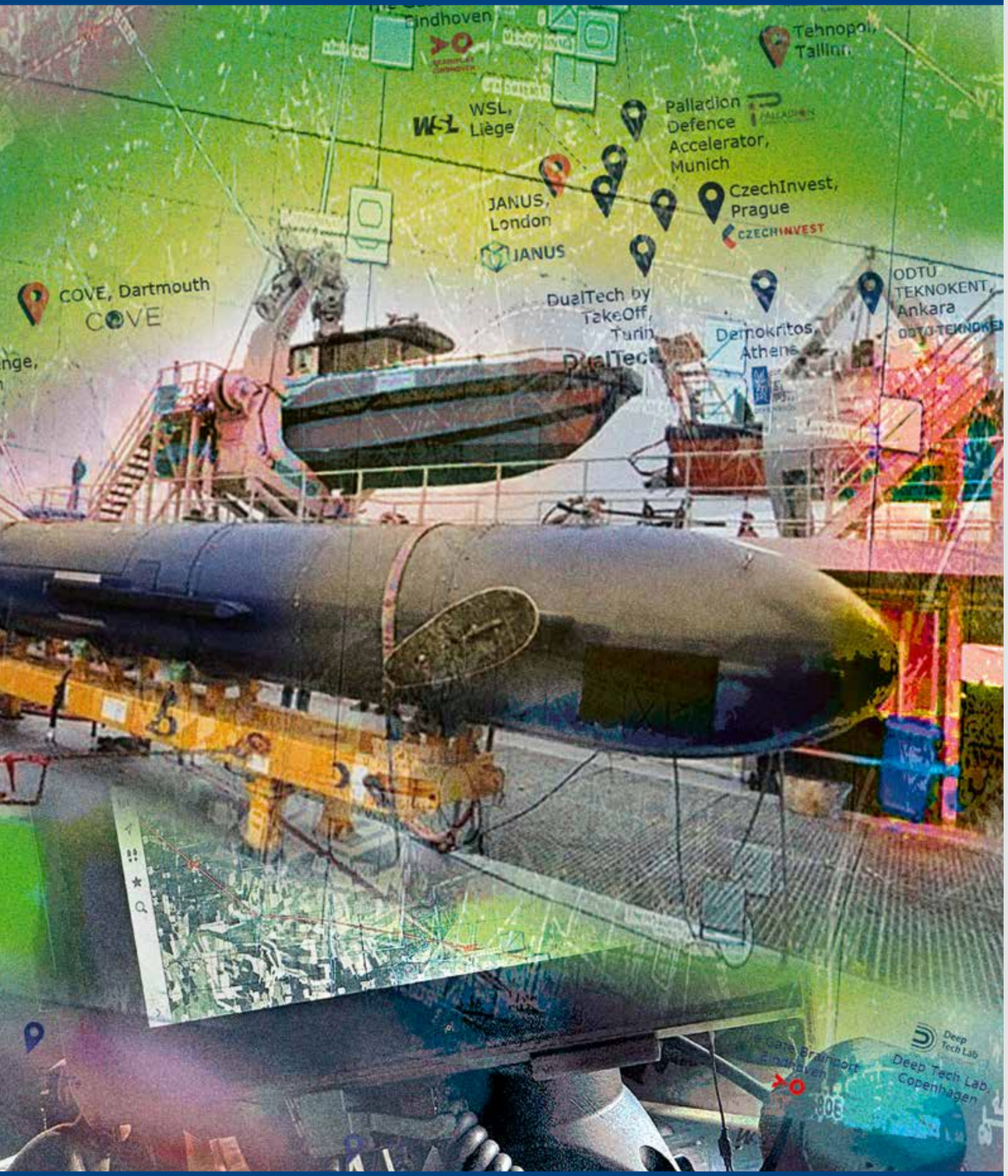

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Innovation Projects and Methods of Future and Further Development in the Bundeswehr

The Bundeswehr currently faces the challenge of having to adapt to new threat situations and environments. The open-ended, experimental approach adopted in innovation management and future and further development enables these fields to make a unique contribution to the adaptability of the armed forces. The articles selected for this report highlight the broad range of applications and added value for the Bundeswehr's efficiency and capacity for action.

CD&E projects with a focus on operational experimentation connect defence technology and processes with their users in such a way that the benefits for military action on the battlefield are more immediately and clearly apparent. Their agile approach also makes it possible to identify unpromising solutions which can be rejected for procurement from the outset.

Innovation projects relating to operational experimentation go even further. In these projects, ideas about how commercially available military technology should be used are already fairly concrete. Through practical trials in exercise scenarios, procedures are evaluated under realistic operational conditions and their added value for the troops can be determined.

The CD&E projects MITTENS and TerrHub focus on specific functions for processing information. Bundeswehr requirements are extremely diverse in this regard, ranging from information exchange in the context of highly agile battle scenarios at high operational tempo to civil-military situation pictures across several areas of responsibility in a whole-of-government approach to defence.

As part of a model-based approach, the FMoD's analytical and control capability will be supported by a comprehensive digital Bundeswehr model – the Enterprise Architecture.

Within the scope of NATO's Defence Innovation Accelerator for the North Atlantic (DIANA), Germany has established the Palladion Accelerator at the University of the Bundeswehr Munich. The Palladion Accelerator is part of the Bundeswehr's innovation ecosystem. With its activities in the fields of technology transfer and maturation as well as knowledge transfer, it contributes to speeding up the introduction of innovative solutions into military capabilities along NATO Capability Targets.

Wargaming is presented as a very valuable methodical trend with a wide range of application options. Simulating potential threat situations and scenarios as well as replicating and developing potential solutions is much more than just a game-based approach. In the context of digitalisation as well as increasingly complex national and international structures and uncertain futures, this method provides the Bundeswehr with a wide range of options.

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Innovation project OPEX Marine: “Large Unmanned Underwater Vehicle Blue Whale”

The Bundeswehr is facing the challenges of continuously expanding its capabilities and of adapting to the changing demands of modern warfare and rapidly changing threat scenarios. A newly established key element of the efforts to meet these challenges are innovation projects involving Operational Experimentation (“OPEX”). In 2024, the Bundeswehr successfully conducted its first pilot initiative.

Unmanned systems are an integral part of the strategic considerations of the German Navy. The “German Navy Planning Objective 2035+” places particular emphasis on the quick and effective integration of unmanned platforms and the provision of optimum additional support to manned systems. Unmanned systems promise increased efficiency and flexibility, which are essential for meeting future challenges.

OPEX enables the Bundeswehr to verify the technical reliability or technical maturity of the tested system, to identify a possible need for adapting the system to military requirements, and to determine framework conditions for the seamless integration and employment of, for example, unmanned systems.

The objective of the Navy’s “LUUV Blue Whale” OPEX innovation project was to evaluate a technology platform to be used in the field of underwater warfare and the associated procedures under realistic operating conditions. In this case, LUUV stands for “Large Unmanned Underwater Vehicle”. The main focus was on testing the system’s capabilities in the fields of long-range underwater detection and covert surface reconnaissance – tasks that have thus far been performed by manned submarines.

Using a holistic approach, the innovation project under the direction of the German Navy Headquarters was conducted with active support from, among others, the Bundeswehr Office for Defence Planning, the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support, the Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research (WTD 71), and the NATO Centre of Excellence for Operations in Confined and Shallow Waters (COE CSW).

The main part of the project was the two-week test at sea of the LUUV type “Blue Whale” conducted in cooperation with industry. “Blue Whale” is an unmanned underwater vehicle measuring approx. 11 m in length and weighing 5.5 t that has a high level of technical maturity. It is fitted with sensors for surface and underwater reconnaissance as well as communication systems. A detailed final report of the campaign is currently being prepared.

It has already become clear that innovation projects based on operational experimentation will offer added value to the armed forces and will continue to play an important role in the Bundeswehr in the future. This is reflected, among other things, by the establishment of the research and innovation hub at ministerial level. The associated merger of the task areas “Methods of the Future and Further Development of the Bundeswehr”, “Research and Technology (R&T)” and “Innovation Management in the FMOD” (*Methoden der Zukunfts- und Weiterentwicklung der Bundeswehr, Forschung und Technologie (F&T) and Innovationsmanagement im Geschäftsbereich BMVg)* will further boost innovation projects such as OPEX campaigns. Active efforts are already being made to consolidate these undertakings and to launch follow-on projects.

Fig. 1: The LUUV “Blue Whale” being lowered from the accompanying ship for tests

Fig. 2: A Bundeswehr ship accompanies LUUV “Blue Whale” off Eckernförde

Fig. 3: LUUV “Blue Whale” during a test

Fig. 4: LUUV Blue Whale on the escort and transport ship

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DIANA – a NATO innovation initiative to promote dual-use innovation

The Defence Innovation Accelerator for the North Atlantic (DIANA) was established in response to the increasing importance of civilian innovation for the development of military capabilities. DIANA not only supports international cooperation, but also fosters specific start-ups and accelerates the development of disruptive dual-use technologies.

With the establishment of the NATO agency DIANA (Fig. 1), an Alliance-wide innovation network has been established to maintain and further expand NATO's innovation and technology leadership in the field of Emerging and Disruptive Technologies (EDT). Above all, DIANA will strengthen civil-military cooperation. DIANA's focus is on fostering start-ups in the field of dual-use technologies that ensure the technological progress of NATO member states and prepare NATO for future challenges.

DIANA is currently working with a unique network consisting of more than 20 so-called accelerators (Fig. 2) and more than 180 associated test centres from across NATO. This will give the sponsored start-ups access to world-class facilities within the Alliance. The German part of the innovation ecosystem DIANA consists of the Palladion Defence Accelerator of the Bundeswehr University Munich and other – currently 14 – test centres.

As part of the accelerator programme, DIANA facilitates the exchange with security and defence mentors and military users, coordinates access to trusted investors, and provides its own funding to enable participation in the accelerator programme (Fig. 3). DIANA thus contributes towards turning the defence requirements of NATO members into drivers of technological developments, in particular through start-ups.

DIANA can be used to foster start-ups that can offer EDT-based solutions for dual-use challenges at a Technical Readiness Level (TRL) of at least four to seven.

The accelerator programme is set up as a competition in the form of annual challenges and consists of two phases. The focus is on military challenges, e. g. with regard to secure information sharing, logistics and supply chain and human health, as well as to the fields of resilience, critical infrastructure and space. As part of a selection process, the proposed solutions will undergo an initial evaluation – technically, militarily and economically. The selected innovators will then join the bootcamp phase, an initial six-month phase. In this phase, the start-ups receive mentoring and coaching at an assigned accelerator, develop the business case further, and are familiarised with the defence sector and its specific features.

Furthermore, they will have access to the worldwide test centre network and can further develop the technology of their solution. Each start-up will also receive a funding of € 100,000.

At the end of the bootcamp phase, the start-ups can apply for a competitive selection process to move forward to what is referred to as the grow phase. In addition to additional financial resources amounting to € 300,000, this phase focuses on scaling through in-depth improvements to mature the technology, on the establishment of networks with capability developers/ procurers, and on identifying pathways to connect with the defence industry and venture capitalists.

DIANA achieved initial operational capability (IOC) in 2023 and launched the first three challenges in June 2023. A total of 1,300 start-ups have applied for them. Of these, 44 were selected for the bootcamp and a total of 10 start-ups for the grow phase. With more than 2,600 applications for the five DIANA Challenges in 2024, the number of applicants already doubled in the following year. Of these, a total of 74, including four German start-ups, were selected for the bootcamp phase.

From 2025 on, and given full operational capability (FOC), up to 10 challenges are to be conducted each year.

With DIANA, NATO is sending a clear signal for dual-use innovations as an important part of the security policy of the 21st century.

DIANA
Defence Innovation Accelerator for the North Atlantic

Fig. 1: Logo of the NATO Agency Defence Innovation accelerator for the North Atlantic

Fig. 2: Locations of the innovation accelerators of the NATO agency Defence Innovation Accelerator for the North Atlantic

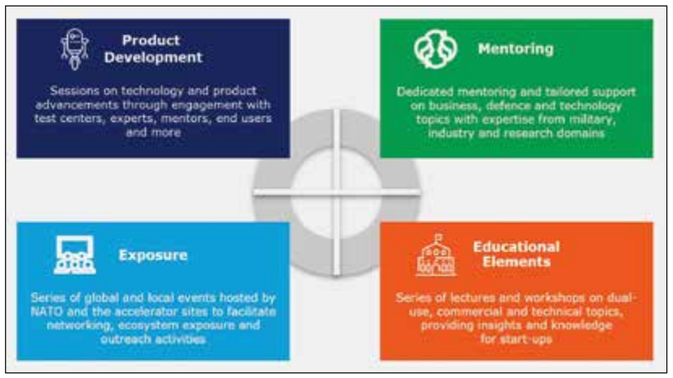

Fig. 3: Overview of the support services of the DIANA accelerator programme

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The Enterprise Architecture Management (EAM) of the Bundeswehr

The architectural vision for the FMoD area of responsibility is to capture and understand the Bundeswehr in all its interdependencies and interactions using consistent and compatible data models in order, amongst other things, to improve management capabilities. To achieve this vision, the Enterprise Architecture Management (EAM) establishes an Enterprise Architecture (EA).

EAM pursues an integrated approach that takes into account international civil standards and requirements established by NATO. It is geared towards strategic planning, procurement, and usage with due regard to the "People, Process and Technology" fields, which also characterise the digital transformation of NATO. The main objective of EAM is to achieve the ministry-approved architectural vision with regard to a model-based analysis and decision-making capability at the strategic level. This aim goes far beyond the previous ambitions of the use of the architecture method in the Bundeswehr.

The Bundeswehr Enterprise Architecture Management (EAMBw) Team at the Bundeswehr Office for Defence Planning is in charge of implementing EAM at the federal level, which also involves organisational structures and procedures in the major organisational elements. In 2024, as part of EAM, a General Publication on Enterprise Architecture Management was released, meetings of cross-service working groups took place, architectural requirements of the major organisational elements were determined as a basis for the future enterprise architecture (EA), and a comprehensive EA development plan for the

Fig. 1: Logo of the EAMBw project

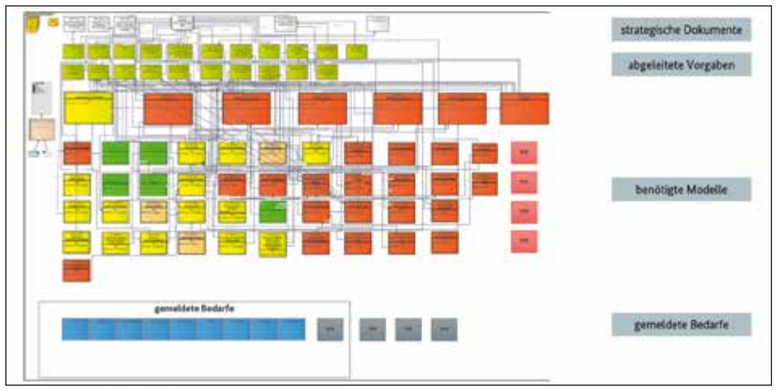

Fig. 2: EA development plan

further strategic orientation was devised and approved by the ministry.

Standards coordinated in multinational bodies, such as the NATO Architecture Framework (NAF) and the EA Policy, form the basis for EAM in terms of interoperability and alignment with Alliance objectives. In 2024, the NATO Architecture Capability Team (ACaT) focused on main topics such as Multi-Domain Operations (MDO), Federated Mission Networking (FMN), and reference architectures for the digital transformation process. Also in the course of the same year, NATO started to establish the organisational structures by introducing central "architecture authorities". ACaT is to administer these functions.

A further key project within the Bundeswehr is the development of the "Air Force reference architecture", which started in 2024 and is meant to contribute to strategic analysis after its finalisation as an architecture model. In 2024, several workshops were conducted particularly for the purpose of methodological support. A model is to be created sometime in 2025.

To support further development work, the Architecture Management Platform (AMP) was established as a central repository for Bundeswehr architectural products. The platform enables cross-architecture analysis and automated quality assurance. In addition, the AMP makes sure that version controls are carried out regularly. In 2025, the development will be followed up in order to enable improved support for the decision-making process at the Bundeswehr's executive level.

Standardisation remains crucial. Processes will be modelled in line with the requirements of the Business Process Model and Notation (BPMN 2.0) and the NATO Architecture Framework (NAF), with uniform modelling conventions being developed.

Process management as an area of application is an integral part of EAM. Due to the reorientation process within process management, it is now possible to bring both sides closer together. This will offer opportunities for a uniform approach in the future, e. g. in the field of NATO C3 taxonomy, in the design of conventions, or the implementation of the process register as a model.

Fig. 3: The EAM specialist group conducting project work

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MITTENS – Enabling multinational tactical operations

The agile CD&E project MITTENS rapidly developed a targeted solution to ensure tactical operational capability in multinational environments. The goal was to make capability enhancements quickly available to troops using a pragmatic approach in order to enable verifiable fulfilment of the German contribution to the NATO Force Model.

MITTENS stands for "Multinational, Interoperable, Tactical Tablet for Operations up to NATO SECRET." The project aimed to establish a minimum viable command capability, including NATO SECRET classification, using mobile devices from various manufacturers in combination with the AN/PRC-160(V) HF radio (HARRIS) and SitaWare® software (Systematic).

The following key questions guided the iterative approach towards developing a practical, field-ready solution:

1. Is MITTENS combat-ready?
2. Does MITTENS provide operational added value, particularly by delivering a NATO SECRET situational picture to tactical command structures?
3. How seamlessly can the solution enable interoperability in a multinational context, and does it comply with the FMN framework?

Field experiments confirmed that MITTENS significantly improves operational picture quality across tactical levels and increases operational tempo. Prototype mobile devices underwent technical evaluation by WTD 81. Feedback from these and other performance-related experiments enabled iterative development during the project.

As part of a dedicated test environment, MITTENS participated in NATO CWIX 2024, where its interoperability was validated under different communication systems and transmission methods. The ability to exchange GPS data within the Common Operational Picture (COP) was also successfully demonstrated. Mobile devices serve only as input and visualisation tools, with no data stored on them. Security-sensitive information and user-specific access credentials remain on an external medium.

During Certification Course 19/24 of the 8th Reconnaissance Battalion under the Commander of Armoured Brigade 12 at the Army Combat Training Centre (*Gefechtsübungszentrum des Heeres*), MITTENS was deployed without influencing of the scripted operational scenario. This allowed for real-world stress testing under combat conditions while presenting its operational value to high-ranking visitors. Simultaneously, electronic warfare (EloKa) units monitored the electromagnetic spectrum, confirming that MITTENS reduces detectability by minimising its digital footprint.

MITTENS is not intended to replace existing communication channels but acts as an add-on, ensuring functionality even in emergency communications (HF radio), in line with NATO's PACE requirements. By integrating sensor and effector data, it provides decision-makers with real-time information across vast distances.

Currently, MITTENS is the only available short-term solution for multinational interoperability at the tactical level while contributing to COP-enabled modern battlespace management. By achieving information superiority, MITTENS plays a crucial role in meeting the demands of highly agile combat operations.

Fig. 1: Investigation ET80/85 with forces from the Air Force Protection Regiment (*ObjSchRgt Lw*) in SCHORTENS

Fig. 2: Situational display SitaWare Frontline with ET 80/85 on Eagle IV platform

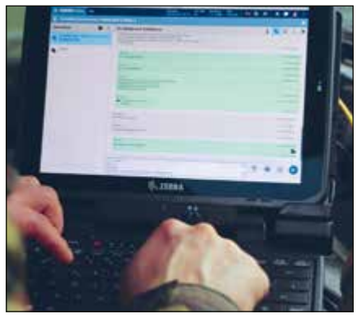

Fig. 3: 9-Line MEDEVAC REQUEST via SitaWare Chat with ET80/85

Fig. 4: BACKBONE© model (*MUSE*), change of security domain by exchanging dongle

Fig. 5: Army Combat Training Centre MITTENS performance show, BACKBONE© model (*MUSE*)

Fig. 6: AN/PRC 160 ManPack; transmission medium within the CD&E project

Fig. 7: BACKBONE© model (*MUSE*), on platform BV206S Fü

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The Territorial Hub – Enhancing the Bundeswehr's interagency command capability

The TerrHub project has demonstrated that, under the principle of "Cyber-Security First", a civil-military situational picture for Germany's total defence is feasible. In 2024, we reached important milestones: accreditation of the IT system (VS-NfD (RESTRICTED)) and validation through experimentation (proof of concept). In 2025, the process will expand to include classified (SECRET) information.

The Territorial Hub (TerrHub) concept development and experimentation (CD&E) project comprises various subprojects aimed at improving command and control capability and making it possible to connect other internal security bodies such as the police, the Federal Agency for Technical Relief, the Federal Office for Civil Protection and Disaster Relief, fire services, and emergency medical services. One challenge is processing and sharing information with different classification levels (from UNCLASSIFIED to RESTRICTED and SECRET). TerrHub links different digital worlds for this purpose.

The focus in 2024 was on improving the Bundeswehr Homeland Defence Command's command and control capability by linking partial (operational) situation pictures of external security into a common situation picture. Experiments were carried out to test information exchange with internal security authorities. The new TerrHub demonstrator was developed within six months with a consortium of companies to enable validation through experimentation. This IT system offers various information spaces and manages secure rights-based access to situational information.

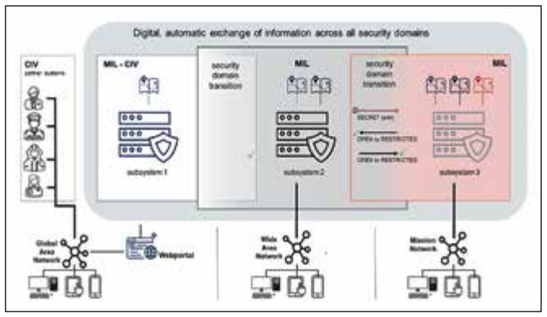

Fig. 1: TerrHub – functional sketch

Fig. 2: ... networked and integrated ... (source: iStock – Quardia)

Experiments verified that sharing situational information between internal and external security authorities is technically possible and can be implemented with organisational security. Information can be exchanged across security domains, complying with cybersecurity requirements and enabling a near real-time civil-military operational situation picture (civ-mil COP). This new situational awareness lays the foundation for the well-known triad information, decision, and effects superiority.

The CD&E project deliberately focused on the Territorial Command & Control System service. Future tools for information management, digital collaboration, prediction, simulation, and evaluation functions have already been conceptualised. According to current scientific and technical findings, the protection objectives of confidentiality, availability, and integrity have been fully achieved. This was confirmed through accreditation by the German Military Security Accreditation Authority.

Providing the right information at the right place and time forms the basis for higher operational tempo and improved decision-making. At the same time, the future operating environment increasingly requires cybersecurity considerations. Findings from TerrHub are being applied directly to the Multi-Domain Operations CD&E project and incorporated into other armaments projects.

The Secure Information eXchange (SecInfoX) solution is a designated MESBw plug-in, offering a secure domain gateway as-a-service for automated situation information exchange.

Recommendations for future command and control capability can be derived from the study's findings. The most critical attributes are:

1. networking and integration depth
2. security and resilience
3. interoperability and high-performance scalability.

Based on these groundbreaking findings, the study continues under the Interagency Situational Awareness (RessüLa) R&T project, with allocated budget funds. The Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support and the Bundeswehr Office for Defence Planning are collaborating on consolidating and further developing the TerrHub IT system for future users. TerrHub and RessüLa exemplify how planning, development, armaments, and procurement can harmonise for rapid capability enhancement in Germany's overall defence. The TerrHub could be integrated into exercises as early as 2025.

Fig. 3: ... safe and resilient ... (source: iStock – Just_super)

Fig. 4: ... interoperable and performantly scalable ... (source: iStock – putilich)

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Wargaming – Training for the real battlefield (using the example of the DEU brigade in Lithuania)

Dice roll, game pieces move, and discussions heat up. But what sounds like a games night is actually a serious Bundeswehr event: wargaming. Elements of commercial board games such as dice, cards, and markers are repurposed to simulate battlefield scenarios. This structured gameplay helps to analyse strategies and develop solutions for potential future threats.

Since the beginning of the war in Ukraine, wargaming has become increasingly important in the Bundeswehr. As a result, in early 2023 a Bundeswehr-wide working group headed by the Bundeswehr Office for Defence Planning for the first time used a uniform approach to deal with this topic. Within a very short time, a common definition and areas of application were developed, which were then included in the "Wargaming Handbook of the Bundeswehr", published in May 2024. This handbook defines wargaming as a method that "uses scenario-based models to represent conflict or competition in a safe-to-fail environment, in which events, human decisions, and resulting outcomes mutually influence one another".

A distinction is made between two general applications: educational and analytical wargaming. While the focus of educational wargaming is on imparting knowledge and gaining experience, analytical wargaming examines the effects and consequences of decisions.

An analytical wargaming project that is currently being developed by the Federal Ministry of Defence, bwConsulting and the Bundeswehr Office for Defence Planning is designed to prepare the DEU brigade deployed in Lithuania as realistically as possible for emergencies. The question is asked as to what decisions must be taken to ensure the C2 capability of the communications and information network, also in a collective defence contingency. For this purpose, it is necessary to ensure not only national but also multinational interoperability at all times.

At the beginning of the project, a data collection and analysis plan (DCAP) was developed to exactly define what questions should be answered in detail. The DCAP is the basis for all further steps. The DCAP is used frequently while the wargame is being developed to check whether new game mechanics or scenario adaptations will come up with better answers to the questions asked at the beginning.

In the next step, the scenario and a prototype of the wargame were developed in close coordination with Bundeswehr experts. This ensured that the reality on the battlefield was reflected as accurately as possible.

At this point, the prototype already consists of a large situation map which is spread out on several tables put together. Various game pieces are placed on the map. They represent pre-defined elements and command posts. Between these, strings of various colours stretch across the map to visualise a wide variety of radio links. Suddenly, the game master severs one of these links.

The enemy has evidently disrupted a link – the situation, and the game begins. The players at the table immediately start to discuss how limited resources can be used to re-establish the link. At that moment, the outcome, i. e. the solution of the game, is unclear and is the aim of the analytical approach.

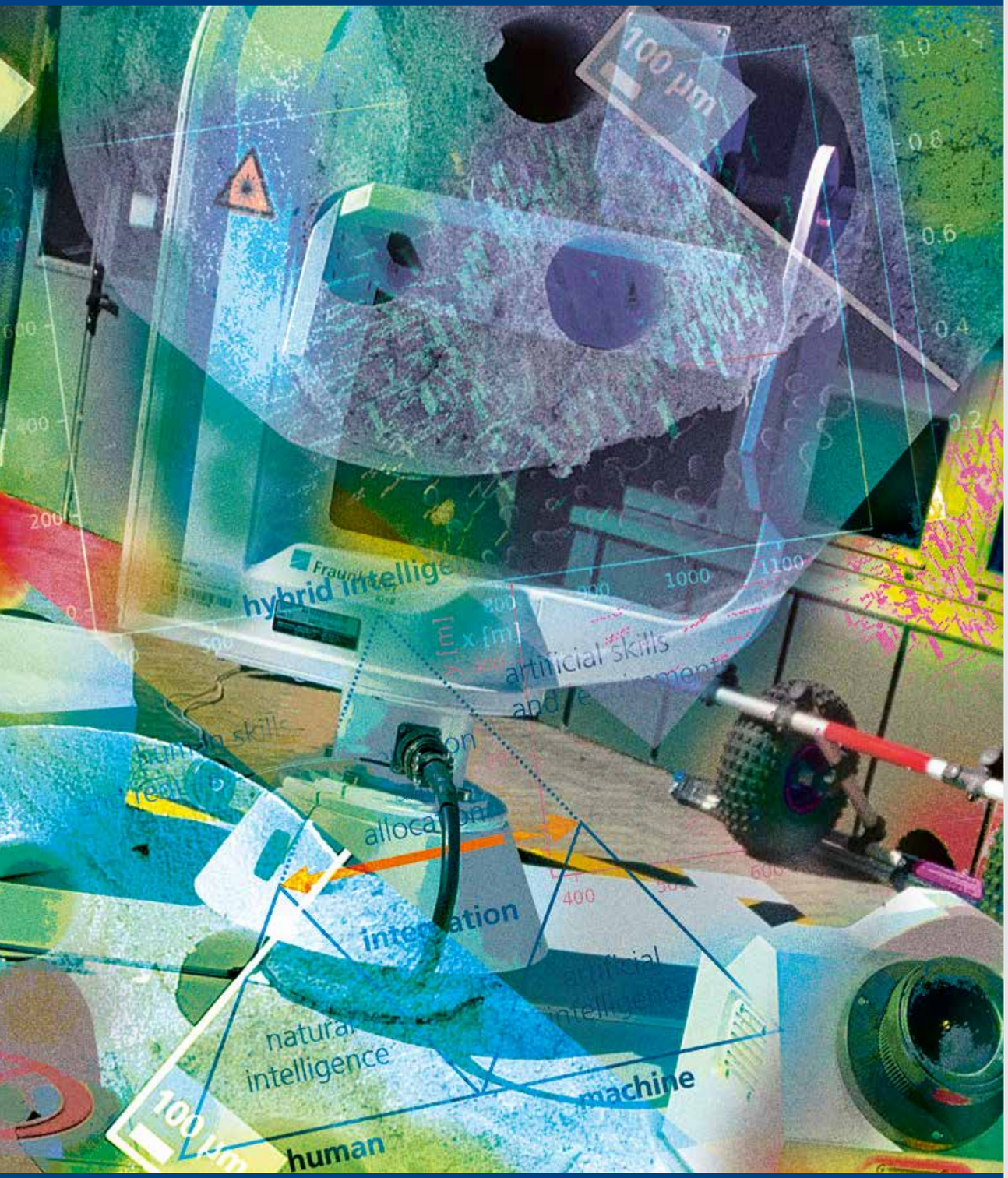
In the following months, the prototype and the scenario will be tested repeatedly, compared with the DCAP, and adapted iteratively. The outcome of this process will be a wargame that prepares the DEU brigade in Lithuania for collective defence in core competencies, such as interoperable C2 capability on a multi-dimensional battlefield with multinational cooperation, enabling the brigade to act before the situation becomes reality.

Fig. 1: Wargaming in testing mode
(right: project manager OTL KUHN)

Fig. 2: HyDRA on WIN24

Fig. 3: Prussian War Game as wargaming

Fig. 4: The Bundeswehr's wargaming handbook



2

Defence research and technology

This chapter impressively illustrates the diverse nature of defence technology research, which is both an integral component of the innovation system to be established in the Bundeswehr and the driving force behind it. Civilian and Bundeswehr research institutes, Bundeswehr technical centres, and industrial companies all play a crucial role in defence research thanks to their outstanding specialist competence.

Key players in the area of defence technology research include the Bundeswehr's own defence research institutes and technical centres, which focus on acquiring expertise for military applications, as well as the Fraunhofer Society for the Advancement of Applied Research, the German Aerospace Centre and its institutes, and the German-French Research Institute of Saint-Louis. As the following individual reports demonstrate, the range of technical competence exhibited by these key players is very broadly distributed across the various fields of defence technology.

The large number of businesses that constitute the German security and defence industry are also active in defence research. This research is usually commissioned for projects relating to specific technology or system integration if the armed forces can foresee its use in the military.

This chapter presents actors from the field of defence technology research that represent the entire scope of technology maturation from specific basic research to applied research to proof of application maturity. In this process, disruptive technologies and tools such as artificial intelligence and quantum technologies are used in a variety of ways. Step by step, the knowledge acquired raises individual technology maturity levels for future products. As a rule, this requires perseverance on the part of all those involved.

By coordinating the various research programmes, the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support and the Federal Ministry of Defence ensure that defence technology competences are available in all relevant fields of technology. Consequently, the Bundeswehr has fundamental capabilities for analysis and assessment in all of these areas. As a result, the Bundeswehr is able to quickly identify and respond to current developments, information and, in particular, new threats.

Through international division of labour, it is possible to develop synergies and save resources. In addition, cooperation takes place both at EU and NATO level and bilaterally with individual partner countries in certain fields of research. In recent years, Germany has also been steadily increasing its participation in the research and development projects of the European Defence Fund financed by the European Commission.

The current global political challenges and the resulting decisions and plans made by the new Federal Government will also create momentum and set new standards in the field of defence technology research. The Research and Innovation Hub has been proactively preparing for this for months, as referred to in the foreword by the Head of Research and Innovation.

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High-energy laser research – from components through system aspects to applications

High-energy lasers (HEL) are modern weapon systems whose potential must be researched and evaluated in detail. At the Fraunhofer IOSB, all aspects of laser technology, beam propagation, target tracking, optronics and system technology, target effects and laser safety, as well as their interdependencies, are investigated and evaluated under real conditions.

In order to be able to evaluate the capabilities of military high-energy-lasers in detail and to make new technologies available to the armed forces, it is necessary to deal with the complex interrelationships of the relevant subject areas in a comprehensive manner, to simulate them realistically, and to also demonstrate and verify them by means of experiments conducted under close-to-reality conditions. The interaction of the laser beam with the atmosphere can significantly change the intensity, focus, and hence the effect of the beam over long distances – a crucial aspect for understanding and optimising the use and performance of a laser weapon system (LWS). For this purpose, the Fraunhofer IOSB is working on a numerical simulation of the HEL beam propagation, which factors in all relevant atmospheric effects such as diffraction, turbulent beam expansion and thermal blooming (Fig. 1) and other non-linear optical effects in the case of ultra-short-pulse lasers. The simulation is currently being extended to other laser architectures such as coherent beam combination. This has the additional potential to compensate for atmospheric turbulence in order to increase the effective range of action.

A new 120-kW laser system with coherent coupling is currently being installed at IOSB for verification and further experimentation. The far field has a very narrow central intensity lobe (Fig. 2). Integrated into a mobile measuring system, this laser system enables investigations of beam propagation and compensation of atmospheric turbulence in real time as well as laser effects and safety aspects under realistic conditions.

Another aspect is the systematic investigation of aerosols and their effects on the weather and the scattering behaviour of laser radiation (Fig. 3). To study these dynamic processes, an expansion cloud chamber is being designed and realised by the IOSB on the site of the WTD91 in Meppen (Fig. 4.) Temperature, pressure and humidity are controlled in a realistic manner, and various atmospheric conditions, including cloud formation, are generated reproducibly. The HEL beam is measured at the outlet with respect to power and beam profile, and scattering phenomena within the chamber are registered. This allows comprehensive considerations regarding laser safety and the development of appropriate concepts for testing, exercise and engagement.

The IOSB is researching new and improved laser components and laser architectures also for future HEL at > 1.4 µm wavelength with a reduced hazard range. These include the realisation of high-power active laser fibres and fibre laser components (Fig. 5) and the growth of laser crystals to ensure national technological sovereignty and supply security. Thereby, the IOSB activities cover all critical steps in the value chains of fibre- and solid-state lasers and enable a well-founded research of what is possible without significant limitations.

After an output power of 940 W at 2 µm from only one fibre was demonstrated with an IOSB thulium fibre laser (Fig. 6) in 2022, integrated fibre laser modules were realised, on the basis of which concepts for further increasing the power of the individual fibre and the coherent coupling to 10-20 kW in the 2 µm range, including atmospheric compensation, are currently being researched and realised. For HEL target illumination short-wave infrared (SWIR), laser architectures with high pulse energy which are used in active imaging are being studied.

The Fraunhofer IOSB provides the German MoD with comprehensive analyses and assessments of interaction and effectiveness of LWS in relevant military scenarios and ensures access to and availability of new laser architectures and components as well as optronics for HEL systems.

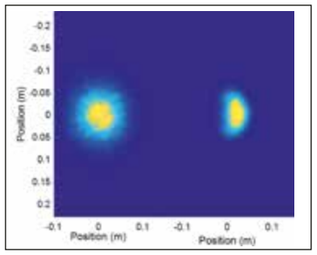

Fig. 1: Measured power density distribution at target with low power and high turbulence (left) and with higher power (with thermal blooming) but low turbulence (right)

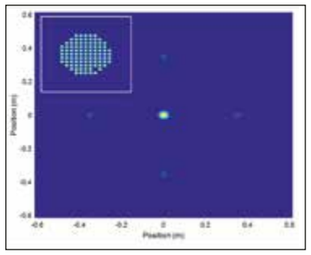

Fig. 2: Power density distribution of the 120 kW laser in the near field (white box) and in the far field (target range) at in-phase emission of all channels

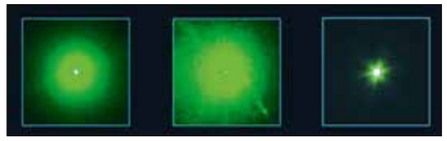

Fig. 3: Scattered radiation in the forward direction as a function of aerosol loads. Left: in atmosphere saturated with soap bubbles. Centre: through floating sand particles. Right: through clean unpolluted atmosphere

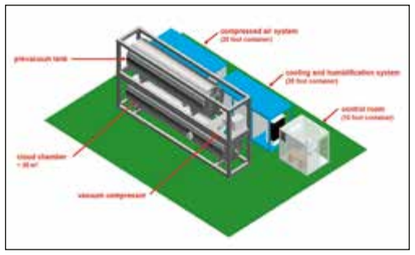

Fig. 4: Schematic representation of an expansion cloud chamber. Fast expansion into a vacuum vessel (expansion volume) causes the pressure in the main chamber to suddenly drop, resulting in clouds to form in a controlled manner

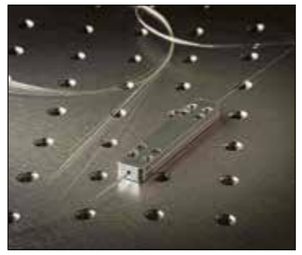

Fig. 5: Special fibre component for coupling signal and pump radiation for a high-power 2 µm fibre laser

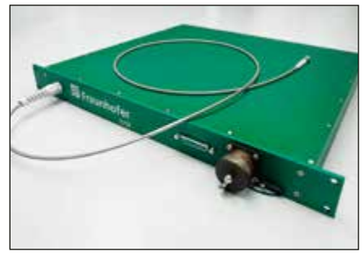

Fig. 6: Integrated high-power thulium-fibre-laser module

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AI methods for drone and object detection using infrared and video sensors

Protection against individual drones and drone swarms requires not only their detection and tracking but also knowledge about their type and threat potential, behaviour, and origin. This can be accomplished in real-time using AI methods with passive infrared and video sensors. These informations then provide a significant contribution to situational analysis in conjunction with other systems.

Drones are a critical element of modern warfare and can be specifically deployed against ground forces, military security areas, and critical infrastructure. Their detection, recognition, analysis, and counteraction thus represent an essential prerequisite for the protection of own troops, critical infrastructures, and other facilities. Researching appropriate methods is therefore of outmost importance. This applies to scenarios both on land, in the air, and in the maritime environment.

Infrared and video sensors are used to capture images of incoming drones on which AI methods (especially: deep learning methods) for image analysis are applied. This makes it possible to detect, track, and analyse the objects and thereby recognise drone type and payload (Fig. 1 and Fig. 2). The IOSB is working on such AI methods (especially deep-learning methods) for image analysis over ten years and integrated them into our MODEAS drone detection system (Fig. 3).

This work is directly related to other real-time methods for video based aerial reconnaissance developed at IOSB, for which also visual optical and infrared (IR) images of small objects and their behaviour in variable environments and under different lighting conditions must be analysed.

Large amounts of annotated image data are used as training data for training the AI methods, showing the object classes from various angles, lighting situations, and environments. In this way, the methods learn how the drones to be recognised appear in different situations (Fig. 4). Creating these training datasets in the visual domain is a challenging and labour-intensive process. In the infrared domain, the availability of training data is even more limited. Therefore, special techniques of frugal learning (learning with little training data) are researched and employed by IOSB to enrich the training datasets by varying existing data, to train IR methods using adapted visual-optical data, or to learn with small annotated training datasets.

For the analysis process, MODEAS firstly carries out an initial detection of the drones. Radio detection has a long range but is only effective for radio-controlled drones. In MODEAS, initial detection based on radar is used, which is also effective for autonomous drones that do not emit radio signals. Although radar has a long detection range and can also detect swarms of drones, it is typically unable to recognise drone types and their payload.

With the help of such a coarse primary detection, the MODEAS-system directs a tele camera with infrared and video sensors at a detected potential target, allowing it to be classified and tracked using AI methods. This also determines the exact directional information.

Further deep learning (AI) methods are applied to the video stream, providing information that goes beyond distinguishing between the classes of drones and confusing objects.

The IOSB has implemented procedures to differentiate between different classes of drones and, in particular, to detect the payload. That payload may consist of video sensors or radio equipment, but can also include droppable munitions or fixed explosives in a kamikaze drone (Fig. 5).

In the case of drone swarms, the drones are processed sequentially and the information obtained is assigned to the tracks in the track management system (Fig. 6). Based on this information, decisions can then be made in the system on the prioritisation of further measures.

Fig. 1: AI methods must be capable of detecting low-flying drones against various backgrounds, such as vegetation and buildings, and not confusing them with other objects, such as birds or whirled-up debris

Fig. 2: Detection against vegetation

Fig. 3: IOSB experimental system MODEAS for the optical detection, tracking, and analysis of incoming drones

Fig. 4: The AI-based object detection in the video analysis system must learn to identify drones under different lighting situations and angles for the various types

Fig. 5: Recognition of payloads makes it possible to assess danger and thus to prioritise counteraction when detecting a drone swarm

Fig. 6: Drone detection using infrared and video sensors makes it possible to determine highly accurate angle information for counteraction and to analyse drone type and usage by applying AI methods, enabling prioritisation in the case of drone swarms

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Development of an ergonomically designed standard console for naval vessels

To standardise workstations on ships, an ergonomically designed console concept was developed involving the relevant user group and implemented with COTS devices. The concept takes into account the special requirements of military workstations on ships and can be adapted to future conditions.

Military workplaces on ships are exposed to special conditions, e. g. highly dynamic situation changes and threat situations, including combat or evacuation, as well as 24/7 shift operation and high level of information security. In addition, the workstations are permanently exposed to sea swell. To meet these requirements, a console was developed by the Fraunhofer Institute for Communication, Information Processing and Ergonomics (*FKIE*) in collaboration with the Naval Support Command (Marineunterstützungskommando (*MUKdo*)) and the FLOT 2 (*Einsatzflottille 2 (EF2)*). The console is to be used for standardising workstations (Fig. 1). Regarding procurement cycles and service life of military platforms, a future-proof concept was also designed. It can be adapted to the available hardware (e. g. display types, sizes, or resolutions).

The development of the standard console was carried out according to the human-centred design process (DIN ISO 9241-210) and included a comprehensive context analysis of guidelines and environmental factors as well as a task analysis involving operators of frigate classes F123, F124 and F125.

The interaction requirements were derived from the context and implemented in an abstract display concept. This can be easily adapted to available interaction devices. The display concept defines both the areas in which monitors can be arranged and a basic concept for displaying information.

The console is designed for a variability of physique ranging from 5th percentile female (‘short woman’) to 95th percentile male (‘tall man’) and for different physique types (e. g. ‘sitting dwarf’, ‘sitting giant’). With the help of the RAMSIS digital human model from Human Solutions, the workstation was designed anthropometrically and reach envelopes and visual spaces were defined (Fig. 2).

The abstract display concept is based on an optimum sitting position for the user. Visual areas for ‘very important / frequent‘ (area I), ‘important / frequent‘ (area II) and ‘occasional‘ work (area III) were determined from the resulting eye position (Fig. 3).

Based on this abstract long-term concept, an example workstation was created using COTS (commercial off-the-shelf) products (Fig. 1). It contains a large monitor in the central field of vision on which, for example, a combat system can be displayed. Two flank monitors are used to display further information, which can also be operated in physically separate networks (IT security). There are also two touch monitors placed inside the reach envelope. These can be used for call stations, checklists, regulations, etc., for example.

Keyboard, joystick and a special mouse adapted for use on ships are available as input devices. The workstation is symmetrical and can be optimised for left- and right-handed users. There is enough space for handwritten notes. A key switch for enabling weaponry, hardware buttons for their haptically controlled use, and a switch for physically separate network assignment of the interaction devices are also important. Furthermore, there is space for personal items, written information, and personal protective equipment.

Fig. 1: Realisation of standard console with COTS hardware

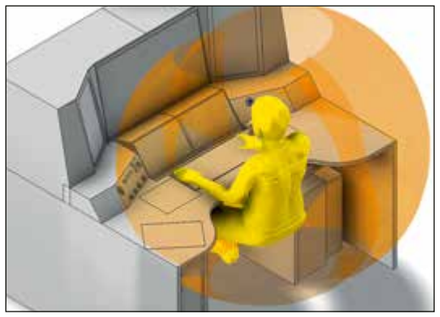

Fig. 2: Application of the RAMSIS digital human model in the design of the standard console, in this case for the design of the reach envelope for touch displays and hardware switches

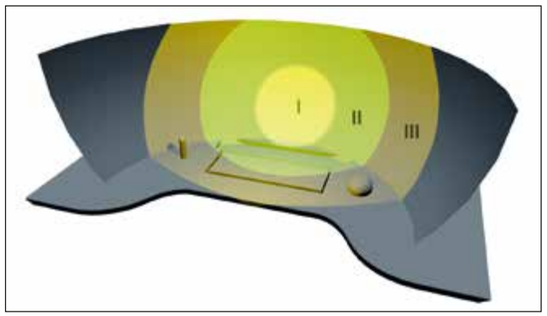

Fig. 3: Abstract concept for the arrangement of screens and information within the user’s field of vision

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Hybrid intelligence and development of a workbench for investigating concepts of complementary integration of human and artificial intelligence

The use of artificial intelligence (AI) can lead to performance enhancements when the capabilities of humans and AI are effectively combined. To explore hybrid intelligence (HI), i. e. the complementary integration of human and artificial intelligence, a HI workbench is being developed as an environment to investigate transparent and controllable AI functionality.

The use of artificial intelligence (AI) in military systems offers great potential, especially when the strengths of humans are combined with those of AI in a complementary fashion. While AI can primarily analyse large amounts of data in a short time, extract insights, and propose task-specific action options (specialised intelligence), humans are able to find creative solutions to make experience-based decisions even in unpredictable situations and with incomplete data (broad intelligence). Therefore, a research thrust at the Fraunhofer-Institut für Kommunikation, Informationsverarbeitung und Ergonomie (FKIE) focuses on how human and technical strengths can be complementarily combined to take quick (AI-supported) and appropriate (under human supervision) decisions. Human-centered AI is a paradigm that seeks to achieve compatibility of high human and high machine control in system design. However, this young paradigm is currently still a theoretical construct that needs to be practically implemented through further research.

Human supervision is necessary to ensure the alignment of AI with predefined mission objectives, to allow for overriding erroneous AI results, and to ensure compliance with ethical and legal frameworks. However, the capability-enhancing potential of AI should not be dampened by overly tight human control. The complementary integration of human and artificial intelligence, considering the respective relative strengths and weaknesses, is referred to as hybrid intelligence (HI). The foundation of HI is the view of humans and machines as separate but closely interacting, goal-oriented intelligent actors that contribute to the system goals cooperatively through their interaction (Fig. 1). This includes role- or context-based task sharing but can also involve assistance, suggestions, or corrective interventions in both directions. For example, an AI could temporarily take the initiative in critical situations, with controllability maintained through the parameterisation of the handover triggers. Based on fundamental requirements for hybrid intelligence, the relative capabilities of humans and machines are continuously evaluated and integrated into a hybrid overall entity through dynamic interaction design (Fig. 2).

To explore and design HI concepts, formation of an experimental development, simulation, and testing environment (HI workbench) is underway at the Fraunhofer FKIE, enabling agile development of HI functions. The focus is on designing and investigating methods of cooperative interaction with AI to create appropriate trust as well as transparency and controllability without stifling the potential of AI. The evaluation in the workbench requires three areas of expertise (Fig. 3): military domain expertise (e. g. on reconnaissance), technical AI expertise, and integrative HI expertise. The HI workbench is utilised not only to capture and optimise the performance of algorithms, but also to measure its impact on hybrid performance (human-AI system performance). This ensures that technically feasible AI functions lead to a higher intelligence of the overall system and thus a secure rollout and added value in field applications.

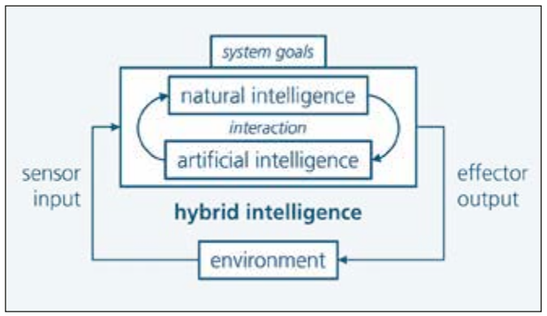

Fig. 1: Hybrid intelligence (HI) emerges from interaction between natural and artificial intelligence in the context of system goals and the environment

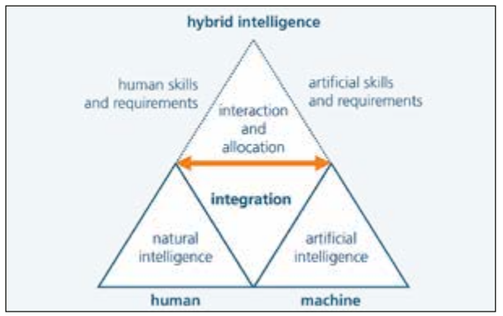

Fig. 2: The hybrid intelligence triad describes the HI design space as the integration of human and artificial properties in the context of the hybrid's behaviour

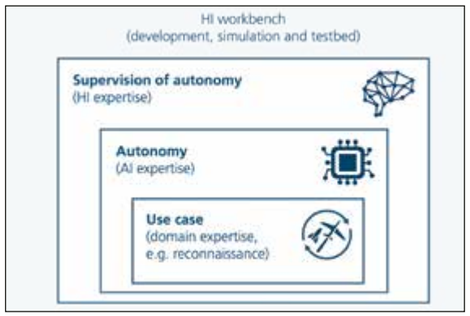

Fig. 3: Roles and nested expertise needed for the HI workbench, exemplified for military reconnaissance

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Success of a research-based computational model for infrastructure protection: Looking back on 25 years of using the RHT concrete model

Impact and explosion effects on reinforced concrete in critical and protective infrastructures became predictable in highly detailed, three-dimensional computer simulations by means of the material model developed at Fraunhofer EMI. Its availability in commercial engineering software led to a broad validation and innumerable national and worldwide applications.

The 1990s made three-dimensional computer simulations with Finite Element Methods (FEM) accessible to high-speed dynamic loading situations, such as automotive crash in the civilian domain as well as protection and effects predictions in the military domain. After years of development on mainframe computers of military large-scale computational centres, primarily in the US, they became commercially available on servers and even personal computers. This allowed numerical simulations of buildings, vehicles and effectors under impact and explosion loading. Soon, simple elastic-plastic models for metals proved to be insufficient. Constitutive models for composites, fabrics and construction materials, especially concrete, had to be improved or redeveloped.

At Fraunhofer EMI, a model for dynamic resistance behaviour of concrete was formulated under the acronym “RHT”, which is derived from its developers Riedel, Hiermaier and Thoma. It describes the complex triaxial, pressure- and strain-rate-dependent strength and failure behaviour of this highly heterogeneous material class. The pressure-density-energy dependency (or equation of state), relevant under strong shock loading from ballistic impact and explosion effects, was made easier to measure and was mathematically defined. Besides the in-house codes, the resulting RHT concrete model was also implemented in commercial FEM packages (Ansys Autodyn in 2000 and LS-DYNA in 2011).

Large-scale impact experiments at the Bundeswehr Technical Centre WTD 91 with 500 kg concrete-penetrating bombs of the type BETAB-500 allowed an initial validation. After that, the concrete model was applied at Fraunhofer EMI and Bundeswehr Technical Centre 52 (WTD 52) for numerous research and development applications in the domain of infrastructure protection. In the following two and a half decades, it came to be one of the standard models in the German community in applications, as for example:

- design of an aircraft shelter
- design of a building for ammunition handling
- protective design against mortar effects (Fig. 1)
- prediction of structural reactions in the large-scale SHIELD test series in Sweden
- prediction of structural reactions in the CUIRA experiments in collaboration with Switzerland
- computational analysis in the context of the Klotz Group collaboration to improve the engineering tool for ammunition-storage safety
- predictions of the effects from culvert mines (Fig. 2)

In addition to its use in the military domain, the model has also been and is still being used in several civilian applications, e. g. in nuclear safety (Fig. 3 and Fig. 4) against terroristic threats and aircraft impact protection of large-scale nuclear plants and facilities. It has also proven suitable for civil engineering applications such as pyrotechnically driven concrete anchoring devices and the explosive demolition of building structures.

Worldwide availability in commercial FEM packages has resulted in hundreds of publications referring to scientific and engineering applications of the model. In addition to some critical feedback, the international scientific community confirmed the broad applicability of the model for a wide range of high-speed loading situations (Fig. 5, left) on concrete and similar materials, such as masonry bricks and rock materials (Fig. 5, right).

The most recent developments now make it possible to analyse the disintegration of concrete structures, including debris sizes and launch conditions (Fig. 6, see also contribution Dr. Grunwald, EMI), for the numerical prediction of safety distances around ammunition storages and silos. So far, this type of application has required extremely costly and rare large-scale experiments.

In summary, 25 years ago the RHT model established an internationally recognised scientific basis on which to accurately predict the dynamic effects on and protection by concrete components and buildings.

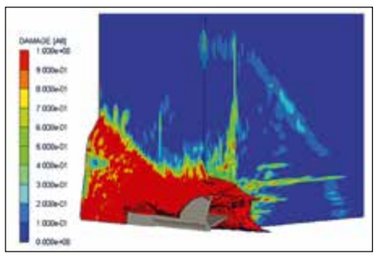

Fig. 1: Penetration of a mortar tail section into a reinforced concrete protective structure (source: WTD 52)

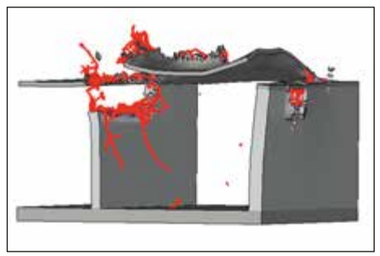

Fig. 2: Catastrophic failure of a culvert structure under a highway by explosion of an improvised device (source: WTD 52)

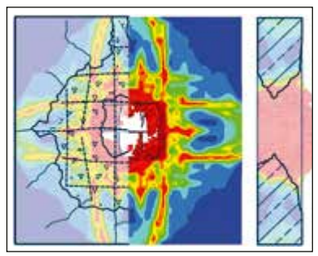

Fig. 3: Simulated breaching of a nuclear containment resulting from contact detonation compared to experimental fracture patterns (left half)

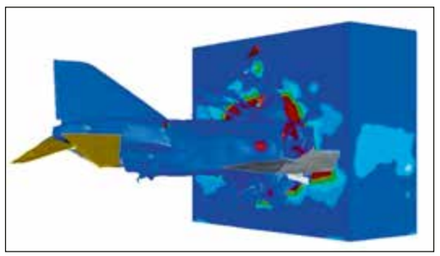

Fig. 4: Aircraft impact of a Phantom F4 on a nuclear-power-plant surrogate structure replicating a large-scale test by USA / Japan

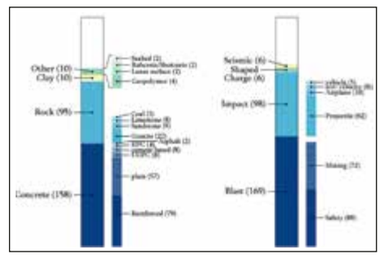

Fig. 5: Dynamic applications (left) and described materials (right), as published worldwide

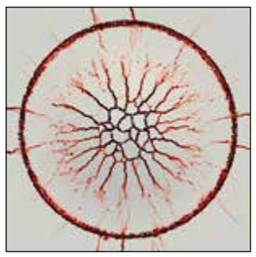

Fig. 6: Latest extension of the modelling approach to quantitatively predict natural formation and launch conditions of debris under shock loading (source: Dr. Grunwald)

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Ability to calculate hazard areas and damage zones due to debris throw in the event of blast loading of concrete structures

Using an efficient mesoscale description of concrete, it is now possible to calculate the damage of concrete under highly dynamic loading up to fracture – and thus up to debris projection. For the first time, the discrete debris pieces can be individually defined and their flight distances determined.

Concrete is one of the most commonly used building materials due to its versatility, durability and economic availability. The majority of large office and residential buildings as well as countless structures for industrial and military purposes are made of concrete. When concrete structures are subjected to highly dynamic loads, stress waves are generated in the material, leading to failure and fragmentation. The fragments ejected at high speed can become dangerous projectiles; in individual cases, a flight range of more than 1000 metres has been measured.

In many cases, concrete structures protect people and facilities, and if they fail, the debris poses a considerable hazard. Until now, related risk analyses have been based on statistical distributions of the debris mass and its launch conditions, which were determined from a few complex large-scale tests. To date, there has been no predictive numerical tool.

At the Fraunhofer EMI, a mesoscale description of concrete has been used in recent years to simulate not only the initial damage but also crack growth, complete fracture, and debris formation. The aggregate is explicitly modelled and embedded in a mortar matrix. By modelling the heterogeneity of the material, local stress states are resolved directly at the structural level.

For the first time, it is now possible to discretely evaluate the concrete debris that forms under highly dynamic loading and to compare it with experimental results (Fig. 1 and Fig. 2). Detailed analysis also makes it possible to determine the shape and aerodynamic factors of the debris, which leads to more accurate trajectory calculations. Overall, this represents a significant advance in the numerical description of the complex problem of debris formation and throw of concrete structures under high-dynamic loads.

This is most relevant for ammunition production or storage. Safety distances are often estimated too conservatively, which means that the available external space is not optimally utilised. With the new method, it is now possible to determine these distances much more accurately. While debris from ammunition storages is projected into the surrounding area, the reverse can also occur. If explosive charges detonate directly in front of the outside of a building, the resulting debris flying into the building can pose a considerable risk to people or equipment. The same applies to unintentional explosions: There are often casualties from flying debris following accidents involving explosive substances. It is now possible to determine much more accurately not only the risk of being hit but also the intensity of the hit.

Furthermore, the increasing threat of terrorist attacks using military weapons poses a danger to critical infrastructure. Could debris in complex industrial plants potentially hit and damage sensitive components? The method can also deliver more realistic results than before in forensic analyses, e. g. to determine the initial cause based on the damage pattern (Fig. 3).

The solution of the models on the mesoscale requires a high degree of computing effort and needs appropriate hardware. Due to limited resources, the method has so far been used prototypically. However, for the planned capacity expansions in ammunition storages, the method can – provided suitable hardware is available – be used to determine space-efficient hazard areas. In addition to this requirement, improved models for factoring in earth cover on ammunition storages as well as sustainable construction materials such as geopolymer concretes should also be considered in the future.

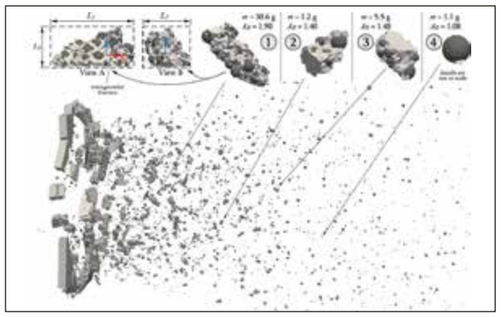

Fig. 1: Concrete slab under explosion load: The slab breaks and a cloud of smaller debris is ejected at speeds of up to 400 m/s. The individual pieces of debris can for the first time be discretely evaluated and analysed

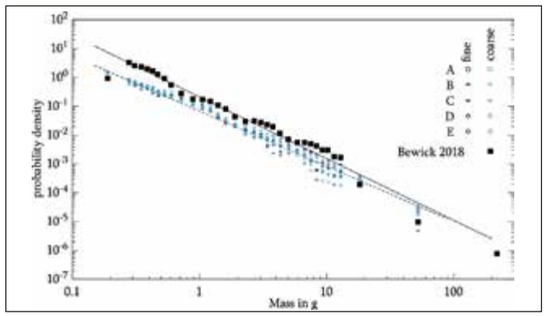

Fig. 2: Comparison of the mass distribution between experiment (black squares) and simulations

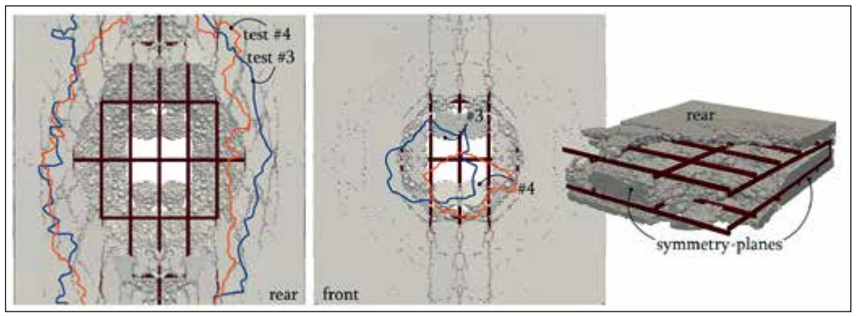

Fig. 3: The final damage pattern is very realistic and can be used for forensic analyses. The lines with the labels (test #3 or #4) mark the crater opening in the experiment

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Passive radar with satellite illumination for covert surveillance and reconnaissance in maritime scenarios

While passive radar exploiting terrestrial illuminators is now a mature technology with several commercial systems available on the market, the exploitation of satellite illuminators is still an open field of research. Satellites might enable passive radar operation in remote areas and at open sea from stealth platforms like submarines.

The last few decades have experienced a surge of importance of the space sector, and of commercial communication and broadcast services provided from space. This has drawn the attention of the passive radar community, aiming at investigating the capabilities of such signals as illuminators of opportunity. In fact, satellite signals constitute a valid source of illumination where no terrestrial infrastructure is available, and this is especially true in remote areas and at open sea.

Exploitation of satellite signals for passive radar purposes might offer several strategic advantages in military scenarios:

(i) a space-based transmitting infrastructure is generally more difficult for the enemy to tear down in a battlefield situation;
(ii) satellites, although exploited in a non-cooperative way, might also illuminate enemy territory;
(iii) a space-based passive radar designed to exploit a satellite signal available worldwide would be able to operate worldwide with perhaps only minor modifications. This is of critical importance in order to reduce development and mission planning costs;
(iv) maritime open-sea military scenarios are characterised by stealth platforms such as, for instance, submarines, for which the capability to operate silently is of highest importance.

A summary of possible satellite illuminators with their characteristics is reported in Fig. 1.

The exemplary operational scenario under consideration is outlined in Fig. 2. In this case, a submarine is considered as a typical military platform constrained to operate as silently as possible and for which the exploitation of passive radar technology might be of particular interest. The submarine is operating at open sea and it requires reconnaissance of another maritime target, whose presence might have been detected by other means. The target reconnaissance can be done for instance in terms of passive radar imaging via inverse synthetic aperture radar (ISAR) approaches. ISAR can provide extremely relevant information about a non-cooperative target by exploiting the relative rotational motion between the radar and the target.

In the last few decades, the Fraunhofer Institute for High-Frequency Physics and Radar Techniques (FHR) was active in the development of the SABBIA® system, a satellite-based passive radar for maritime targets imaging. During a first measurement campaign, which was conducted in 2018 along the river Rhine, near Bonn in Germany, the SABBIA® system was deployed in a stationary configuration, i.e. it was fixed to the ground. The resulting ISAR image of a ferry sailing along the river is shown in Fig. 3. During the recent PaRMeSTO NATO SET-320 Trial, conducted in September 2024, the experiment was repeated with the same ferry as a target and the SABBIA® system now mounted on a moving ship (see Fig. 4). This simplified setup emulates the operational scenario, where the passive radar is deployed from a stealth platform to enable a covert reconnaissance.

Passive radar imaging exploiting satellite illumination might significantly influence maritime operations in the next decades. Adding target imaging capability in a purely silent mode can bring significant strategic advantage and thus guarantee domain superiority.

	Orbit	Signal bandwidth	Signal power density at Earth surface [dBW/m²]	Continuous illumination	Detection range
GNSS (GPS, Galileo, Beidou, Glonass)	MEO	up to 15 MHz in L-Band	ca. -130	yes	limited
DVB-S / DirectTV (e.g. Astra)	GEO	up to 2 GHz in Ku-Band	ca. -108	yes	medium/limited
FSS (Starlink, OneWeb)	LEO	up to 250 MHz in Ku-Band	ca. -98	yes	medium
SAR Constellations (e.g. Capella, Iceye)	LEO	over 1 GHz in X-Band	ca. -50	no	big

Fig. 1: Overview of potential space illuminators for passive radar

Fig. 2: Considered scenario

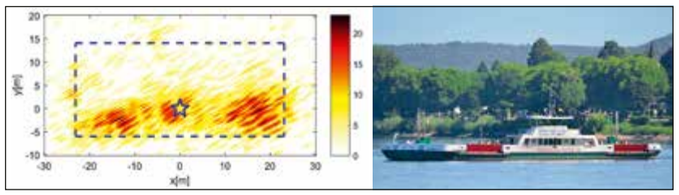

Fig. 3: Passive ISAR image (left, in dB scale) of a ferry (right) obtained with the SABBIA® system deployed in stationary configuration

Fig. 4: SABBIA® system mounted on a moving ship

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Broadband and robust front-end modules in the Ka-band

Broadband front-end modules in the Ka-band (26 – 40 GHz) enable wireless communication at high data rates over long distances and are key components for radars with high spatial resolution. High-electron-mobility transistors (HEMTs) in the gallium nitride (GaN) material system offer significant advantages in terms of resistance to electronic attacks and interference signals.

Indium gallium arsenide (InGaAs) and GaN-based compound semiconductors offer valuable advantages in the field of high-frequency technology compared to silicon-based semiconductors. For MMICs (Monolithic Microwave Integrated Circuit) realised with InGaAs processes, the very high operating frequencies up to over 1 THz and the very low noise figures are particularly noteworthy. As a result, these circuits can amplify signals that would be indistinguishable from noise with silicon-based technologies.

In addition to the low-noise amplifiers (LNA) used, a radio frequency (RF) switch and a high-power amplifier (HPA) are required to set up a communication link or radar system, which together are referred to as a front-end module (FEM) (Fig. 1).

The Fraunhofer-Institut für angewandte Festkörperphysik IAF has developed communication and radar systems with extremely high sensitivity and resolution using FEMs made of InGaAs semiconductors. Because of the advantages mentioned, InGaAs MMICs are successfully used for applications that place very high demands on performance.

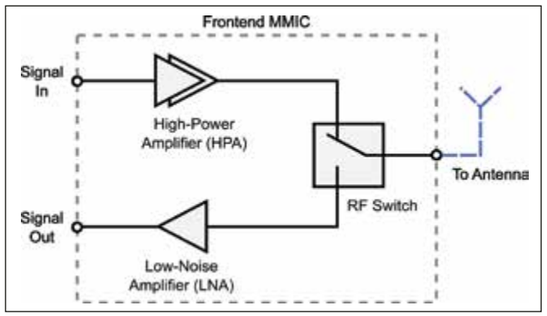

Fig. 1: Architecture of a frontend module (FEM) including a low-noise amplifier, high-power amplifier and an RF switch

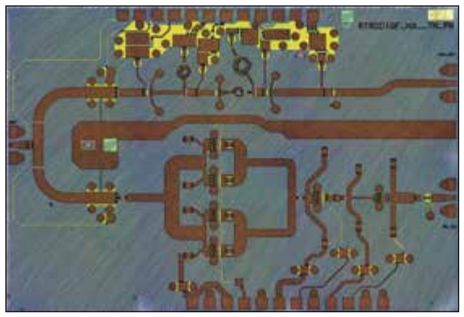

Fig. 2: Chip photo of the Ka-band FEM, processed with the GaN15 process of Fraunhofer IAF. The chip has the dimensions 4 x 2.75 mm²

In connection with LNAs and FEMs, Fraunhofer IAF has recently examined GaN-based semiconductors. Due to its larger band gap compared to InGaAs, GaN enables higher operating voltages with significantly improved robustness against high-power signals. The noise figures achieved with GaN are slightly higher than those of InGaAs, but the better robustness of GaN circuits means that there is no need for a protective circuit before the LNA, which improves the noise behaviour of the overall system.

As part of ongoing research, Fraunhofer IAF has designed, manufactured and metrologically characterised one of the world's first Ka-band FEMs in GaN technology. A photo of the 4 x 2.75 mm² chip can be seen in Fig. 2. The institute's own GaN15 process was used for processing. It has a gate length of 150 nm, an operating voltage of up to 30 V, and a proven long lifetime.

In the operating frequency range between 31 and 40 GHz, the FEM MMIC achieves a linear gain of up to 22 dB in transmit mode and an HPA output power of up to 34.9 dBm (3.1 W). The LNA achieves an even wider bandwidth, with a noise figure of less than 3.5 dB between 26.5 and 40 GHz (Fig. 3). This is the largest demonstrated bandwidth of an LNA in a GaN FEM to date and by far the lowest noise figure achieved with a high robustness process.

In this context, extensive experiments have been conducted to investigate the robustness of GaN MMICs. The input (i. e. the gate) of several test circuits was exposed to high continuous wave RF power levels of up to 35 dBm (3.2 W) – a situation that can also occur with strong electromagnetic signals such as in terrestrial transmission systems (Fig. 4). The detailed metrological characterisation before and after exposure shows that no impairment of the circuits can be observed with regard to noise figure and small signal amplification.

In summary, we can say that a GaN FEM technology has been developed for the Ka-band that surpasses the previous state of the art. This lays the foundation for future applications that require both high performance and high robustness. Especially in environments where high signal levels are expected due to crosstalk or jamming, the robust FEMs have major advantages.

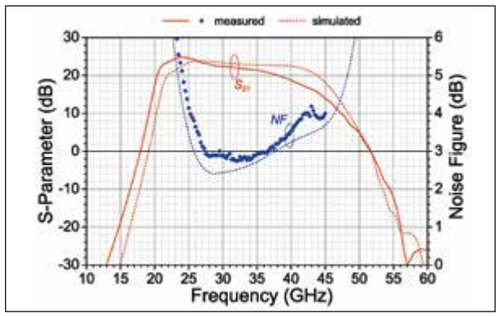

Fig. 3: Measured gain (red, left) and noise figure (blue, right) versus frequency for the realised FEM in the receive path

Fig. 4: Terrestrial transmission system (*TÜtrSys*) for long ranges (source: Bundeswehr / Martina Pump)

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Performance enhancement of gun systems through simulation-based optimisation of loading density

To predict the performance of a propulsion concept, it is necessary to determine the bulk density of the ammunition. Bulk density is currently estimated on the basis of empirical values or determined for each individual geometry by means of experiments. In any case, for each propulsion design the achievable bulk density is only validated under real system conditions at the end of the design process.

Experimental determination of bulk density is carried out in accordance with the technical specification TL 1376-0600T500. To achieve this, a large amount of solid propellant must be produced, which is particularly time-consuming and costly for new solid propellant formulations and geometries. Furthermore, bulk density is determined in a static standard vessel, which means that the influence of loading space components, e. g. solid propellant charge igniters or penetrators protruding into the powder bed, is neglected and the real ammunition loading process, e. g. with jolting or turning, is not modelled. As a result, the bulk density determined experimentally under laboratory conditions does not correspond to the achievable bulk density in the real system.

Furthermore, new manufacturing methods such as 3D printing offer promising options in the context of geometric degrees of freedom in solid propellant design. With simulative bulk density optimisation, these degrees of freedom can be fully investigated in solid propellant development in a way that makes efficient use of resources.

For this reason, a simulative methodology for predicting the bulk density of solid propellant was developed at the Fraunhofer ICT. The simulation is based on the discrete element method (DEM), in which the behaviour of granular materials is considered as a set of individual particles or solid propellant grains. This includes the effect of external forces on the grains and their interactions with each other. Furthermore, interactions with the loading chamber and its components, such as the solid propellant charge igniter or penetrator, can be considered. The geometric shapes of the solid propellant grains and the components can be freely selected. In addition, aspects of the filling process, such as the shaking or turning of an ammunition casing, are evaluated. This makes it possible to simulate both conventional extrudable solid propellant geometries as well as those produced using 3D printing (Fig. 1), and to optimise them for the planned application.

The methodology was implemented in a software solution and enables the variable definition of process parameters such as the mass flow during filling and the mechanical properties of the solid propellant and the loading space. The solid propellant grains are then randomly filled into the loading space and counted (Fig. 2). By simulating the filling process multiple times with randomised initial conditions, a statistical distribution function of the bulk density can be calculated (Fig. 3).

In an example study for performance optimisation, the cutting angle of a conventional seven-fold perforated cylindrical solid propellant grain with an aspect ratio of 1.5 was optimised. For this purpose, simulations were carried out with four different cutting angles between 45 degrees and 90 degrees. The results show that the optimal cutting angle in the selected parameter space is approximately 60 degrees. In this case, a 1 % increase in loading density can be achieved compared to a straight cut edge (90 degrees) (Fig. 4).

Since the method can be used for any geometry and process parameters, it offers potential in terms of increasing the performance of existing barrelled weapon propulsion systems and developing future systems using new and established manufacturing processes.

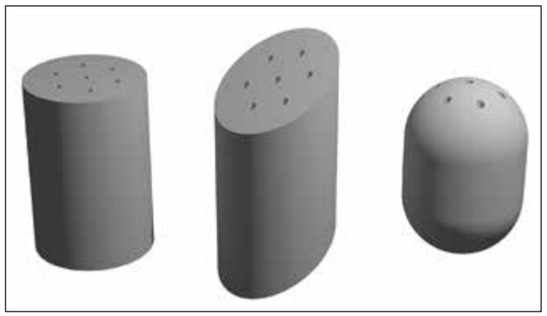

Fig. 1: CAD model of a conventionally manufactured cylindrical solid propellant with varying cutting angle (left, centre) and a solid propellant that cannot be manufactured conventionally (right)

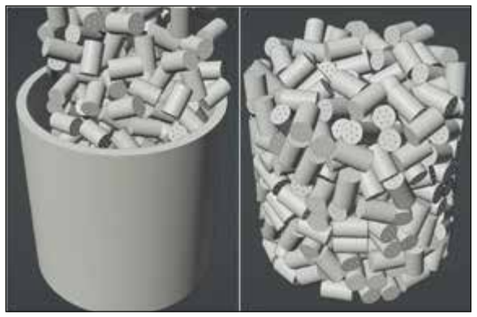

Fig. 2: Filling process of a generic loading space (left) and resulting powder bed (right)

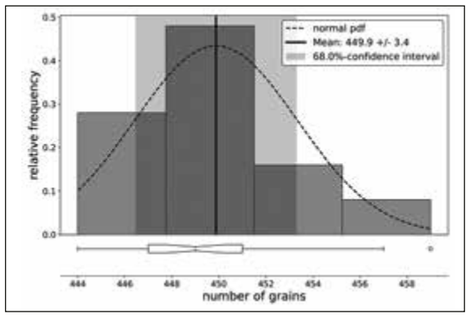

Fig. 3: Statistical evaluation of 25 bulk density simulations using a cylindrical solid propellant

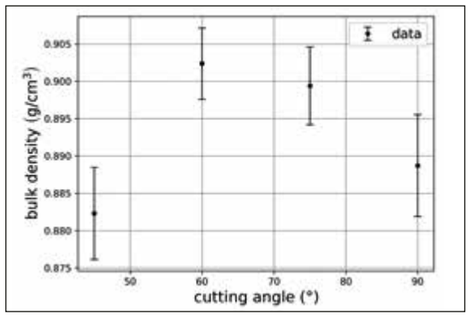

Fig. 4: Resulting average bulk density of a cylindrical solid propellant powder with varying cutting angle

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Plastic-bonded gun propellants – trends and developments

Plastic-bonded gun propellants (GP) are based on (energetic) polymer binders. They offer a variety of beneficial properties that are essential for achieving the high requirements of modern GPs. In current research, high-performance formulations have been developed that contain new plasticisers for adjusting the required mechanical properties and processing behaviour.

Nowadays, requirements placed on modern gun propellants (GP) are high and diverse. In addition to high performance, gun propellants require a high level of reliability as regards supply and availability and secure long-term storage and handling in various climatic environments in combination with low sensitivity against external stimuli. Furthermore, an increasing amount of attention is being given to environmental and health aspects.

Plastic-bonded gun propellants offer various possibilities to achieve this complex profile of requirements. They are based on polymeric binders and are usually composed of their combination with plasticisers and energetic filler materials. This composition distinguishes them from conventional gun propellants, which contain nitrocellulose as the binder material (monobasic) or additional explosive oils (dibasic) and, where applicable, energetic fillers (tribasic).

Application of polymeric binders facilitate many positive properties for the development of high-performance gun propellants. Synthetic binders are characterised by high thermal and chemical stability, low sensitivity, as well as a high degree of independence from their feedstock supply. In particular, their generally good compatibility with other materials in combination with the ability to carry high fractions of energetic fillers means that they can be used to develop new high-performance GP formulations (Fig. 1).

The research carried out at the Fraunhofer Institute for Chemical Technology (ICT) covers the entire spectrum of the development and design of plastic-bonded gun propellants, from raw materials to prototypes. In particular, new polymeric binders, plasticisers and energetic fillers are being investigated. For processing and shaping, there are conventional processes such as kneading systems and extrusion presses as well as innovative centrifugal and acoustic mixing techniques. The processing capabilities range from laboratory to technical scale (Fig. 2). Produced GPs are defined in detail regarding their basic properties as well as burning behaviour, achievable performance and erosivity.

In current research, new plastic-bonded GP formulations based on energetic binder materials are being developed. An especially challenging task is the adjustment of mechanical properties along the entire temperature band ranging from – 40 °C up to + 50 °C while maintaining good formulation processing properties. This is essential to avoid embrittling and softening under extreme temperatures, as this would cause loss of performance and pose safety risks. Generally, these issues can be overcome by applying suitable plasticisers. Nitrate-based plasticisers and azido plasticisers have been investigated and are especially suitable in plastic-bonded formulations due to their good material compatibility. The investigated energetic plasticisers contribute significantly to achieving the required GP mechanical properties and also enable good processing behaviour of the formulation for high geometric fidelity and quality (Fig. 3 and Fig. 4). Furthermore, the formulations achieve a high performance with comparably moderate burning temperatures and low erosivity, good long-term stability, and low sensitivity.

Future research in the field of plastic-bonded gun propellants will focus on further optimisation and performance increase of the formulations by using new energetic materials. Furthermore, formulations should be adapted for different calibres by adjusting their compositions.

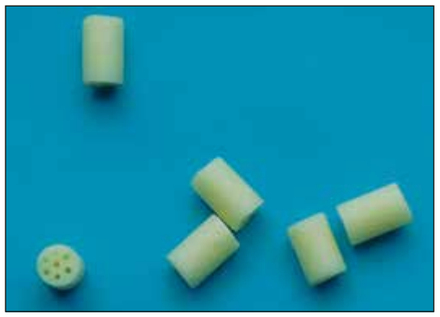

Fig. 1: Plastic-bonded gun propellants in cylindrical geometry with seven perforations for the evaluation of new materials and formulations with new and modern nitrate-based and azido plasticisers

Fig. 2: Press extrusion at Fraunhofer ICT enabling the processing of small batch sizes for gun propellant development and characterisation as well as the supply of extensive campaigns for performance evaluation

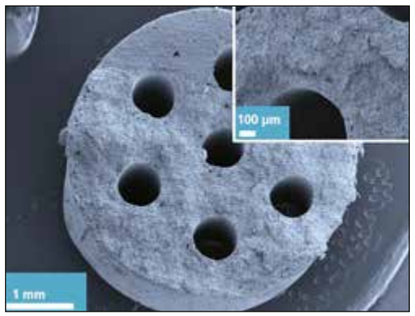

Fig. 3: Scanning electron microscope images of a plastic-bonded gun propellant in different magnifications. Artificially produced cross section of a grain which shows the good production indicated by a nearly defect-free matrix and a homogeneous distribution of the components

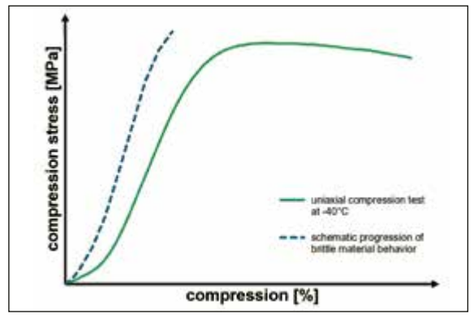

Fig. 4: Stress-compression curve of the uniaxial compression test of a plastic-bonded gun propellant with modern plasticiser at an extreme temperature of – 40 °C. The GP shows a high maximum compression stress but no brittle material behaviour (progression of brittle behaviour is schematically shown in the diagram)

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Preparatory work for certifying new sensors for the German observation platform A319 OH

The Bundeswehr Verification Centre receives scientific and technical support from the German Aerospace Centre for its work on the Open Skies Treaty. The work centres on developing methods for verifying the properties of imaging sensors, particularly in the thermal infrared spectral range.

The 1992 Treaty on Open Skies allows its 32 member states to observe each other's territories from the air in full, at any time, and at short notice. To make this possible, the treaty text provides for various types of sensors: Optical cameras in the visible and near-infrared spectrum, thermal infrared cameras, and imaging radars. These sensors were selected to enable airborne observation at all times of day and in all weathers.

So far, only the procedures and rules for taking images in the visible and near-infrared part of the spectrum have been defined. New camera systems from the member states Romania and Germany were certified according to these specifications in 2022 and have been in use since then. However, these sensors only allow images to be taken in daylight and under suitable weather conditions.

Sensors for thermal infrared have already been installed in the German observation platform Airbus A319 OH (Fig. 1). To ensure that these sensors can also be used in future for work under the Open Skies Treaty, the basic principles for their operation must be developed within the Informal Working Group on Sensors (IWGS) and then approved by the Open Skies Consultative Commission (OSCC). The German Aerospace Centre (DLR) is supporting the German Armed Forces in this fundamental work.

In 2024, a draft decision was developed together with representatives of other treaty state parties. This document describes procedures to check and ensure compliance with the treaty limits for thermal infrared images. For the creation of this draft, the cooperation of scientific experts and experienced military personnel was essential (Fig. 2).

Work was also carried out to simplify existing procedures. Due to the long lifespan of the treaty and antagonisms between some treaty state parties in the past, a complex set of rules with sometimes overly complicated regulations has evolved. In addition, developments in sensor technology offer the possibility of simplifying certain verification procedures.

While the resolution of a certain combination of lens and film material could only be determined empirically for cameras using chemical film, current digital sensor technology with its discrete spatial sampling makes it possible to calculate a limit for the resolution of a digital sensor system. However, different geometric parameters of the recording configuration must be known or measured. For this purpose, imaging geometry for several sensors has been calculated and modelled at the DLR Institute of Optical Sensor Systems (Fig. 3).

From a scientific or technological point of view, there are no obstacles to the certification of the thermal infrared sensor technology built into the German observation platform A319 OH if the new regulations are approved by all treaty states. A considerable reduction in the effort and time involved in certifying sensors can be implemented in the short term. With the necessary political support, a significant modernisation of the Treaty on Open Skies could be achieved as early as 2025.

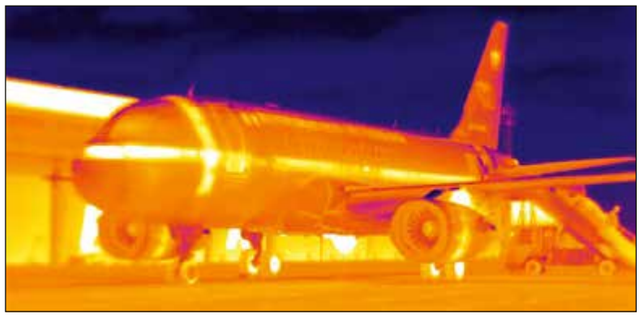

Fig. 1: Thermal infrared image of the Airbus A319 OH during a campaign to obtain test data (source: Bundeswehr / Michael Donaubauer)

Fig. 2: Working meeting of sensor experts from several state parties to develop new procedures for the Treaty on Open Skies (source: Bundeswehr / Anika Bückendorf)

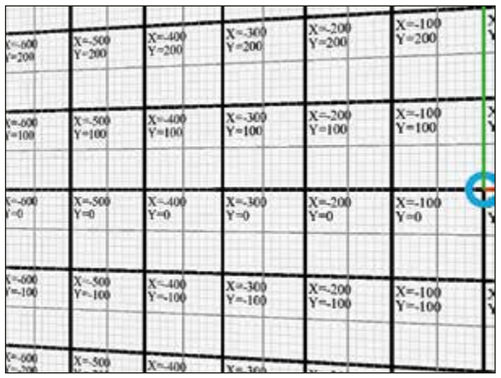

Fig. 3: Projection of the sensor pixel grid of one of the two thermal cameras of the A319 OH onto a virtual image plane (source: DLR / Dirk Frommholz)

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Risk analysis for the use of laser weapon systems – numerical and experimental work at DLR

The assessment of the risk from laser radiation reflected and scattered at the target is essential for compliant use of high-energy laser weapon systems. With the combination of experimental investigations in the laboratory and on a laser test range and the development of numerical models for exposure probabilities, important tools are being created for this purpose.

High energy lasers (HEL) are regarded as versatile weapons for a broad range of threats. In several countries, including Germany, research and development has reached a significant technology readiness level, including first HEL weapon system demonstrators. Risk assessments are required for the future deployment of such systems in accordance with legal regulations and international humanitarian law. The reflection and scattering of HEL radiation at the target can create specific risks for third parties and own and allied forces. Data on the reflection and scattering properties of laser radiation at the target – including the change of these properties during engagement – as well as models to calculate the probability of exposure to hazardous levels of radiation in specific scenarios are essential for a reliable risk assessment.

A specific lab infrastructure was developed during the last decade to generate the necessary data. In our HEL interaction laboratory (Fig. 1), we irradiate targets while recording the evolution of reflected laser power with a fast power sensor and at the same time capturing the spatial distribution of scattered laser light using a combination of a scattering screen and high-speed cameras. As an example, Fig. 2 shows the light distribution on the screen during laser interaction using a PMMA target. We also characterise laser effects on targets, e. g. temperature increase and penetration time.

Current research indicates that the pronounced and rapidly varying spatial structures (hot spots) of the scattered radiation observed in many target materials are confined to a near-field zone around the target. At larger distances, the influence of hot spots is supposed to decrease significantly. To investigate this effect, HEL interaction experiments have been conducted on the 130 m long laser test range at the Lampoldshausen DLR site (Fig. 3).

In particular, special laser sensors with high sensitivity were developed to measure scattered laser radiation at large distances from the target. Recently, novel tests using a scattering screen set at a medium distance of 20 m on the test range have been started.

In parallel to the experimental work, numerical models were developed to calculate hazard areas where dangerous levels of scattered and reflected radiation are reached. Since neither the exact position, movement and orientation of the target nor the exact point of impact of the laser beam on the target can be predicted for a specific operational scenario, statistical considerations are required. Based on the computation across numerous target trajectories and impact points (“realisations”), the probability of exposure to hazardous levels of radiation can be analysed.

To allow such large number of “realisations” to be computed, the numerical models need to be resource-efficient. This is primarily achieved by post-processing the experimental data (data reduction). The loss of complexity of the input data is mitigated by the averaging behaviour of the statistical methodology. Additionally, a fast identification of “relevant areas” for more detailed calculations is implemented (Fig. 4 and Fig. 5).

First results show that for elevated (i. e. flying) targets with realistic surface curvature and realistic surface properties, the “hazard areas” on the ground can be quite small and can even vanish once the target is at a sufficient height. Accordingly, the exposure probabilities are also quite small. To support this first assessment, additional experimental data need to be captured and a larger number of operational scenarios need to be analysed. This dual approach, based on experiments and simulations, are likely to create sufficient evidence to foster acceptance of and trust in the risk analysis methodology across all stakeholders.

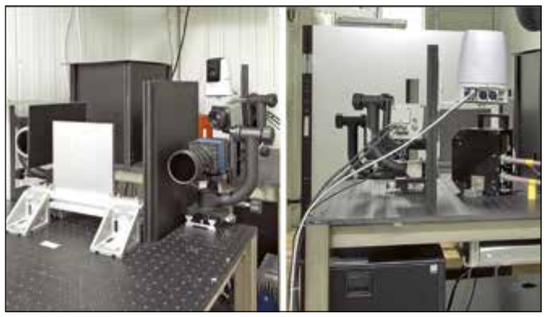

Fig. 1: HEL interaction laboratory, left: target zone with sensors and cameras; right: rear view, scattering screen in the background (distance screen to target zone 1 m)

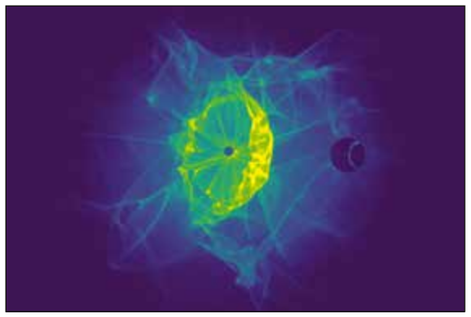

Fig. 2: False colour plot of the recorded intensity on the screen – PMMA after 500 ms laser irradiation

Fig. 3: One of the sensors being tested on the laser test range (adjusting position with green laser)

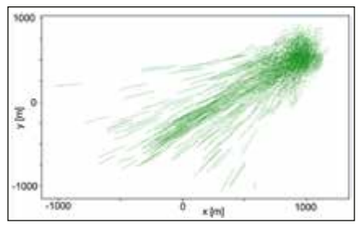

Fig. 4: Hazard and risk analysis model – distribution of identified “relevant areas” for 2000 “realisations” of a specific scenario

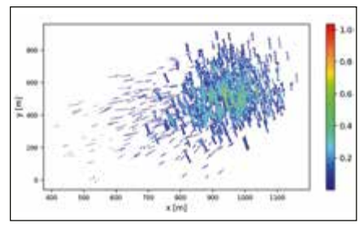

Fig. 5: Hazard and risk analysis model – local probability for exposure to hazardous intensity levels for 2000 “realisations” of a specific scenario, colour-coded by probability in percent

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Mobile hydrogen peroxide storage and fuelling system for the worldwide supply of rocket systems

The importance of hydrogen peroxide as a propellant in space transportation has recently grown. In order to enable a safe and reliable supply of rocket systems even at small launch sites, DLR's RSC³ has developed the mobile, rapidly deployable transport, storage and supply system "MoHyPer".

The last few years have seen a continuous increase in the demand for more cost-effective access to space. As a result, many new launch sites for space transportation systems are being planned and built around the world. Launches to polar orbits, which are often served by micro-launchers, require launch sites at higher latitude degrees, a fact that has significantly expanded the range of possible locations. However, the increase in launch activity has also raised concerns about the potential environmental impact of space transportation, leading to intensified research into environmentally friendly propellants.

Highly concentrated hydrogen peroxide (high-test peroxide: HTP) is an environmentally friendly propellant alternative for use in rocket upper stages and orbital applications. It is catalytically decomposable with only water vapour and oxygen as reaction products. In addition, it is neither toxic nor carcinogenic and is liquid at room temperature, making it much easier to handle and cheaper than commonly used (cryogenic) propellants. Its use, for example in hybrid rocket engines, enables inherent re-ignition capability and good thrust throttling over a wide range of applications. In addition, the use of HTP in attitude control and satellite engines, especially as a substitute for the carcinogenic hydrazine, is currently receiving more attention in scientific research and with commercial suppliers due to increasingly stringent environmental requirements. Nevertheless, most of the current launch sites do not have a reliable and safe infrastructure to carry out launches requiring HTP.

The "Mobile Hydrogen Peroxide Transport and Storage Container" (MoHyPer), which was developed by DLR's "Responsive Space Cluster Competence Centre" (RSC³), aims to close this gap (Fig. 1). The system, which is integrated into a standard 20-foot high cube container, is used for the safe transport and storage of HTP and also offers the option of safe refuelling and, if required, pressurisation of rocket stages and payloads. The equipment includes heating and cooling systems, overpressure protection, safety and emergency equipment, as well as a monitoring system. The MoHyPer is thermally insulated and can be fully remote-controlled.

The HTP itself is stored and transported in five tanks, each with a capacity of 220 litres and patented by EVONIK. The MoHyPer is certified for land, sea and rail transport.

It combines the following capabilities:

- Transport and storage of up to 1100 litres of HTP (air-conditioned and remotely monitored)
- Ultra-pure water supply with an integrated treatment system (Fig. 2)
- Remote-controlled oxidiser refuelling via integrated pump and pipework system
- Remote-controlled high-pressure supply for pressurised systems with inert gases up to 1000 bar
- Provision of necessary safety equipment (e. g. emergency shower, emergency barrel flooding).

For this purpose, the interior of the container is divided into two rooms to ensure the necessary conditions for stable storage and safe handling of the HTP (storage room) and to accommodate the necessary technical equipment (engineering room, Fig. 3). Only an external supply of electricity, water of any quality, and the necessary pressurised gases are required at the operating site. By combining these different capabilities, the MoHyPer enables reliable, responsive, flexible and safe operation of hydrogen peroxide powered rocket stages and payloads at any launch site in the world.

Fig. 1: The Mobile Hydrogen Peroxide Transport and Storage Container „MoHyPer"

Fig. 2: MoHyPer integrated ultra-pure water system

Fig. 3: MoHyPer engineering room

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Concept design for software-defined aircraft with Integrated Serverless Avionics (ISLA): DLR's approach for the next generation of Integrated Modular Avionics

The future of avionics requires systems that can react dynamically to errors and adapt accordingly. This is enabled by a shift to the so-called serverless paradigm, in which applications are developed independently of the hardware. The result: Easier runtime migration and reuse as well as reduced effort for airworthiness approval of applications.

Research into increasing resilience through runtime adaptation of Integrated Modular Avionics (IMA) is entering its second round with D-RESILIENZ. As before, the objective is to make on-board software in avionics more resilient. Historically, the focus was primarily on the development process, i. e. software was developed to be as robust and safe as possible (while considering economic constraints) and then delivered after extensive testing. However, with the rapidly growing amount of software found in modern IMA systems, this approach is reaching its limits: Even under the strictest quality management (Fig. 1, Task 2), statistically speaking, some errors remain undetected. Since today's avionics systems contain millions of lines of software, more and more errors are finding their way into aircraft.

In addition, a further increase in development effort threatens to bring software development in avionics to a complete standstill. This is why we are pursuing a complementary approach in D-RESILIENZ: runtime error adaptation. This means that errors are detected at runtime, e.g. through intelligent monitoring. The detected errors are then treated, mitigated or isolated using targeted mitigation strategies. In short: although a great deal of effort continues to be invested in error prevention during the development process, the software is better equipped to deal with the occurrence of errors during operation.

Traditional avionics software is very rigid, an example being the fixed allocation of applications to a computer. This simplifies the design (Fig. 1, Task 1), since the possible scope of interactions between different applications is restricted. At the same time, however, this also limits the degrees of freedom for runtime error adaptation. The conflict: a rigid system is easier to design and secure while a dynamic system has many more degrees of freedom to deal with errors at runtime.

In D-RESILIENZ, we attack this false dichotomy with the serverless paradigm. Serverless does not mean that no servers (or computers) are used but that it largely does not matter where the software components are located or how many of them there are. It is precisely this decoupling that makes serverless architectures very scalable and exceptionally robust. As long as there is still a sufficient number of computers running, the platform will find a solution to execute the software. It is precisely this property that we utilise in D-RESILIENZ to enable more robust, error-tolerant operation – not despite but through the dynamic allocation of software to computers.

Another advantage of decoupling software and hardware is that porting becomes much easier. In a conventional IMA system, applications are compiled specifically for the target hardware on which they are executed (Fig. 2). Although this enables execution on systems with similar hardware, it requires recompilation and thus recertification for a different hardware architecture. With our serverless platform, on the other hand (Fig. 3), we have the option of executing applications independently of the underlying hardware (strengthening of Fig. 1 Task 6). This saves costs for the development of new aircraft and greatly simplifies the porting as well as reuse of existing software.

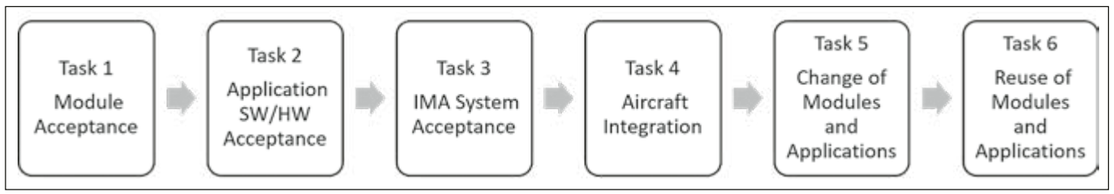

Fig. 1: Life cycle and certification of modules/applications in Integrated Modular Avionics (IMA

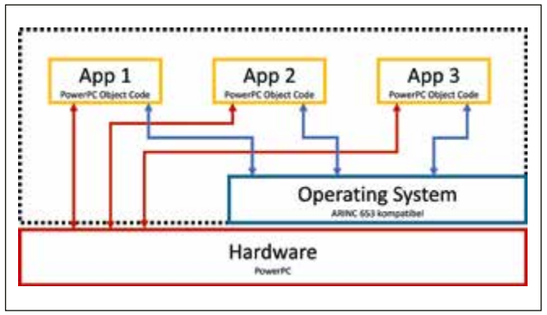

Fig. 2: Exemplary IMA system with three applications that are closely linked to the operating system and the underlying hardware

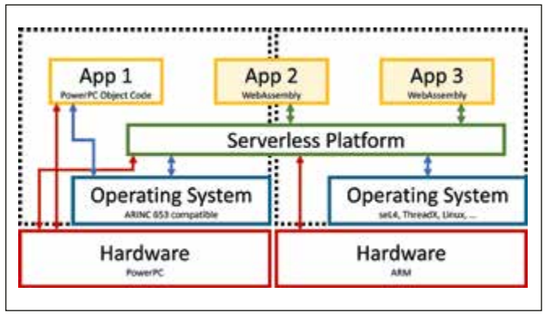

Fig. 3: Exemplary serverless system with a serverless platform as an abstraction layer between applications and operating system

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Improvement of systems for microwave remote sensing with quantum sensor technology

At the DLR Institute for Quantum Technologies, application-oriented research is carried out in cooperation with the DLR Microwaves and Radar Institute. Our goal is to translate quantum mechanical effects and predictions into specific components and systems for microwave remote sensing. Of primary interest are high-precision clocks and time and frequency standards, along with innovative receiver technology.

Quantum technology promises future technological performance improvements in many areas. Quantum radar, for example, is a frequently discussed topic in microwave remote sensing. However, in its BMBF project QUARATE, the Microwaves and Radar Institute was able to show that quantum radar will only be of very limited use in the foreseeable future (Fig. 1).

Fundamental quantum mechanical conditions, the still necessary cryogenic environment, and the achievable quality of the circuits still prohibit practical application for modern radars. Nevertheless, it seems possible in the foreseeable future to develop a) clocks or time and frequency standards with unprecedented accuracy based on quantum technologies. In addition, b) new application scenarios could also be possible in the field of microwave receivers using Rydberg sensors.

Application a) is required, for example, when modern radars use a large number of transmitters and receivers that are spatially separated from each other. Application b) would be of great interest for purely passive imaging surveillance and

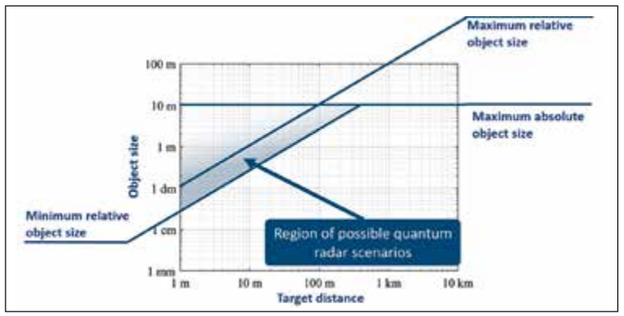

Fig. 1: Limitation of possible application scenarios for a quantum radar. Even in these, only an improvement in the signal-to-noise ratio by a factor of <2 is possible

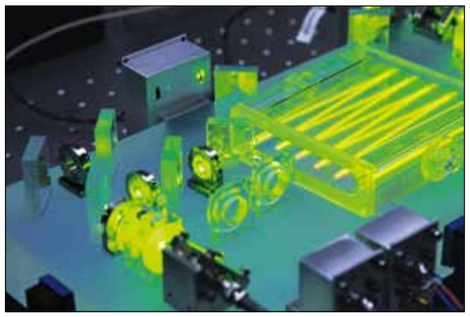

Fig. 2: Photograph of an optical frequency standard

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reconnaissance sensors in the microwave regime (radiometer systems), as this could drastically reduce technical complexity.

The DLR Institute for Quantum Technologies has developed a quantum frequency standard that is one of the world's best optical clocks based on vapour cells. With new ideas for motion-insensitive spectroscopy of iodine molecules, the team has laid the foundations for maximum precision for use on moving platforms. The frequency stability achieved in the laboratory surpasses the best commercial atomic clocks in the relevant range by two orders of magnitude and thus promises a breakthrough in the accurate phase synchronisation of spatially widely distributed remote sensing systems. These quantum clocks could provide decisive advantages for the realisation of such a system, or even make them possible in the first place. In addition, an improved phase noise compared to typical radar oscillators was demonstrated. This opens up prospects for an increased signal-to-noise ratio in the detection and identification of objects as well as for high-quality imaging using conventional radar technology (not quantum radar).

Furthermore, experiments are currently being set up for research into new types of sensors based on so-called Rydberg atoms. In certain cases, this technology, which is also quantum-based, promises increased sensitivity compared to classical principles. It also opens the possibility of determining absolute values with the highest accuracy. In purely passive microwave-based measuring systems such as imaging radiometers or so-called passive radars, these advantages could not only increase sensitivity but also reduce circuitry complexity. In contrast to radar, purely passive systems cannot be localised due to the lack of self-emission.

After more than a hundred years of existence, quantum mechanics is now undergoing a major transition from pure theory to concrete application. Microwave-based remote sensing systems for detection, reconnaissance and surveillance could be a broad field of application, for which their potential in the defence context should be further explored in the coming years.

Fig. 3: Example of radiometric imaging in the 80-100 GHz frequency range using conventional scanner and receiver technology (left). Rydberg sensors could be used here to significantly increase performance. Radiometric images are similar to optical images in terms of interpretability (right) and are also possible in poor visibility conditions

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Synergy of proven technologies and future-oriented concepts for advanced space situational awareness

In the future, space situational awareness will become an essential task for the security of Germany and Europe. New and much more powerful technologies will become necessary. To this end, DLR conducts exclusive radar research to provide future solutions using innovative methods. This involves combining tried and tested technologies and novel technologies.

The utilisation of outer space, especially in the low earth orbit of up to 2,000 km zenith distance to the earth's surface, has almost grown exponentially in the last decade, a tendency that continues to increase. This circumstance requires considerably extended and improved capabilities in space situational awareness (SSA), in both the spatial as well as the temporal dimension. Imaging radar technology provides an essential basic module for this. To ensure a high level of imaging quality, a few quite powerful individual systems have existed for several decades around the world using very large antennas with a diameter of approximately 30 – 40 m.

Even today – as will also be the case in the remote future in particular – SSA requires a quantum leap as regards its capabilities. The reasons are manifold. Firstly there is the enormous growth of space objects –actively operated systems such as satellites as well as space debris measuring a few millimetres, e. g. residues of explosions, or several meters as with burnt-out rocket stages or satellites that are no longer in use. Furthermore, the fact that nowadays almost every nation has available space technologies and, in many cases, launch capabilities is a formative driving force. Finally, the new geo-political situation will create new and massive threat potentials.

DLR performs research on concepts for novel high-performance radar-based SSA capabilities and, during the last decade, has configured and operated the imaging X-band radar system IoSiS (Imaging of Satellites in Space) around 10 GHz for experimental purposes (Fig. 1). With a spatial resolution of currently up to 5 cm, a world-wide peak value has been achieved on that score according to known literature (Fig. 2). With the help of such images, functional aspects as well as the tiniest of changes in a space object can be detected. The two-dimensional radar image in Fig. 2 shows a horizontally continuing signature in the upper part of the zoom, something that is not present in the photography from the year 2000. Without any knowledge about the structure of the ISS, it would not be possible to derive any three-dimensional (3D) structure as it really exists. This is why, amongst other things, the IoSiS-Fu (Future) concept was developed (Fig. 3).

Using this novel technology, revolutionary innovations in radar-based SSA with exclusive advantages over the large antenna solutions are possible: 3D and multi-static signature recordings within a short time for providing images at an ultra-high resolution of up to 2 cm, small design size of single subsystems offering the capability for continuous modernisation and performance increase, difficulty to interfere or even to destroy the system, dynamic (even mobile) scaling depending on demand. The thus generated information content opens up a new dimension in ground-based radar SSA. In this connection, investigations on space-based radar SSA must also be considered. However, more detailed analysis shows that this concept in space-based implementation will require very expensive technology and a challenging operational management. Depending on the desired operational distance of the single systems, a multitude of satellites approximately the size of a washing machine will be necessary to provide effective performance when accessing objects of interest.

For high-quality long-range radars, sufficiently high transmit power is essential. Efforts to achieve transmit powers in the two- or three-digit kilowatt range using modern semiconductor technology prove very difficult and unfavourable, especially at higher frequencies. Hence, new developments based on approved tube amplifier technology are the right choice. Research and development for IoSiS-Fu are a challenge, but this challenge can be met. At the moment, there is a new basis antenna system in its planning phase.

Fig. 1: IoSiS radar system at DLR facilities in Weilheim, Upper Bavaria. The medium-sized antenna is used for transmitting, the two laterally arranged small antennas for receiving

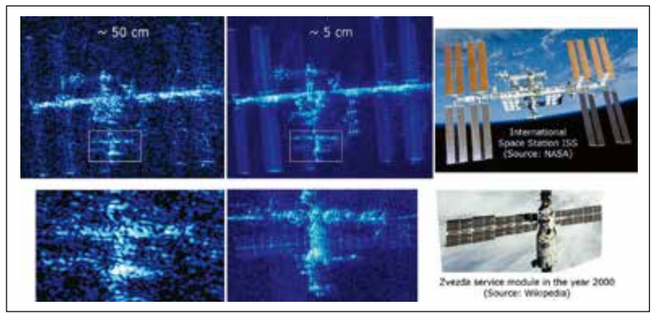

Fig. 2: IoSiS radar images of the ISS from the year 2021 for different spatial resolution. The bottom images show a zoom image of the section framed in white

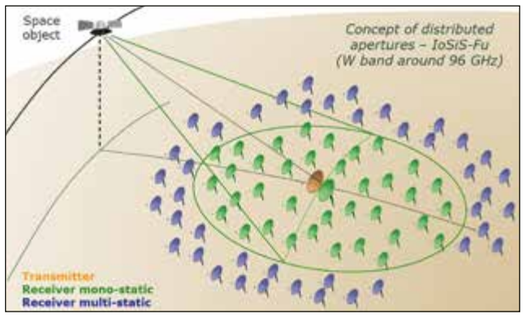

Fig. 3: Functional principle of IoSiS-Fu – a medium-sized transmitter and several spatially distributed very small receivers allow mono-static (a few ten kilometres diameter) and multi-static (several ten kilometres diameter) 3D imaging. The transition between the two features is to be seen as fluid rather than sharp

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Reactive structural materials (RSM) – Advances in the research of energy release and fragmentation behaviour

Reactive structural materials (RSM) combine high mechanical strength with the ability to release chemical energy under external influences. As part of the cooperation between the French-German Research Institute of Saint-Louis (ISL) and Helmut Schmidt University/ Bundeswehr University Hamburg (HSU), progress has been made in the experimental and simulative research of RSM. Experiments show the correlation between fragmentation, energy release and velocity.

Reactive structural materials (RSM) cover a wide range of materials that release chemical energy under external stimuli such as temperature or impact and at the same time exhibit high mechanical strength. These properties offer the potential to significantly increase the combat value of conventional warheads, munitions or protection systems by replacing inert materials with RSM. However, the exact mechanisms that lead to energy release are not yet fully understood. In-depth research into these mechanisms is essential in order to exploit the full potential of RSM and optimise existing weapon systems.

The close cooperation between ISL and HSU creates a basis for comprehensive research. ISL contributes its expertise in the fields of ballistics and material behaviour in highly dynamic events, while HSU contributes its analytical and theoretical expertise, in particular through the use of computed tomography and simulations, to the understanding of reaction mechanisms on various scales.

The ballistic laboratories at ISL enable detailed investigation of the terminal ballistic behaviour of RSM under controlled

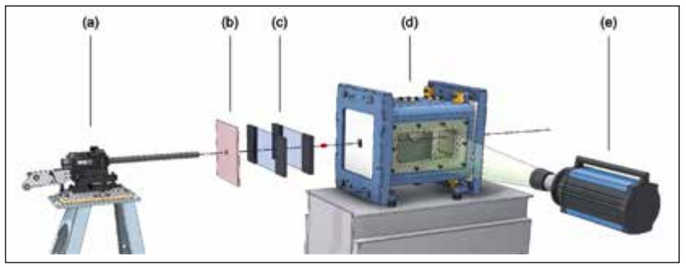

Fig. 1: Experimental setup at ISL with simultaneous measurement of quantitative reaction values using a pressure chamber and recording of flight and impact conditions. The image shows the propellant gun (a), the sabot stripper (b), the light barrier (c), the pressure chamber (d), and the high-speed camera (e)

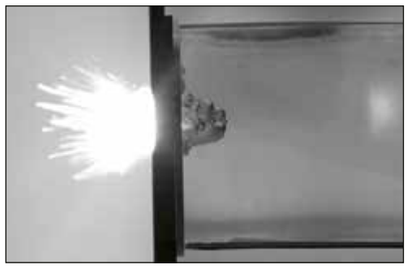

Fig. 2: High-speed image of a fragment surrogate perforating an aluminium plate from left to right. Fragment debris is caught by the soft-catch medium behind the target plate. The image shows the release of energy during perforation

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conditions. Propellant, gas, and rail guns cover a broad velocity profile, simulating different deployment scenarios.

In initial tests, a specially developed pressure chamber was used to identify the velocity threshold above which the energy release of RSM increases significantly (Fig. 1). Spectroscopic analyses of the resulting reaction species provide valuable insights into the chemical processes that occur during the impact.

A significant proportion of the energy released is due to oxidation processes during the impact. The fragmentation behaviour of RSM was analysed to investigate this process in more detail. For this purpose, RSM fragment surrogates were used to perforate target materials (Fig. 2). The resulting fragment debris was captured at different distances using a soft-catch medium. This experimental setup made it possible to relate the size distribution of the debris to the combustion process.

Fragment size distribution was analysed using computed tomography equipment at the Chair of Computational Material Design (CMD) at HSU. Initial results indicate a possible correlation between the degree of fragmentation and the energy release depending on impact velocity (Fig. 3 and Fig. 4).

At the CMD Chair, quantum chemical modelling and molecular dynamics simulations were used to investigate the reaction mechanisms at the atomic level. It was revealed that specific strain states which could occur during an impact benefit the release of energy. These findings form the basis for further developing models to describe the reaction behaviour of RSM.

The experimental and simulative results, together with the developed methodology, make it possible to identify the first mechanisms of RSM's reaction behaviour. These findings contribute to the adaptation and further development of existing models. The long-term goal is to gain a holistic understanding of the material behaviour in order to significantly increase the combat value of existing systems.

The work is made possible by base funding, additional government funding, and national and international collaborations.

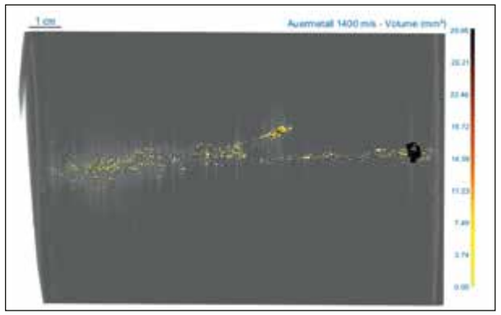

Fig. 3: Resulting 3D reconstruction after measuring the fragment debris in the computed tomography system – in grey the soft-catch medium and from yellow to black, fragments with increasing volume

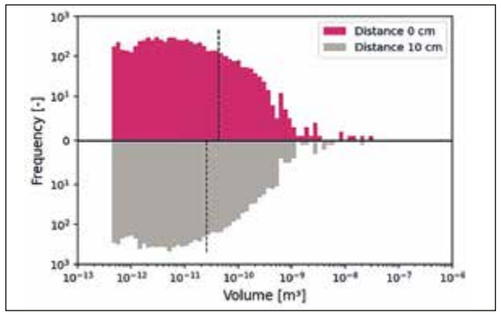

Fig. 4: Fragment size distribution of Ferrocerium after impact at 1400 m/s. The fragment debris was captured at 0 cm and 10 cm behind the target plate

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Resilient & intelligent GNSS – a real-world test

Global Navigation Satellite Systems (GNSS) are becoming increasingly vulnerable to intentional interference. Addressing this "Navigation Warfare" requires rigorous testing of anti-jamming technologies under realistic conditions. Jammertest 2024 in Norway offered an essential platform for ISL to evaluate two advanced GNSS anti-jamming systems suited for guided munitions in a controlled outdoor environment.

Jammertest 2024, held in Bleik, Norway, provided a vital opportunity for ISL to assess the resilience of its developed GNSS systems against diverse interference threats such as jamming, meaconing, and spoofing. This "real-world" outdoor field test focused on evaluating two anti-jamming systems designed to mitigate signal degradation in the upper GNSS bands (L1, E1, B1, and G1). The first system employed digital filtering on a Xilinx FPGA board, using real-time signal processing to detect and suppress narrow band interference. The second system utilised spatial filtering through an adaptive antenna array, applying null-steering techniques to suppress interference from specific directions while preserving genuine GNSS signals.

Testing was conducted within a designated GNSS interference zone, ensuring controlled and replicable conditions. GNSS receivers, with and without anti-jamming systems, were evaluated under identical conditions. A reference GNSS antenna, provided by the organisers, was fixed alongside the test systems (Fig. 1).

Performance metrics included signal-to-noise ratio (SNR), positional accuracy, and satellite availability. Jammers with

Fig. 1: Two ISL GNSS systems on the test range with the high-power jammers (on the top of the mountain side) at a distance of 1.5 km

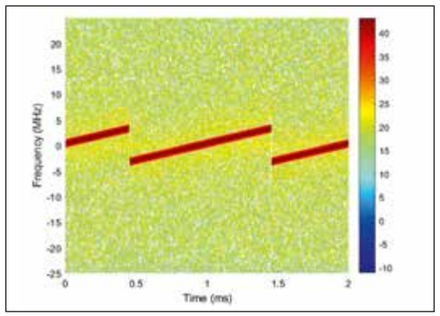

Fig. 2: Spectrogram of a sample of the recorded jammer plus GNSS signal on L1

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power levels from 10 mW to 100 W were deployed, emitting both continuous wave (CW) and chirp signals (Fig. 2). Additionally, interference signals were recorded using a software-defined radio (SDR) for subsequent laboratory analysis.

The ISL digital filtering system demonstrated exceptional performance against narrow band interference, effectively suppressing CW and chirp jammers. This maintained SNR levels adequate for GNSS signal acquisition and tracking. Positional errors remained sub-metric, underscoring the system's reliability for operations where narrow band interference is predominant (Fig. 3). Its targeted design and low complexity make it a valuable solution for specific operational requirements.

Conversely, the spatial filtering system exhibited remarkable versatility, effectively mitigating both narrow band and broadband interference. Its adaptive null-steering capabilities preserved signal integrity and positional accuracy even under severe jamming conditions. This adaptability positions the system as a robust solution for dynamic and unpredictable interference environments.

The results highlight the complementary strengths of both systems. The digital filtering system offers a precise and efficient defence against narrow band interference, while the spatial filtering system provides comprehensive protection across a broader range of interference types. Their combined use could significantly enhance GNSS resilience, providing layered defence against diverse jamming threats.

Future developments will aim to extend both systems' capabilities to cover lower GNSS bands, including L2, L5, and E5ab. This enhancement will deliver more comprehensive protection across the GNSS frequency spectrum, strengthening anti-jamming solutions for critical navigation and positioning applications.

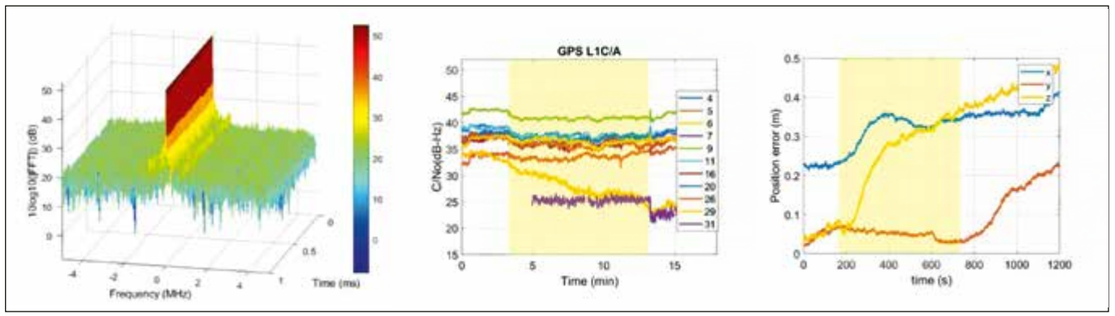

Fig. 3: (a): Spectrogram of CW on L1 (EIRP: 50 W), (b): Carrier-to-noise density ratio of the tracked satellites, (c): Position error in WGS-84. Jammer broadcast period highlighted in yellow

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Simulation-driven development: Accelerating real-world deployment of UAV-UGV systems

The use of UxVs in the military context is an extremely fast-developing field. Simulation-driven development significantly accelerates the deployment of UAV-UGV systems by enabling validation of communication protocols, sensor integration, and algorithms in controlled environments. This approach thus supports rapid prototyping, seamless integration, and robust systems.

Current military conflicts show not only that the use of UxVs is becoming more and more important but also that new innovation cycles can be observed in extremely short time frames. Keeping up with traditional development and testing procedures is an almost impossible challenge. It is therefore of utmost importance to be able to test new prototypes, new functionalities, or new sensors used in these platforms in a near real-world simulation environment.

This research employs cyber-physical systems (CPS) and internet of robotic things (IoRT) methodologies to address topics through the OODA-Loop framework: Observe, Orient, Decide, Act. CPS ensure seamless integration of physical systems and computational algorithms, while IoRT enables connectivity and real-time data exchange, both critical for coordinating detection tasks and improving operational efficiency. It represents an evolving system that can be easily redefined and adapted to specific research contexts.

The simulation framework, containerised using Docker, enhances usability and portability by enabling seamless integration of UAV and UGV models with minimal modifications (Fig. 1). It provides a cost-effective environment for testing complex interactions, reducing the need for physical prototypes and allowing rapid iteration. This makes it possible to test diverse scenarios, fine-tune control algorithms, and evaluate system behaviour under varied conditions, significantly accelerating development cycles. This flexibility is evident in the ability to deploy detection and control algorithms, supporting robust testing and adaptation across diverse scenarios.

A forest scenario (Fig. 2) was simulated with 3D models of a mine, UAV, and UGV, where both UAVs and UGVs navigated collaboratively to detect mines.

This setup replicated real-world challenges, refining control systems before deployment. The framework supports tasks like object detection, classification, and collaborative missions. Its software-in-the-loop architecture uses tools such as ROS for UGVs, PX4 Autopilot for UAVs, and a lightweight publish-subscribe mechanism for reliable data transfer. Gazebo enhances the framework by simulating complex scenarios with multiple UAVs, UGVs, and customisable environments.

Object detection technology was integrated into the simulation for mine identification. A customised dataset was created from videos of various mine categories captured on diverse terrains and lighting conditions, both indoors and outdoors, using a UAV platform. High-resolution images were extracted, processed with specialised tools, and used to train the detection model for efficient classification. The trained model was then integrated into the simulation framework, enabling UAV and UGV models to collaboratively detect mines in simulated environments.

Simulated tests confirmed the object detection module's integration and efficiency, suggesting its potential for real-world application with minor adjustments (Fig. 3).

Simulation is essential for real-world deployment since it addresses integration, communication, and testing challenges. It refines algorithms and hardware, accelerating development while reducing risks and hardware dependency. Its adaptability has been shown with mine detection but is actually much more versatile and can also be used for applications such as reinforcement learning and large language model integration, highlighting its crucial role in efficient robot system deployment.

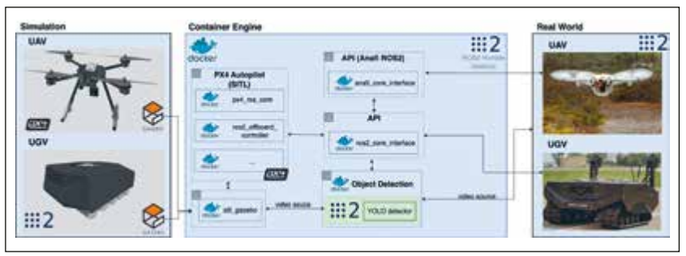

Fig. 1: Containerised architecture (screenshot)

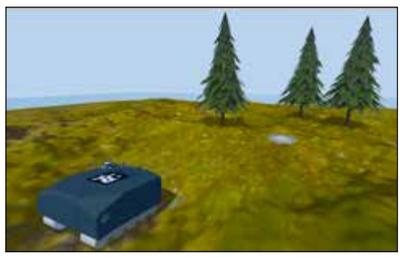

Fig. 2: Simulated scenario

Fig. 3: Simulated (left) and real (right)

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Research on a compact energy supply for pulsed loads of electrical weapons

A key component of electric weapons is a compact power supply. Current research focuses on investigating supercapacitors and the development of a compact high-voltage capacitor charger. This work is being conducted as part of a collaboration between the French-German Research Institute of Saint-Louis (ISL) and the Chair of Power Electronics at Helmut Schmidt University / Bundeswehr University Hamburg (HSU).

The French-German Research Institute of Saint-Louis (ISL) is deeply engaged in research on railguns and the power supplies they require. With its unique test facilities, ISL serves as a key European player in advancing this technology – both within the framework of the EU project "THEMA" and beyond (Fig. 1). The institute has gained worldwide attention through the development of the XRAM generator (Fig. 2) – an energy-dense pulsed-power generator based on inductive energy storage rather than conventional capacitor banks. Recent advances led to the development of a 2 MJ prototype to supply a medium-sized railgun with an inductive energy density of 9 MJ / m³. In addition, a repetition rate of 13 Hz was demonstrated using a battery-based energy supply.

The collaboration between the ISL and the HSU focuses on designing a small primary power source and a compact high-voltage charger. Both are indispensable elements of the energy conversion chain.

Since high-voltage chargers for railguns only operate in pulsed mode, the power density offered by current devices found in the research and industrial sector is far too low. In 2021, the partnership established a new benchmark in power density by using a topology specifically optimised for pulsed operation. Ongoing research suggests that integrating the latest silicon-carbide (SiC) power semiconductors into a resonant circuit topology could boost power densities to over 10 kW/L – roughly 20 times higher than commercially available systems. Fig. 3 shows the inverter – a key component of this charger.

The primary energy storage unit, which is used to charge the inductive pulsed generator, significantly influences the size of the overall system. In order to keep the energy storage system as compact as possible, it is crucial to maximise the power output of each cell. As part of their collaboration, the HSU and the ISL developed a pulse test bench (named "Power Flower") that uses discharge pulses under "impedance-matching" to push individual cells to their performance limit (Fig. 4). This unique test bench can discharge individual cells with peak currents of over 16 kA. With a pulse duration of 0.5 seconds, the cells experience a pulse that resembles the charging process of the current XRAM generator in terms of time and even exceeds it in terms of current level. This innovation enables the evaluation of maximum performance and aging effects in single cells, eliminating the need for expensive module configurations. Extensive testing with various energy storage devices, including numerous batteries, hybrid solutions and supercapacitors, revealed that one of the latter excelled in terms of power density. After more than 615 pulse discharges, with currents four times higher than the values specified by the manufacturer, the cell showed only slight ageing effects (Fig. 5). A decrease in capacitance of 5 % and a 7 % increase in internal resistance are impressive results and emphasise the potential of supercapacitors for this application.

This scientific progress illustrates how the collaboration between the ISL and the HSU contributes to overcoming challenges of power supplies for electrically powered weapons, bringing their potential deployment within reach.

Fig. 1:NGL 60 railgun "PEGASUS" and capacitor-based power supply

Fig. 2: XRAM – inductive pulsed generator for railguns

Fig. 3: Power inverter prototype for a 250-kW-capacitor charger

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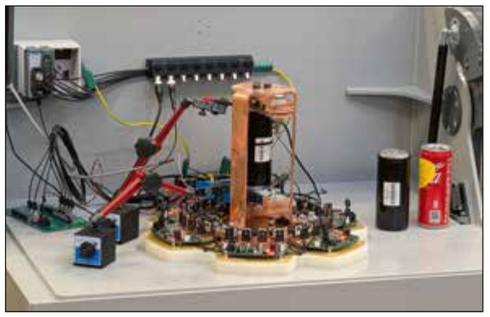

Fig. 4: „Pulse test bench "Power Flower" next to a supercapacitor cell

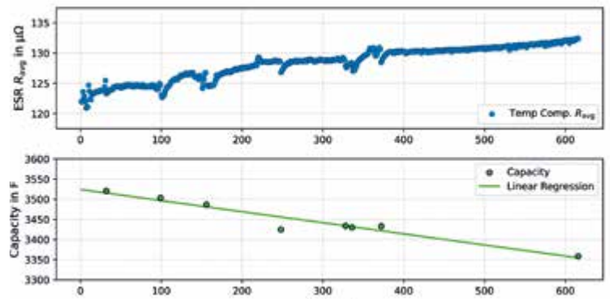

Fig. 5: Degradation of internal resistance and capacitance of a SCH3400 supercapacitor cell over 615 pulse discharges

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Scientific research of robust and resilient power electronic systems for critical infrastructure and the defence sector

In close cooperation with the Bundeswehr Research Institute for Protective Technologies and CBRN Protection (WIS), the Chair of Power Electronics at the Helmut Schmidt University/ Bundeswehr University Hamburg (HSU) conducts experiments and analyses on the hardening of power electronic systems against ionising radiation effects. Here, important insights have been gained, especially with regard to applications in critical infrastructure.

As part of the dtec.bw projects at the Bundeswehr universities, the first phase of the research project "Digital Life Cycle Monitoring, Hardening and Optimisation of the Resilience of Power Electronics in Critical Infrastructure" (DiMoLEK) was successfully carried out between 2021 and 2024 at the Chair of Power Electronics (LEK) at the HSU.

The DiMoLEK consortium consists of several professorships at the HSU and industrial partners located in the Hamburg metropolitan region, all of which have high-performance research and development departments. Another important research partner involved is the Bundeswehr Research Institute for Protective Technologies and CBRN Protection (WIS) in Munster. Described by the German Science and Humanities Council in its evaluation report of July 2023 as strategically very well positioned, the cooperation network is characterised by a particularly high scientific level.

Furthermore, the composition of the consortium enables targeted implementation of the important dual-use aspect of DiMoLEK. This is facilitated in particular by the outstanding

Fig. 1: Laser-opened SiC-MOSFET

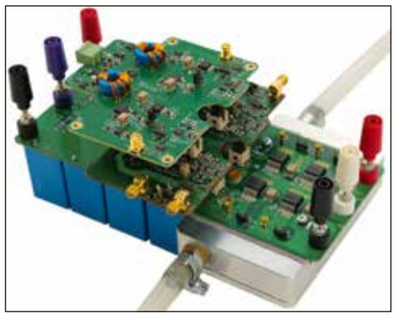

Fig. 2: DiMoLEK reference design with modular driver and power board

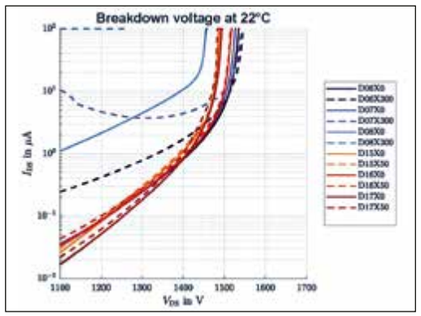

Fig. 3: Degradation of the breakdown voltage after gamma irradiation

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infrastructure and equipment of the WIS for analyses of high-power electromagnetics (HPEM) and ionising radiation effects.

Currently, the field of power electronics is undergoing forward-looking developments due to the widespread introduction of power semiconductors based on wide-bandgap materials. Their advantages are clearly characterised by lower conduction and switching losses and thus the ability to achieve higher switching frequencies and power densities. However, the introduction of these new semiconductors also involves technical challenges. These include more complex construction and connection techniques or electromagnetic compatibility. The research activities within DiMoLEK focus on silicon carbide (SiC) devices, which have been used to demonstrate complex failure mechanisms associated with many influencing factors. During the investigations, both single, discrete power semiconductors (Fig. 1) and the application-oriented interaction of several components such as a parallel connection of devices (Fig. 2) have been analysed in detail.

Another important aspect is the robustness of complete power electronic systems against ionising radiation events. Especially in the aerospace industry, which is steadily transitioning towards electrification, it is important to rule out critical failures and ensure resilience with respect to ionising radiation. At the research partner institute WIS, the effect of both gamma and neutron radiation on power electronics can be specifically investigated. Analyses following the exposure of discrete power semiconductors to gamma radiation have revealed critical degradation of, for example, the breakdown voltage (Fig. 3). In addition to the investigation of discrete semiconductors, future research activities will also analyse entire assemblies and systems selectively against radiation events. A complex shielding box was developed especially for these investigations in connection with neutron irradiation, and its function was simulated successfully (Fig. 4 and Fig. 5). In 2024, the first experiments with discrete SiC-MOSFETs from different manufacturers and with different technologies were carried out in the neutron beam chamber at the WIS (Fig. 6).

Fig. 4: Shielding box for selective neutron irradiation

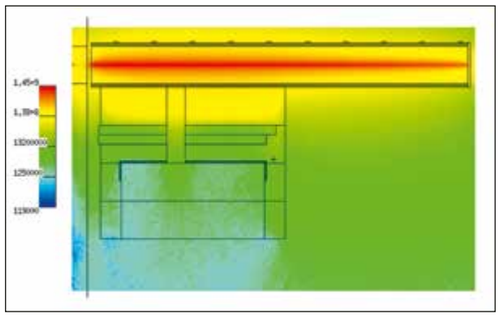

Fig. 5: Simulation of the radiation exposure within the neutron chamber when using the shielding box

Fig. 6: Neutron beam test chamber at the WIS with shielding

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Numerical simulation of nuclear weapon effects for nuclear protection purposes

The hardness of defence materiel against the direct effects of a nuclear explosion can be assessed and improved using modern numerical simulation methods as early as in the design and development phase. The Bundeswehr Research Institute for Protective Technologies and CBRN Protection (WIS), together with the Fraunhofer EMI and INT, is developing a simulation chain for all relevant nuclear weapon effects on defence materiel.

The current geopolitical situation has brought the topic of nuclear weapons back to the forefront. The use of non-strategic nuclear weapons in particular can no longer be ruled out in conflicts. In certain distances from ground zero, military equipment can survive the direct effects of non-strategic nuclear weapons use. A balanced nuclear protection system attempts to maximise this area. Since testing options are limited and constructive measures must be incorporated during the planning and design phase, the numerical simulation of the direct effects of nuclear weapons (initial radiation, heat flash and pressure wave) and their effect on military equipment is urgently needed. In the research project “Nuclear Protection Initiative”, WIS and the Fraunhofer EMI and INT have joined forces to establish a modern simulation chain for all relevant nuclear weapon effects on military equipment, which enables an early nuclear protection analysis.

To simulate the thermal effects (heat flash), a numerical solver was developed that calculates the radiation propagation through the near-Earth atmosphere. The discontinuous Galerkin method (DG-FEM) is used here. The visualisation of the simulation results enables a comprehensive analysis of the irradiated objects (Fig. 1). This makes it possible to identify hotspots on the defence materiel that are particularly badly affected by the heat flash. Such analysis is crucial for quickly identifying critical points on the object. The data obtained can later be transferred to structural mechanics simulation modules. This makes it possible to analyse the effects of the heating caused by the heat flash on the mechanical stability under blast loads (combined effects). Using another simulation method, it is now possible to simulate the heating of the ground as a result of the heat flash. This means that the effects of the thermal heating of the ground on the blast wave can be considered in further steps of the simulation chain (Fig. 2).

To simulate the blast propagation, a source model for nuclear explosions was developed and integrated into the in-house CFD code (FhG-EMI) “Apollo Blast Simulator” (https://apollo-blastsimulator.de/). Furthermore, the coupling of different modelling regions was introduced, which combines an efficient 2D simulation of the blast wave from the explosion site to the target site (where the military equipment to be examined is located) with the 3D simulation in the region of the object to be examined. This allows blast loads to be calculated on rigid body models. The suitability was demonstrated on some example models, like a 20-foot container, a civilian truck and a generic battle tank. With the developed method, it is now also possible to consider topological height structures of the terrain (Fig. 3). It turns out that steep flanks in the terrain lead to significant increases in peak overpressure due to reflection of the blast wave compared to propagation over flat ground. In general, the heat flash that acts first leads to a warming of the air layer near the ground. This again leads to a vertical dynamic pressure component close to the ground when the blast wave arrives with time delay (Fig. 4). This generally promotes the tipping of vehicles. Initial simulations on a battle tank model resulted in a significantly larger tipping moment compared to a simulation without taking ground heating into account.

The results concerning the heat flash and the blast wave create the conditions for numerically simulating the comprehensive effects of nuclear weapons on defence materiel, such as deformation, compression and tearing, in further work. For this purpose, the development of structural dynamic simulation models of the defence materiel with temperature-dependent materiel models, which are much more complex than rigid body models, is planned for the future.

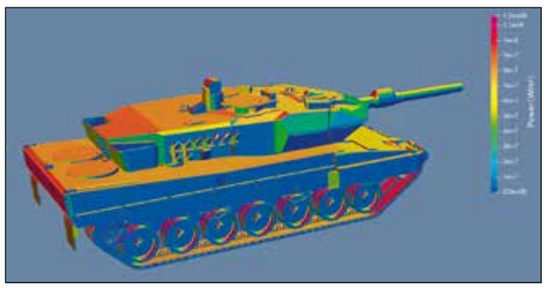

Fig. 1: Irradiated thermal power on a main battle tank during a nuclear explosion (source: FhG EMI)

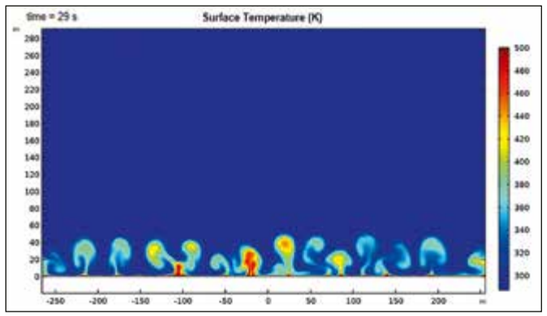

Fig. 2: Temperature field of air above ground surface heated by nuclear a nuclear heat flash (source: FhG EMI)

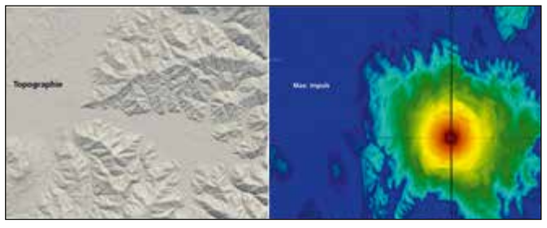

Fig. 3: Distribution of peak pressure from a nuclear explosion in a valley-mountain terrain (source: FhG EMI)

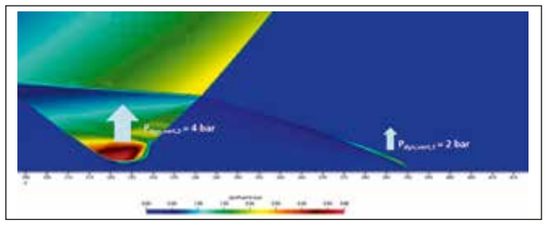

Fig. 4: Vertical dynamic pressure in the ground near pressure front, caused by ground near temperature layers from a nuclear heat flash (source: FhG EMI)

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Selective detection of toxic chemical agents with high kinetic energy ion mobility spectrometry

High-kinetic energy ion mobility spectrometers (HiKE-IMS) operate at reduced pressure with increased reduced electric field strengths. Their improved analytical resolution minimises false-positive results during the detection of toxic gases. Optional field-dependent fragmentation patterns deliver additional information that can be utilised to further reduce cross-sensitivities.

The majority of contemporary mobile gas detectors used for the detection of chemical warfare agents (CWA) and toxic industrial chemicals (TIC) are based on ion mobility spectrometry. This technology operates at ambient pressure and differentiates ions via their movement in an electrical field against a counter-flow of neutral drift gas. Ion mobility spectrometers (IMS) offer a comparatively simple technical design that enables the construction of compact handheld devices while allowing trace gas detection at extremely low concentrations (ppb_v) within a matter of seconds. However, their limited resolution is prone to producing false alarms, in particular when analysing complex gas mixtures. Furthermore, competing ion-molecule reactions, such as with residual moisture within the system, can cause a suppression of characteristic signals that leads to false negatives.

HiKE-IMS has been specifically developed to increase the selectivity of traditional IMS. These devices operate at reduced pressures of 20 to 60 mbar and at high reduced electric field strengths E/N of up to 120 Td. Water cluster dissociation is facilitated under these conditions, which permits an easier differentiation of substance specific ion mobilities, and also

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reduces the overall impact of sample humidity on the detection result. Likewise, the experimental circumstances suppress the negative impact of competing ion-molecule reactions on the resulting ion populations. Additional effects, such as fragmentation of ions at higher E/N or determination of field-dependent ion mobilities, can be exploited to further reduce false alarms.

The capabilities of HiKE-IMS were determined in extensive laboratory studies with the CWAs tabun (GA), sarin (GB), soman (GD), cyclosarin (GF) and sulfur mustard (HD), as well as selected TICs (Fig. 1). Characteristic signals of the target substances were obtained at various reduced electrical field strengths E/N. The combined analytical data was used to create distinct analytical fingerprints (Fig. 2). This allows a confident identification of structurally related compounds, such as the nerve agents GB, GD and GF, as well as a safe exclusion of common cross-sensitivities (Fig. 3). All examined TICs were successfully detected and identified due to suppressed water cluster formation.

Generally, it was possible to ionise all tested substances in dry or humid air without significant changes in their signal intensities. Additionally, an experimental setup that uses common thermal desorption tubes was established to further increase the application range of HiKE-IMS. This permits the analysis of externally collected gas samples in addition to direct online detection.

The advantages described above make HiKE-IMS a powerful tool for the selective detection of toxic gases. The required instrumentation periphery results in suitcase-sized devices, which may be used on future mobile CBRN reconnaissance platforms or in mobile laboratories. An explicit disadvantage of the technology is the reduced sensitivity when compared with conventional ambient-pressure IMS. However, current laboratory prototypes with pending optimisation are already reaching NATO targets for concentration levels in the ppb_v region (Fig. 4).

Fig. 1: The HiKE-IMS laboratory prototype was connected to a gas generation system for an extensive quantitative characterisation with chemical warfare agents

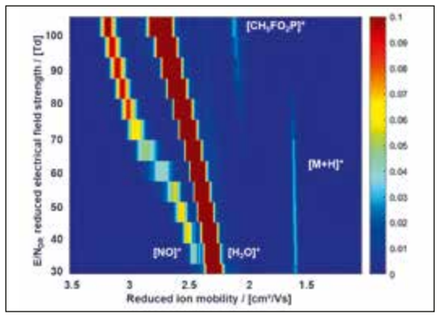

Fig. 2: Heatmap plot of the field-dependent ion mobility of cyclosarin (GF) using HiKE-IMS. High field strengths in the drift region E_{DR}/N induce fragmentation of the quasi-molecular ion $[M+H]^+$

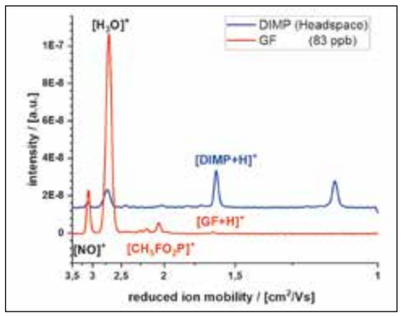

Fig. 3: Simulant compounds diisopropyl methylphosphonate (DIMP) and cyclosarin (GF) show significant spectral differences from fragmentation at higher field strengths accessible with HiKE-IMS. In contrast, conventional IMS tend to falsely identify DIMP as GF

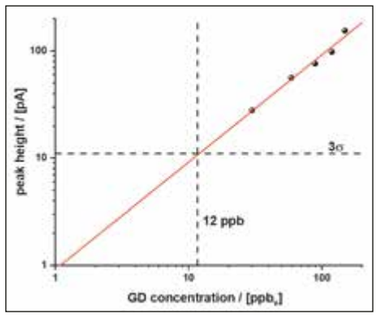

Fig. 4: Calibration curve of soman (GD) to determine sensitivity at 50 % relative humidity. The 3σ-confidence interval yields a detection limit of 12 ppb_v, which conforms to NATO requirements

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Innovative defence technologies within the medical evacuation chain

Current threat situations that arise in the context of national and collective defence lead to new challenges in casualty care. New technologies are being analysed to improve emergency medical treatment and health care. A variety of individual technologies is available.

The foundation of this project lies in a thorough analysis and assessment of relevant regulations, coupled with their practical application within the medical evacuation chain of the German Armed Forces. This evaluation and inspection enabled the identification of innovative improvements which were further refined through collaboration with subject matter experts from the Bundeswehr Joint Medical Service. This systematic approach ensured a clear identification of the underlying challenges and fostered the development of solutions tailored to address these issues in a result-oriented and technologically advanced manner.

A vital constituent of the project was the development of a digital field medical card which consolidates all information currently recorded on traditional field medical cards while enabling the processing of additional data critical for medical care. This could be achieved through the functional extension of the identification tag by enhancing the ability to gather, store, and manage essential data in a more comprehensive manner.

Sensors, such as Global Positioning System (GPS) or acceleration sensors, in combination with the vital parameters captured by wearables, support the first aider in initial emergency treatment. This is supported by the intuitive user interface as well as corresponding assistance within the digital field medical card itself. Thanks to the digital information-processing, almost real-time data transfer to subsequent instances within the medical evacuation chain and logistics is possible. The data transmission by means of near-field communication (NFC) consequently ensures rapid, secure, and reliable transfer, expediting patient treatment while maintaining the integrity of critical information. In addition to basic work on various vital parameter sensors in wearables and their integration into textile products, the digital field medical card uses an “intelligent identification tag” as storage medium. This innovation represents a possible technological advancement, establishing a foundation for further development.

Further analyses conducted in the course of the project have shown that commercially available wearables already have considerable potential for use within the armed forces, for example in the medical evacuation chain. However, the findings also underscored the necessity for significant modifications to meet the stringent requirements of military environments. This is particularly the case in regard to the aspects of signals intelligence, camouflage as well as implementing robust data protection measures.

The symbiosis of the examined and identified technological options could consequently assist in ensuring optimised and accelerated patient treatment, through lossless data transfer and assistance in data collection. Moreover, advanced features such as technology-assisted triage systems and real-time monitoring of vital parameters offer the prospect of preventing health risks associated with physiological stress, thereby enhancing the overall well-being and operational readiness of personnel.

The subject area of wearables and smart textiles has a high potential for military use in a range of scenarios (e. g. training, medical evacuation chain, overload prevention, human-machine interaction), thus forming the technological basis for the further development of the complex system of the medical evacuation chain. Despite these promising opportunities, there are still some challenges to be addressed, particularly regarding ethical and data-protection considerations that arise from the areas of interest.

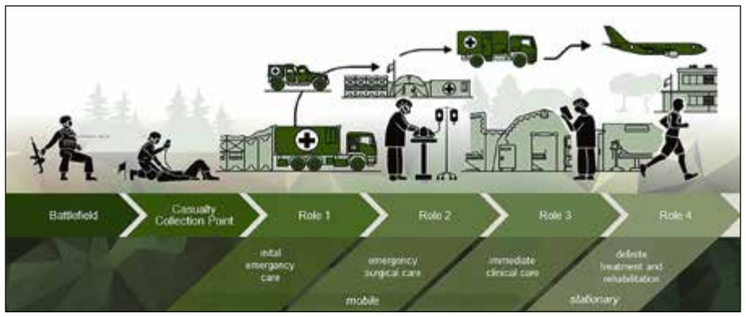

Fig. 1: Illustration of the medical evacuation chain

Fig. 2: Transmission of relevant emergency data through the “intelligent identification tag” with integrated NFC tag. These data can be displayed on a handheld device (here smartphone)

Fig. 3: Currently used field medical card (in paper) and the digital demonstrator, which also can display and record vital signs

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Deep cryogenic treatment of additively manufactured steel: Flexible and efficient

Deep cryogenic treatment (DCT) can triple the wear resistance of an additively manufactured hot work tool steel without the need for re-austenitization while simultaneously reducing process-induced residual stresses. This presents a promising approach for manufacturing, maintaining and extending the service life of highly stressed components in the German Armed Forces.

Additive manufacturing (AM) facilitates the production of complex metal components and allows armed forces to manufacture spare parts and interim solutions directly on-site or in decentralised production facilities. This reduces logistic dependencies, shortens repair times, and increases operational readiness. The wire-based Laser Metal Deposition (w-LMD) process offers significant advantages (Fig.1): It enables targeted deposition onto existing semi-finished products or the rebuilding of worn components, thus conserving resources and reducing costs. Additionally, it eliminates the need for complex and challenging metal powder handling, which is required in other AM technologies. Despite these advantages, the mechanical performance of additively manufactured metals remains a key factor for optimisation. The material properties in the as-built state rarely meet the requirements and must be adjusted through subsequent heat treatments. Especially for components subjected to high wear, these are often complex and require elaborate surface and edge layer post-treatments. Deep cryogenic treatment (DCT) offers a promising opportunity here for performance enhancement.

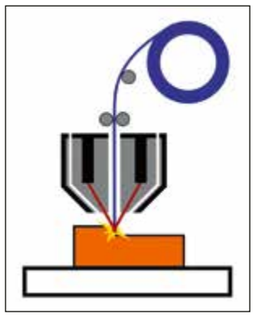

Fig. 1: Schematic representation of the w-LMD process. A wire (blue) is fed concentrically into the deposition head (grey) and melted using a laser (red). Through the layer-by-layer process of the deposition head, the component (orange) is built

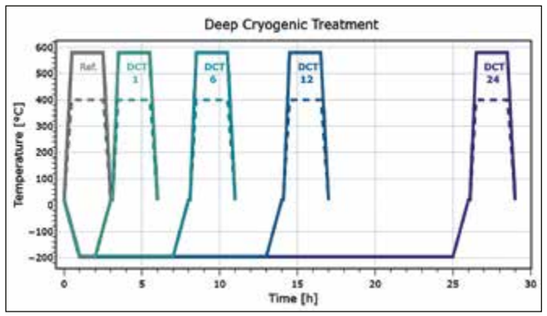

Fig. 2: Temperature profile of deep cryogenic treatment

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DCT has been widely used in industrial applications for conventional steels, primarily to improve wear resistance in gear components, cutting tools, and forming tools. The DCT process involves the slow cooling of components to temperatures below – 190 °C, maintaining this temperature for several hours, and then the careful reheating with additional tempering cycles (Fig. 2). This treatment reduces retained austenite and enhances carbide precipitation. Depending on the component and material, this can significantly extend service life. Since the exact mechanism behind DCT is not yet fully understood and remains the subject of ongoing research, it is also of interest from a scientific perspective.

Studies conducted by the Bundeswehr Research Institute for Materials, Fuels and Lubricants (WIWeB) and the Bundeswehr 3D Printing Centre have demonstrated that the wear resistance of w-LMD manufactured tool steel can be increased by 190 % through DCT, while simultaneously reducing process-induced residual stresses (Fig. 3 and Fig. 4). These findings illustrate that the benefits of DCT also apply to additively manufactured components, making it a promising method for property optimisation. The study examined two different manufacturing parameters, each with four different deep cryogenic soaking times and two different tempering temperatures, to analyse their effects on wear resistance and residual stress distribution.

The reference group consisted of non-cryogenically treated samples and conventionally heat-treated bar stock of the same material.

For military applications, the combination of DCT and additive manufacturing technologies such as w-LMD offers several advantages. The robust and cost-effective w-LMD process enables flexible manufacturing and repair of metallic components. Enhanced wear resistance extends the service life of high-load components and reduces repair requirements. Particularly for the w-LMD process, DCT presents a significant advantage, as it can be applied without re-austenitization. This ensures that the original heat treatment state of a repaired component remains largely intact – an essential benefit for mobile and decentralised operations.

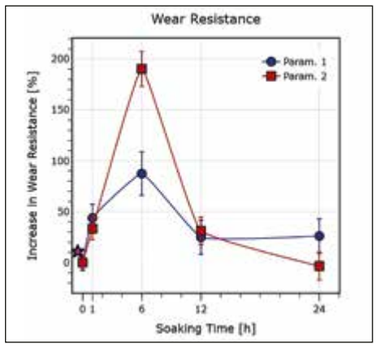

Fig. 3: Percentage change in wear resistance relative to the non-DCT-treated sample. The magenta-coloured star indicates the wear resistance of the conventionally manufactured material

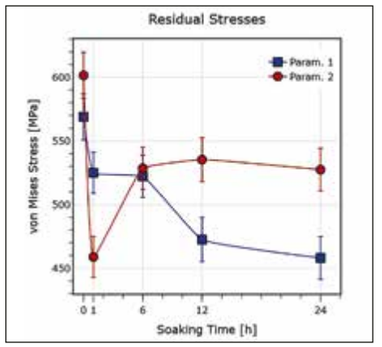

Fig. 4: Residual stresses depending on the DCT soaking time

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Standoff-capable detection of explosive ordnance with UAV-mounted sensors

With the focus shifting to national and collective defence, the reconnaissance of large-scale minefields is of growing importance. A concept for a UAV-mounted multi-sensor system for the detection of surface-laid and buried explosive ordnance was drafted to meet a German Armed Forces staff target. A range of sensor types was investigated to verify their suitability.

Currently, the detection of explosive ordnance in the German Armed Forces is carried out by EOD personal with handheld detectors. Major progress in the further development of unmanned aerial vehicles (UAVs) as sensor carriers offers a considerable technological potential for new operational approaches to standoff explosive ordnance detection.

To take advantage of this opportunity, the German Armed Forces issued a framework of functional requirements. These requirements form the backdrop for a concept designed by the Bundeswehr Technical Centre for Protective and Special Technologies (WTD 52) for the detection of buried explosive ordnance using a UAV-mounted multi-sensor network (Fig. 1).

The need to meet these requirements creates a need for military research with two key aspects. The first is sensor integration into UAVs and the second is automated data analysis with advanced algorithms. The spectrum of possible sensor systems ranges from camera systems in the visible and infrared spectral range to magnetometers and ground penetrating radar (GPR) systems. Since no single sensor is capable of reliably detecting the full spectrum of ordnance by itself, it is imperative to operate several sensors in a network.

The aim of the military research at WTD 52 is the evaluation and improvement of detection algorithms based on data sets that have been acquired in a reproducible manner. For this purpose, test scenarios were designed at WTD 52 on open-field areas with different types of buried explosive ordnance that simulate a broad range of military threats. Different soil types (including sand, basalt, humus) were used to cover various physical soil parameters that represent different challenges to the investigated sensors.

UAVs with cameras in the optical range are available in a wide range of variants. Automated detection algorithms have been investigated as part of international measurement campaigns, and their functionality has been demonstrated for surface-laid test objects. Due to the large influence of environmental conditions such as ground temperature and solar radiation, detection with infrared cameras requires a high level of complexity in automated data reduction. However, under suitable environmental conditions, it is even possible to detect buried objects. Initial test measurements have been carried out at WTD 52 (Fig. 2). The results identified the need for a long-term campaign to determine the influence of daytime and environmental conditions on reliable detection.

Explosive ordnance containing ferromagnetic materials allows detection via magnetometry. For this purpose, the prototype of a UAV-borne magnetometer system was examined in a measurement campaign at WTD 52. The subsurface test objects were detected and position-referenced automatically (Fig. 3).

To detect metal-free explosive ordnance, more complex technologies such as GPR must be used. For this purpose, an R & D demonstrator of a UAV-mounted GPR system is being developed as part of a study contract with the German Aerospace Centre (Fig. 4). Measurement campaigns at WTD 52's specialised infrastructure show the potential of the technology for detecting buried objects. The recorded measurement data will be used for the development of new algorithms for object detection.

These fundamental investigations and the evolving understanding of each sensor's capabilities are meant to ultimately lead to an operational multi-sensor system. Controlling flight formation of several UAVs and automated sensor data fusion are key features of a future system. Both topics are subjects of additional R&D projects.

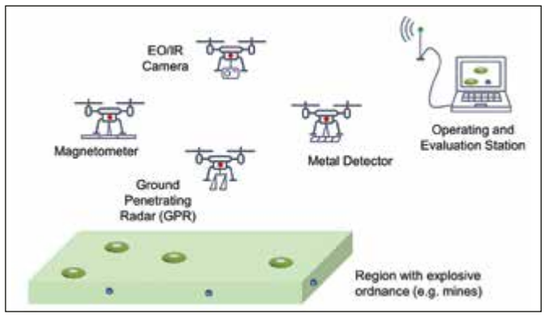

Fig. 1: Concept of a UAV-mounted multi-sensor system for standoff explosive ordnance detection

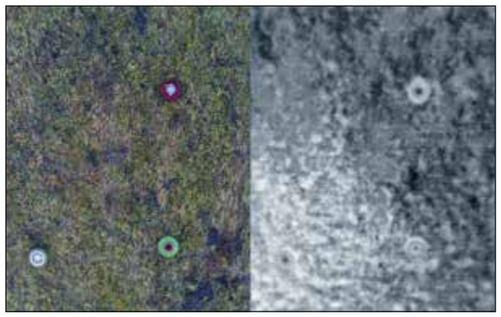

Fig. 2: Image of anti-tank mines laid on the surface in the optical (left) and infrared spectrum (right)

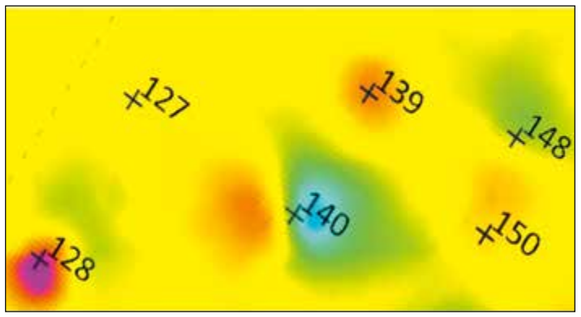

Fig. 3: Image of a magnetometer UAV with automatically marked and numbered suspicious objects

Fig. 4: R&D-demonstrator of a UAV-borne ground penetrating radar system for explosive ordnance detection

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Fluidic thrust vectoring: Design, characterisation and influence on engine and mission

In the design of future aircraft, the implementation of more powerful electronics and subsystems as well as the improvement of aerodynamic and stealth properties are of paramount importance. A development that has the potential to positively influence the efficiency, agility and detectability of the aircraft is fluidic thrust vector control.

In order to enhance the efficiency, agility and signature (both radar and infrared) of unmanned aerial vehicles, the Institute of Jet Propulsion (IJP) at the University of the Bundeswehr Munich is conducting research into fluidic thrust vector control (FTV) on behalf of the Bundeswehr Technical Centre for Aircraft and Aeronautical Equipment (WTD 61). This method has been utilised for the first time in space travel but remains largely untapped in aviation. The utilisation of FTV promises to offer numerous potential advantages over conventional mechanical thrust vector control, including reduced mass and mechanical complexity, a reduction in aerodynamic drag, and a radar signature enhancement due to the elimination of external moving components.

To date, numerical investigations at the IJP have primarily focused on the integration of the FTV methodology into the B300 turbojet engine from the manufacturer AeroDesignWorks. The concept for deflecting the exhaust plume is based on the Coanda effect. The functional principle of this phenomenon is demonstrated in Fig. 1. In addition to the classic primary exhaust gas jet (red), an additional Coanda mass flow (blue) is

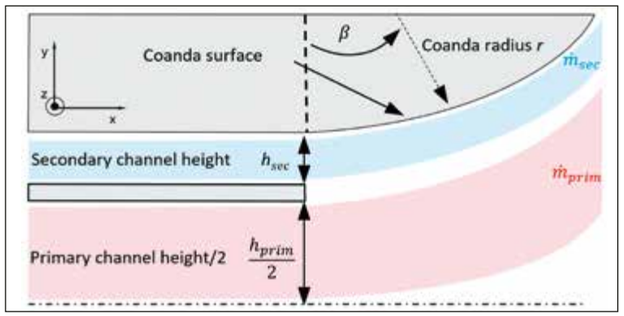

Fig. 1: Operating principle: fluidic thrust vector control based on the Coanda-effect

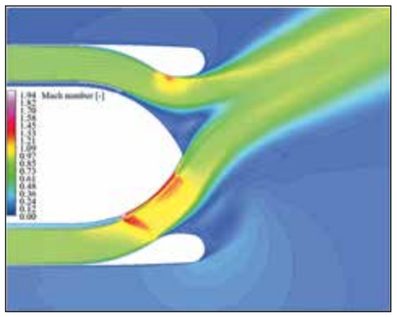

Fig. 2: CFD-simulation of a Coanda-coflow nozzle

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blown into the nozzle between the primary jet and the wall, as required. Due to the high velocity and the resultant low pressure in the Coanda jet, it adheres to the convex surface and is thus deflected in the direction of this surface. A momentum exchange occurs between the Coanda jet and the primary jet, resulting in the deflection of the primary jet in the desired direction. The investigation of the nozzle at the IJP has shown that maximum thrust deflection angles (β) of up to 30° can be achieved, depending on the geometric design (Fig. 2). These values are comparable to those of conventional systems, such as the Lockheed Martin F-22 ($\beta_{max} \approx 20°$). Furthermore, the FTV method under investigation demonstrates an operating point-independent behaviour. The investigation of FTV concepts at the IJP focuses on two-dimensional thrust vector nozzles, which have the capacity to generate an additional thrust component in the y-direction (F_y).

In addition to the behaviour of the thrust vector nozzle in a stationary ground state, the unsteady behaviour of the nozzle is also evaluated and the performance is analysed over a generic flight mission of an aircraft designed at the IJP (Fig. 3) with an integrated FTV nozzle. It has been demonstrated that the fluidic thrust vector nozzle exhibits an excellent responsiveness, with no discernible hysteresis effects, a property that is of paramount importance for its integration into a flight control system.

Moreover, the investigation is underway to ascertain the influence of the fluidic thrust vector nozzle on the performance of the engine and the mission. The Coanda mass flow can be provided in a number of ways, for example, in the form of bleed air from the engine compressor or by an additional external compressor. It is observed that both variants exert a distinct influence on the engine cycle. Moreover, the impact of fluidic thrust vector control on the potential reduction in elevator size has been examined. A preliminary analysis indicates a 21 % reduction in elevator area, concomitant with a decrease in aerodynamic drag. As part of its research on this topic, the IJP has initiated the development and validation of design tools for such nozzles and will also expand the investigations with regard to scalability to large-scale applications such as combat aircraft.

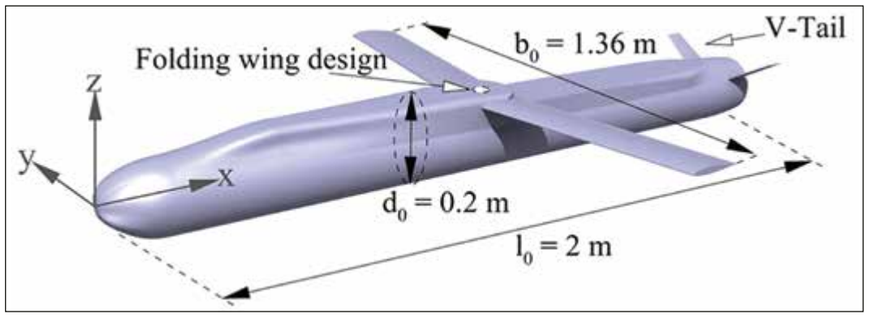

Fig. 3: Generic reference aircraft used for FTV nozzle integration

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The ALFACaD project: Automated Low-Flying Aerial Cargo Delivery

The ALFACaD project examines a drone for the safe and autonomous transport of heavy loads in difficult terrain. The goal is a cost-efficient system with a payload of up to 125 kg and a range of 250 km. In 2024, flight capability, sensor integration, and integration into the Bundeswehr command and control system were successfully demonstrated. Future updates will enhance efficiency and reliability for deployment in challenging conditions.

The ALFACaD project aims to explore a modern solution for transporting heavy loads in challenging operational environments. Modern military missions require fast and reliable logistics, especially in rough terrain. The focus is on loads exceeding 100 kg to be transported efficiently and safely to inaccessible locations that are difficult or impossible to reach by vehicles.

The project involves a drone that can be deployed without specialised personnel or infrastructure on-site. Using drones is intended to reduce risks for human crews in dangerous missions and alleviate the burden on manned air transport systems. Moreover, the drones need to be cost-efficient to enable large-scale deployment.

Technologically, the project focuses on testing an unmanned helicopter drone with vertical take-off and landing capabilities. The drone is to operate highly autonomously and deliver loads precisely from a hovering position using a winch. The goal is to achieve a range of up to 250 km and a payload capacity of up to 125 kg. The necessary technologies are tested in realistic scenarios to ensure a balance between performance, availability, and cost.

Significant progress was made in the project's first phase in 2024. The drone's baseline configuration successfully demonstrated its flight capabilities (Fig. 1), including an operational approval for the German airspace and a hovering time of one hour. Key sensors were also integrated to enable future features such as gesture control and low-altitude flight. Data collected during the tests are being used to optimise the sensor system. Furthermore, the drone was integrated into the Bundeswehr's digital command and control system (Fig. 2) and successfully deployed in realistic logistics scenarios (Fig. 3).

The system tested in ALFACaD offers numerous advantages for Bundeswehr soldiers. It enables a rapid supply of materials and equipment, even in hard-to-reach areas, and can operate without additional infrastructure on-site. The drone helps reduce risks for personnel in dangerous missions and eases the burden on manned air transport systems, providing flexibility for critical operations.

The next phase of the project will test advanced configurations. An avionics update will ensure the drone's reliability under disrupted conditions, such as GPS interference, and add features like automatic take-off, rotor shutdown, and fully automated flight missions. These developments aim to further enhance the drone's efficiency and operational capabilities.

The results from the first project phase provide a solid foundation for future developments. In the long term, the ALFACaD system is expected to offer the Bundeswehr a modern, safe and efficient solution for transporting heavy loads, which will significantly improve both the operational capability and the safety of military personnel.

Fig. 1: Drone in hover flight

Fig. 2: Integration into the Battle Management System of the German Armed Forces

Fig. 3: Drone in a logistics test scenario

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Flight testing of an aerospike rocket engine in the RDRS project

The Rapid Deployable Reconnaissance System (RDRS) project is an innovation initiative of the Bundeswehr Drone Innovation Hub (DIH), in collaboration with POLARIS Raumflugzeuge GmbH and branch 470 "UAS Overall Systems & UAS National Competence Centre" at the Bundeswehr Technical Centre for Aircraft and Aeronautical Equipment (WTD 61). The project focuses on developing technologies for future spaceplane and hypersonic systems.

Horizontal-take-off spaceplanes represent a novel category of space transportation systems that operate like conventional airplanes from standard runways and do not require specialised ground infrastructure in the form of a spaceport. Due to the potentially high value for military applications, the RDRS project is conducting an investigation and an evaluation of POLARIS's Aurora spaceplane (Fig. 1) for use as a flexible and globally deployable space-based and hypersonic reconnaissance platform.

The system is powered by a combination of turbojet engines and rocket engines, with the turbojet engines used for takeoff, landing and cruise flight, while the rocket propulsion is ignited in the air to execute acceleration missions.

In a subtask of the project, flight tests were conducted in 2024 using various scaled demonstrators (Fig. 2). One of the objectives was to flight test a novel propulsion system, known as a linear aerospike rocket engine. A proof-of-concept demonstrator engine with a design thrust of 1 kN was also developed and manufactured as part of the RDRS project.

Linear aerospike rocket engines promise efficiency improvements of up to 30 % compared to conventional rocket engines and can also be constructed in a more compact manner. Previous work on linear aerospikes, such as that conducted by NASA in the USA, has been limited to ground tests.

However, on October 29, the 5-meter-long flight demonstrator MIRA II successfully ignited such a rocket engine in the air for the first time – a world premiere (Fig. 3). The approximately 4-minute flight, with an initial aerospike burning time limited to 3 seconds, took place from Peenemünde airfield over the Baltic Sea in restricted airspace. Kerosene and liquid oxygen (LOX) were used as propellants. After completing the mission, MIRA II safely landed back at the airfield. Despite a reduced combustion chamber pressure for safety reasons, a thrust of around 900 N was measured during the aerospike operation. This marked the first successful demonstration of a thrust-generating linear aerospike in an aircraft.

As another component of the global operational capability of spaceplanes, the topic of automatic aerial refuelling was also investigated. Promising initial flight tests were conducted in parallel to the aerospike activities, aiming for automatic approach and formation flying of two aircraft (Fig. 4).

Both the aerospike flight tests and the flight tests for automatic aerial refuelling will continue throughout 2025.

The next development steps on the way to the spaceplane include the development of a supersonic demonstrator, which is expected to be ready to fly by the end of 2025. The first flight of the first full-size spaceplane is planned for 2028, provided that the necessary funding can be made available in a timely manner. The funding of the project is largely intended from private investments. The Bundeswehr can play a significant role as a potential anchor customer in realising the project.

Hypersonic spacecraft leverage the synergies between commercial spaceflight and military application scenarios to the fullest extent as dual-use systems. As intrinsic multipurpose platforms, they offer the Bundeswehr and allied partners the potential to provide entirely new capabilities in satellite transport, high-speed aerial reconnaissance and the deployment of effectors.

Fig. 1: Spaceplane Aurora

Fig. 2: MIRA II flight preparation

Fig. 3: Aerospike ignition

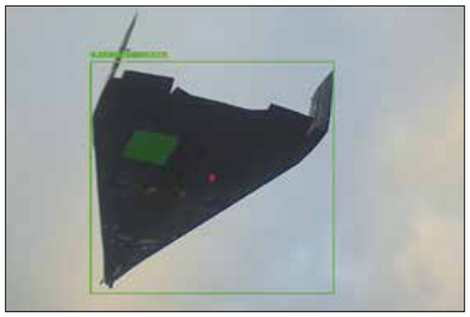

Fig. 4: Approaching the simulated tanker

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Underwater glider for military applications

The German Navy's objectives for 2035 and beyond ("Zielbild 2035+") call for a forceful exploitation of the use of unmanned underwater vehicles and platforms. To this end, the Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research (WTD 71) investigates the potential of underwater gliders for military applications. As part of the Portuguese-led NATO exercise REPMUS 24, the use of underwater gliders as a means for underwater acoustic surveillance was examined.

Underwater gliders are a special type of unmanned underwater vehicles (UUV). They are a well-established oceanographic measurement system used both in civilian and – to a somewhat lesser extent – military applications. Due to their efficient buoyancy propulsion drive, gliders achieve operating times in the range of weeks or even months, depending on the sensor configuration. Noteworthy civilian deployments are an Atlantic crossing and below polar sea ice operations. Gliders will surface only if data are to be transmitted or new mission parameters are to be received. During periods of diving, gliders operate covertly. A disadvantage of gliders is their limited mobility.

WTD 71 investigates two possible military applications of gliders. The applications are based on very low levels of vibration and acoustic self-noise of gliders. The first feature enables gliders to serve as platform for microstructure sensors to detect underwater turbulences, e.g. the turbulent wake of UUVs or submarines. The second feature offers the possibility to equip gliders with high-sensitivity acoustic sensors for underwater acoustic surveillance. In 2024, underwater acoustics was the primary focus of WTD 71's work with gliders.

Fig. 1: A photo of WTD 71's Slocum glider taken during an in-sea swap of hydrophones. The acoustic recording system OceanObserver is integrated into this glider. The embedded image shows the official REPMUS 24 logo

Fig. 2: Photograph of the two TWR gliders. For both of them, the OceanObserver acoustic recording system was built into an extra housing, mounted on top of the glider. As part of the data analysis, the pros and cons of the different configurations are being evaluated (with respect to flow drag, acoustic self-noise, ease of maintenance, etc.)

In September 2024, WTD 71 participated with two Slocum gliders, manufactured by Teledyne Webb Research (TWR), in the NATO exercise Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 24, which is led by the Portuguese Navy and is currently considered the largest maritime exercise for experimentation with unmanned systems. A total of 11 underwater gliders from two different manufacturers and owned by various institutes and nations were operated simultaneously. One of WTD 71's Slocum gliders (Fig. 1) and two TWR gliders (Fig. 2) were equipped with an array of four hydrophones (Fig. 2) and the acoustic recording system OceanObserver from JASCO Applied Sciences. The use of an acoustic array allows for acoustic bearing estimation.

With these three acoustic gliders, it was examined whether a swarm of gliders is suitable for underwater acoustic surveillance. The gliders were tasked to collect acoustic signals (including signal bearing) that were emitted by various other UUVs. They were programmed to detect some pre-defined signals and to transmit these detections via satellite telemetry to operations control on shore. It is worth noting that due to limited bandwidth, only information about the detection events can be transmitted via satellite telemetry, but not the underlying acoustic raw data. Hence, the detection algorithms had to be implemented in the OceanObserver on the glider. Detection events (if existing) were transmitted during surfacings together with other data like status, position, oceanographic data, etc. All these data were integrated into the data visualisation tool SeaSuite (Fig. 3, Fig. 4), developed and operated by Blue Ocean Marine Tech Systems (BOMTS). Using the Collaborative Autonomy Tasking Layer (CATL) protocol, SeaSuite distributed the information to a number of REPMUS 24 operational picture tools.

From an operational point of view, the surface-on-detect behaviour of the gliders is of particular interest. It is a feature that has been implemented and tested by JASCO for the first time at REPMUS 24. Its goal is to enable near-real-time transmission of a detection event to the operational picture, achieved by programming the glider to immediately surface as soon as a detection has occurred.

Current estimates indicate that underwater acoustic gliders may already be considered a viable means for underwater acoustic surveillance. Because of their limited mobility and due to the latency of the information they provide, gliders should not be considered tactical assets but to provide strategic persistent maritime surveillance and early warning and indicating in support of the NATO ASW Barrier Concept.

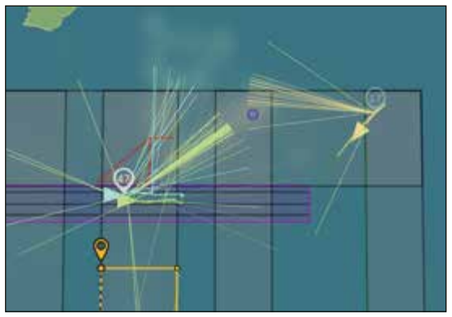

Fig. 3: Near-real time operational picture of glider position and tracks from 18 Sep 2024 along with associated bearings from detections throughout the day, all displayed in SeaSuite. All three gliders appeared to be detecting a target in the same area

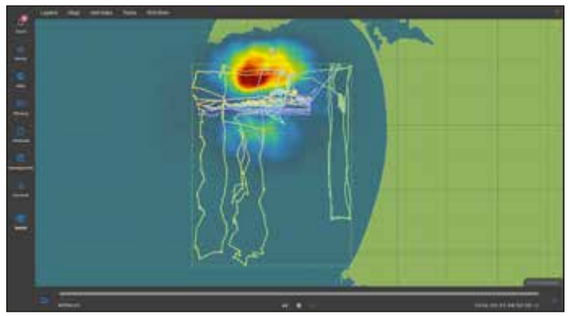

Fig. 4: SeaSuite replay of tracks of all five Slocum gliders for the entire deployment period from 11 to 24 September 2024. The three acoustic gliders were operating mainly along east-west oriented tracks, and the acoustic targets were located in the reddish area north of the gliders

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Synthetic aperture sonars: More than a better side scan sonar

Commercially available synthetic aperture sonars (SAS) were developed with the aim of avoiding the disadvantages of a classic side scan sonar. The synthetic aperture offers further potential, which is being investigated as part of research at the Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research (WTD 71) together with Helmut Schmidt University / Bundeswehr University Hamburg.

In minehunting, the aim is to reliably detect and classify objects with a high area coverage rate. Side scan sonar systems are ideal for this purpose. These systems image an area perpendicular to their direction of travel. However, this sensor has several limitations. A high frequency is required for a good angular resolution, but the attenuation of sound in water also increases with frequency, thus reducing the area coverage rate. In addition, the constant angular resolution leads to the problem that the detection and classification performance of the system is dependent on the distance to the object.

These undesirable properties can be avoided by using SAS. The successful implementation of SAS was only achieved about 50 years after the realisation of a synthetic aperture radar. Since the first realisation of SAS, the systems have been developed to such an extent that they are now commercially available from various companies. SAS does not have the above-mentioned negative characteristics of a conventional system. The resolution is distance-independent, and the system can be used with lower frequencies, which improves the area coverage rate. The system can therefore be regarded as a better side scan sonar.

With the commercial availability of these new sonar systems, the development could be regarded as completed. However, if we look at the possibilities offered by the design of a synthetic aperture system, a completely different picture emerges. For example, although the freedom of choice of the frequency band is used to increase the range or the distance-independent resolution compared to a conventional side scan sonar, almost all current SAS systems only use one frequency band. This ignores the fact that the backscattering and propagation properties of the sound on objects – especially on soft sediments – are frequency-dependent. Furthermore, conventional side scan sonar requires the straightest possible movement in order to avoid distortions in the sonar image. This is not the case when using a synthetic aperture per se, as the changes in movement and orientation are considered when processing the images. For example, circular missions can be realised to further improve the imaging of the objects.

Fig. 1 shows a 25 m x 25 m image from a circular SAS mission, in which the sound is reflected at the uppermost boundary layer between water and sediment. Fig. 2, on the other hand, shows the same scenario with a signal with a lower frequency being used. Here, an additional object can be seen in the upper left half. The data of both images were recorded at the same time on the same vehicle. Apart from the frequency, the only change in Fig. 2 is focused on a plane 60 cm below the surface of the sediment, i. e. the object is buried. In this case, the diameter of the additional object matches its expected size. To better illustrate the difference, the data resulting from the high-frequency signal were stored on the red RGB channel and the data from the low-frequency signal on the green RGB channel (Fig. 3).

This example shows that the synthetic aperture sonar can be more than just a better side scan sonar. However, in order to exploit this potential, a design adapted to the possibilities of the synthetic aperture is required. This applies not only to the sonar, but also in particular to the carrier platform in order to be able to implement the necessary travel profiles. For example, a spiral movement, i.e. a variation in height, while travelling in a circle would provide three-dimensional information, and the objects shown in Fig. 2 could be separated vertically. Even though SAS is now offered as a high-performance product by various companies, the potential of this sensor technology is far from exhausted.

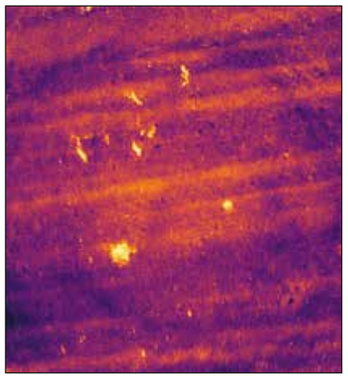

Fig. 1: Circular SAS image based on high-frequency sonar signal

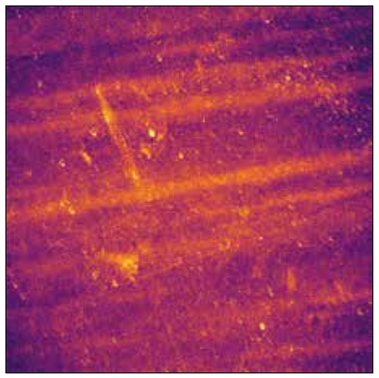

Fig. 2: Circular SAS image based on low-frequency sonar signal

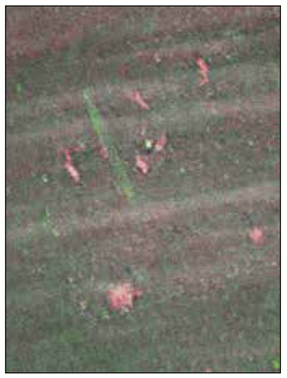

Fig. 3: Section of the overlay of both image data with high-frequency data on the red RGB channel and low-frequency data on the green RGB channel

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Target Handoff System and OSINT geolocation

Methods for optically supported self-localisation and target handoff were upscaled to analyse the usability for the geolocation of images and recordings from open sources (open-source intelligence – OSINT). AI-supported 3D information from map services and geolocated recordings was extracted and transferred to localisation indices, which were compared with the recordings to be localised.

In conflicts, GPS jamming and disinformation play a significant role. In the Ukraine war, both Russian and Ukrainian armed forces are using electronic warfare to impair the enemy's navigation and communication systems. Russia is using GPS jamming to decrease the precision of the systems used by the Ukraine and is spreading targeted disinformation in public sources to conceal its own activities.

Image-based 3D localisation technologies can enable systems to counteract these disturbances and disinformation. Image-based localisation is achieved by determining a common coordinate system (registration). This is based on comparing visual information from images or sensors with existing cartographic, preferably georeferenced databases (Fig. 1). Relevant features are extracted from the images and compared with previously created and indexed reference data.

Specialised algorithms of machine learning are used to identify matches and to precisely localise the position of the image and the objects. A combination with other localisation methods such as GPS, inertial measurement units (IMU) or visual-inertial odometry (VIO) and simultaneous localisation and mapping (SLAM) is possible at any time of the process to enable continuous, real-time position determination.

This technology also allows a highly precise derivation of target coordinates and their efficient distribution in a network, a target handoff based on optical 3D data. The bandwidth required for transmission is extremely low, since only individual coordinates are transmitted with metadata. A purely optically supported target handoff system (THS) with accuracies of less than one metre, partly even under non-line-of-sight conditions, has already been demonstrated. The procedure was robustified to optical changes and also transferred to the infrared spectrum.

The application of these registration procedures to localise image data from open sources and without georeferencing was further examined. This can significantly simplify the interpretation of images from uncertain or unknown origin as a contribution to open-source intelligence (OSINT). For example, images from current conflict regions can be spatially assigned and thus contribute to military reconnaissance and to checking the alleged image content and locations – and therefore detecting false claims or so-called fake news.

Among other things, photogrammetric methods were used to index data and create a localisation database purely from open maps and sources such as Mapillary or other known or assignable image and video data (Fig. 2) or to supplement existing georeferenced indices. Three-dimensional models were generated from public data, which in turn can be used to localise images from open sources (Fig. 3).

The AI-supported algorithms developed for object localisation compare the image registration with the sometimes very large localisation index database. These automatic, AI-supported processes allow precise geolocation of social media image and video data to be determined and checked with very high reliability (Fig. 4).

An OSINT analysis can also be enhanced with textual image descriptions. Multimodal foundation models trained to link image and text data can combine information from both modalities – visual and textual data. Complex relationships between images and descriptions can be created automatically and help to determine locations precisely.

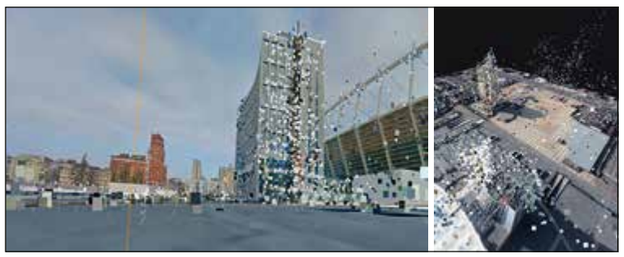

Fig. 1: Registration of an image (Kyiv, Ukraine) with generated 3D localisation index

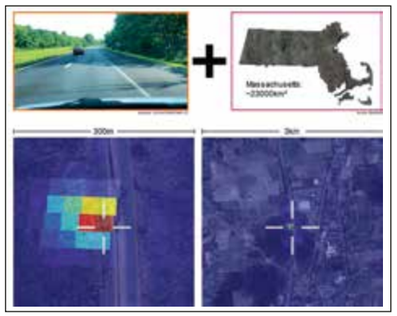

Fig. 2: Geolocation of an image content from a public source and without geoinformation, based only on available aerial photographs and a completely untrained environment. A georeferenced accuracy of less than 50 metres – depending on the quality of the aerial photograph data – is achieved in this special case

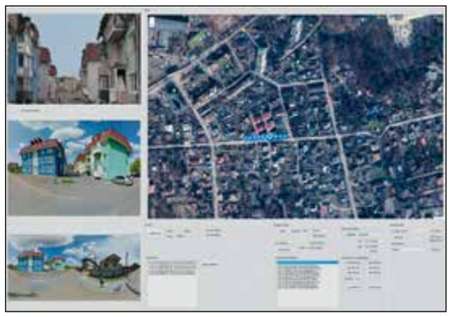

Fig. 3: Example of a 3D reconstruction (top left) and localisation of image content (top) from the Bucha region in Ukraine based on publicly available image data

Fig. 4: Example of a 3D reconstruction (bottom left) and localisation of image content (top) from the Bucha region in Ukraine based on publicly available image data

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MILOS-D laser weapon system: High-precision and cost-effective effector for land-based and special operations forces

The military use of lasers as an effector offers significant advantages: In addition to cost efficiency, precision and scalability, there is also no need to stockpile ammunition. Small, portable laser weapon systems (LWS), such as MILOS-D (Modular Integrated Laser Optic System – Dismounted), developed by MBDA Deutschland GmbH in coordination with the government, also offer high operational potential for land-based forces.

The use of LWS in military technology opens up a wide range of applications across all types of troops. In close cooperation with the army, the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support (BAAINBw) and the Bundeswehr Technical Centre for Weapons and Ammunition (WTD 91), MBDA Deutschland GmbH developed the MILOS-D, a mobile LWS that can be operated in a portable/dismounted mode (Fig. 1) to significantly expand the possibilities of military warfare.

In its current configuration, MILOS-D is primarily designed to covertly combat infrastructure, to breach, create access points, or trigger mines.

This results in a target spectrum that includes static targets such as barbed wire barriers, electro-optical sensors, antenna structures, or mines (IEDs). In general, the creation of access is not time-critical. Therefore, the focus in terms of system design was primarily on low weight and secondarily on engagement time. In dismounted operations, the system should be able to be carried and operated by two to three soldiers.

Fig. 1: MILOS-D test sample consisting of laser effector, pan / tilt unit, tripod, laser source, battery and tablet

Fig. 2: Laser effector with pan/tilt unit mounted on UGV – Rovo self-propelled platform

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Critical technological issues regarding the development of such an LWS relate to precision capability, system complexity, operability, and interfaces. The influence of turbulent air masses is a particular challenge for ensuring precision capability when used against static targets close to the ground. For autarkic laser operation, it is also necessary to provide maximum electrical power at very short notice.

The current test sample operates with 3000 W power at distances of up to 1 km. It is operated via tablet. Additional safety devices ensure the safe operation of the LWS. The use of modular components and standardised interfaces ensures synergies during development and in the logistic concept. The common technology basis has already been developed as part of R&T contracts. In addition, it is already possible to use the laser effector on an unmanned ground vehicle (UGV) (Fig. 2).

MILOS-D is the first version of a multi-stage system family with laser effectors of different performance classes to cover the requirements of the army. Based on an initial laboratory sample, MBDA Deutschland GmbH has iteratively developed the mobile LWS. In 2024, the test sample was presented, which was operated independently by trained WTD 91 personnel for the first time and thus allows extensive testing within the Bundeswehr (Fig. 3).

The system demonstrated its capabilities in several campaigns – most recently as part of the “experimental series land”, in which its applicability was examined from an operational perspective and an LWS was used impressively for the first time in a tactical land-based operation on a military training area (Fig. 4). The knowledge gained on transportation and handling will be incorporated into the further development of the system.

With the current configuration level, another important milestone has already been reached in the development and introduction of LWS in the Bundeswehr. Future efforts will focus on a significant increase in power, the realisation of the engagement of moving targets such as drones by means of coarse and fine tracking and the use of the laser effector on a UGV for engagement on the move, which will further expand the range of military applications.

Fig. 3: Laser effector with pan/tilt unit mounted on UGV – Rovo self-propelled platform

Fig. 4: Use of MILOS-D in a military tactical training scenario; army soldiers operate the test sample to breach barriers

3

Military Medical Research and Military Psychology Research

In 2024, the departmental research institutes and hospitals of the Bundeswehr Medical Service once again performed a wide range of research aimed at protecting and restoring the health of soldiers in a variety of situations.

The Bundeswehr Central Hospital Koblenz presents iMEDCap, a project financed by third-party funds from the European Defence Fund, in which civilian and military partners are jointly developing a capability to rescue casualties with autonomous aircraft or ground vehicles.

The Bundeswehr Hospital Ulm reports on the treatment of a soldier suffering from lung cancer whose tumour was successfully treated by precise characterisation and the use of state-of-the-art active substances, despite having developed high-grade resistance.

The Bundeswehr Hospital Berlin has been examining life-threatening bacterial resistance and presents bacteriophages, i. e. special viruses that exclusively infect bacteria, as a new treatment option.

The department of tropical medicine at the Bundeswehr Hospital Hamburg has been developing and validating a system for detecting malaria pathogens in the insects that transmit them (so-called vectors) that can be used in the theatre of operations.

The Bundeswehr Institute of Radiobiology has been able to detect effects on gene expression even through low radiation doses, e. g. in X-ray computed tomography, thus underlining the importance of radiation protection in medical diagnostics.

The Bundeswehr Institute of Microbiology describes methods for the detection and molecular characterisation of the bacterial pathogen Francisella tularensis, which occurs in natural outbreaks but is also a cause for concern as a potential bioweapon.

The Bundeswehr Institute of Pharmacology and Toxicology reports on the development of new drugs for the treatment of nerve agent poisoning, from their molecular design to tests in tissue models.

The Bundeswehr Institute of Preventive Medicine presents its studies on maintaining operational readiness during marches.

As a contribution to flight safety, the Air Force Centre of Aerospace Medicine has been investigating the duration of the effects of simulator training on the vestibular organ. The Naval Institute of Maritime Medicine outlines its research into combat swimmer training, including a new approach to reducing unnecessary discontinuation of training.

In terms of topics and funding through national and European third-party funds, military medical research is thus consistently pursuing innovative ways to provide an efficient Medical Service in a fit-for-purpose Bundeswehr with optimal capabilities for protecting the health of its soldiers.

The Psychotrauma Centre at the Bundeswehr Hospital Berlin and the University of the Bundeswehr Munich have jointly analysed how many soldiers with symptoms of deployment-associated mental disorders have sought medical treatment following deployments in Afghanistan, Mali or Iraq. The analysis is based on anonymised data from a deployment database. This database contains information on soldiers who have presented themselves to military psychiatric or military psychotherapeutic facilities of the Bundeswehr Medical Service and who suffer from a mental disorder that can be traced back to their deployment. The results of this study show that the frequency of diagnosed disorders differs between deployments.

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Cultural detection and molecular epidemiological analysis of *Francisella tularensis* from ticks

An improved isolation method for *Francisella tularensis* was developed and tested on infected ticks. Outbreak isolates generated by this method can be used for antibiotic sensitivity tests for therapeutic advice and high-resolution epidemiological investigations, e.g. to differentiate between natural and intentionally induced disease outbreaks.

Francisella tularenesis, the causative agent of tularemia, is a gram-negative bacterium that can be transmitted via aerosol, food and bloodsucking vectors, ticks or mosquitoes. Due to the very low infectious dose and the sometimes very severe course of the disease, it has been part of various bioweapon programmes in the past. Further military medical relevance for tularemia results from vector transmission, as the risk of exposure is increased by being outdoors. For in-depth analysis of the pathogen, both to support the therapeutic treatment of patients and to differentiate between natural and intentional outbreaks of the disease, cultivation of the pathogen is the best option. Clinical materials from patients as well as environmental samples can be used for this purpose. In order to improve the success of cultural isolation, a new medium was designed, based on examples from the literature, and its applicability for the isolation of *Francisella tularensis* from ticks was tested. Since *Francisella tularensis* is fastidious to cultivate, the medium is enriched to propagate Francisella growth, i. e. by the addition of haemoglobin, and the growth of accompanying germs is also suppressed by adding antibiotics that would otherwise make isolation more difficult.

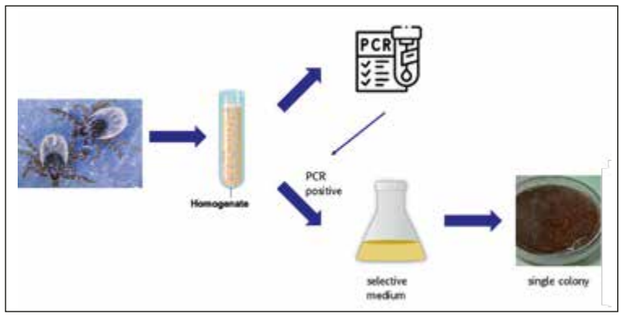

Fig. 1: Workflow of the isolation of *Francisella tularensis* from ticks

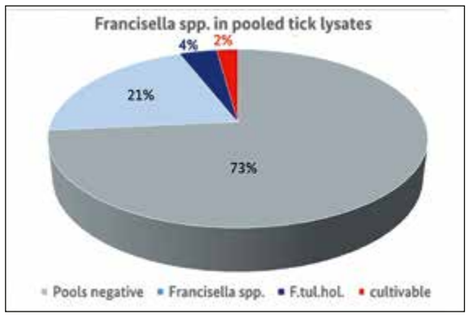

Fig. 2: Results of the analysis of ticks for *Francisella tularensis*. In 6 % of pooled ticks, *Francisella tularensis holarctica* DNA was detected by PCR. In 2 % of the pooled ticks, the isolation was successful

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In order to test the new isolation medium on real samples, ticks from an area in which a patient had developed tularemia after a tick bite were analysed. The ticks were analysed for the presence of *Francisella tularensis* using PCR, and isolation of *Francisella tularensis holarctica* strains with the new medium was attempted. Isolation was successful for tick samples from the years 2022 to 2024. The sensitivity of all isolates to therapeutically important antibiotics was then determined using microdilution assays. Only through this testing with the isolated strains can sound therapeutic advice be given for treatment. As expected, the strains were sensitive to all antibiotics tested. Furthermore, the DNA of the strains was prepared and the genetic information sequenced and bioinformatically analysed.

This revealed a very close genetic relationship between the strains. The strains form a separate cluster within the *Francisella tularensis holarctica* strains known from southern Germany. As all isolates belong to this cluster, a natural focus for *Francisella tularensis holarctica* could be identified, i. e. an area in which the bacterium is in equilibrium with its natural hosts (rodents, lagomorphs) and the transmitting ticks.

Through these investigations, an improved method for the isolation of *Francisella tularensis* has been established, which can now be used to isolate strains of the bacterium from difficult sample materials. This can be carried out with clinical and environmental samples to investigate suspected intentional release. It is thus possible to determine the resistance spectrum of strains, allowing targeted countermeasures to be taken. In addition, high-resolution analyses, e. g. of the genome of the strains, can provide information on the natural or non-natural origin of the inducing agent.

	MHK (µg/ml)	Breakpoint CLSI	
Gentamicin	0,25	4	S
Streptomycin	0,5	16	S
Doxycyclin	0,125	4	S
Tetracyclin	0,125	4	S
Ciprofloxacin	0,004	0,5	S
Levofloxacin	0,25	0,5	S

Fig. 3: Results of antibiotic sensitivity testing. All isolates were sensible to the antibiotics used therapeutically against *Francisella tularensis*

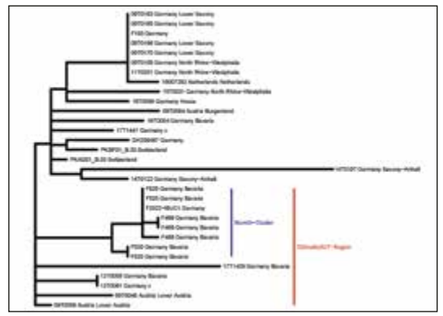

Fig. 4: Phylogenetic tree of *Francisella tularensis* from central Europe. The isolates form a separate natural cluster (blue bar) within the strains originating from the southern part of Germany and Austria (red bar)

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Novel antidotes for the treatment of warfare agent poisoning: From virtual structure suggestions to testing in tissue

One possible approach for the development of novel antidotes for the treatment of chemical warfare agent poisoning is the iterative process of molecular modelling, targeted synthesis and pharmacological testing on the corresponding target organs. The efficient coupling of these three methods increases the identification of promising drug candidates.

The development of new antidotes for the treatment of chemical warfare agent poisoning is a particular challenge. A process consisting of three iterative approaches has proven to be successful. These are virtual, synthetic chemical and pharmacological methods. Standard methods cannot be used in molecular modeling and chemical synthesis, but new strategies must be developed. Specific methods are required for the pharmacological screening of the target organs to gain a realistic insight into the pathological processes of warfare agent poisoning.

This iterative concept has been used for several years in drug development for the treatment of nerve agent poisoning. The current global political situation makes it clear that nerve agents represent a major threat more than ever before. The limited medical treatment options are extremely critical, especially in a mass casualty situation with poisoned patients. An antidote that has a broad spectrum of activity and can be administered as part of self and buddy aid would be helpful.

After incorporation, nerve agents inhibit the essential enzyme acetylcholinesterase, leading to an accumulation of acetylcholine in the synaptic cleft and thus to receptor dysfunction. If left untreated, the poisoning leads to death by respiratory arrest. The current therapy of atropine to treat the muscarinic symptoms and obidoxime to reactivate the inhibited acetylcholinesterase is not sufficiently effective, as is the case, for example, with poisonings with soman, tabun, and novichok. In these cases, the muscle function remains impaired because the nicotinic acetylcholine receptors (nAChRs) remain in a dysfunctional state and the transmission of stimuli in the neuromuscular endplate fails. An innovative therapeutic approach would therefore be active substances that interact directly with these receptors and restore their function despite the existing toxic effect.

Molecular modelling is used to generate a human homology model of the nAChR, with the functional receptor state reflecting the pathological situation of nerve agent poisoning (Fig. 1). A virtual screening is then carried out (Fig. 2), which is based, among other things, on the docking of structures in binding pockets of the receptor (Fig. 3). The structure suggestions obtained in this way are then checked for synthesis possibilities.

For this, new synthesis strategies usually have to be developed so that reproducible, chemically stable compounds can be produced in the highest possible yield. These chemical compounds are examined in pharmacological test systems that, on the one hand, reflect various molecular pharmacological levels (receptors versus tissue) and, on the other hand, reflect the poisoning as realistically as possible. In the screening methods, the dysfunctional receptor state is induced and the effects of the new test substances on the affinity at the receptor are observed (Fig. 4).

In myographic measurements of muscle tissue, the diaphragm hemispheres of rats are paralyzed with soman, and then examined for a possible restoration of muscle function after the addition of test substances (Fig. 5 and 6).

Clear correlations of the results obtained by the different testing approaches reflect the quality of the virtual screening. Undesirable effects can be eliminated in the next steps and selectively acting compounds can thus be developed. The results achieved so far show that the iterative process of molecular modelling, targeted synthesis and screening in various pharmacological test systems has proven successful in this extremely special drug development.

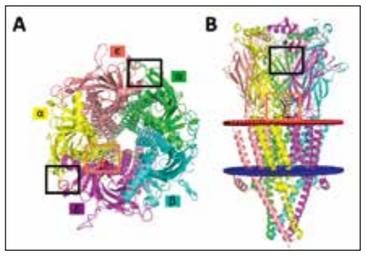

Fig. 1: The human muscle-type nAChR viewed from (A) the extracellular space and (B) the side. The orthosteric binding pocket (binding site of the endogenous ligand acetylcholine) is marked with a black box. The orange box indicates the location of the newly identified allosteric binding site. The membrane is marked with red (extracellular) and blue (intracellular) border spheres (source: Kaiser et al., 2023)

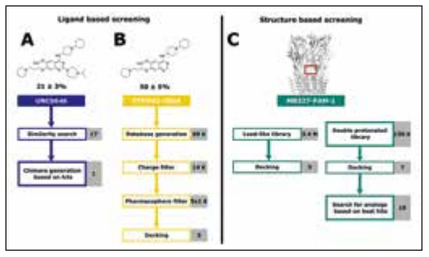

Fig. 2: Screening strategies to identify novel binders. A, B: ligand based screening; C: structure based screening in the human homology model of the nAChR. (source: Modified figure from Kaiser et al., 2024)

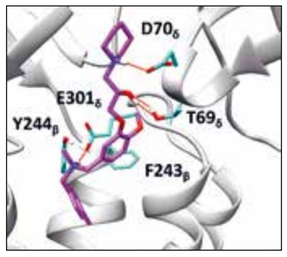

Fig. 3: Docked binding mode of an active ingredient candidate in the binding pocket between the α- and δ-subunits of the human muscle-type nAChR (source: Kaiser et al., 2024)

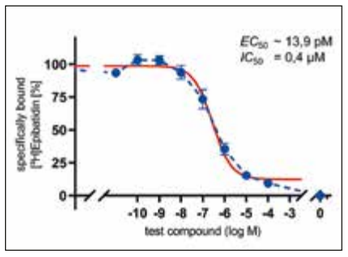

Fig. 4: In the radioligand binding assay, the reporter ligand [^{3}H]epibatidine is displaced by the test substance in a concentration-dependent manner. The dashed line shows a biphasic curve

Fig. 5: Multi-organ bath with 12 myographs to examine the function of respiratory muscle preparations from different species. Investigation of new compounds on respiratory muscle poisoned by chemical agents

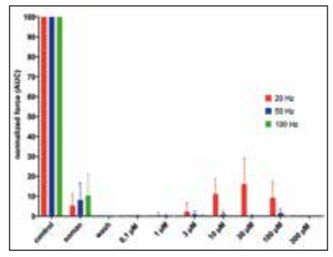

Fig. 6: Restoration of muscle strength after paralysis of the respiratory muscles with the nerve agent soman through addition of a test substance. Contraction of the rat respiratory muscles were measured after indirect electrical field stimulation

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Efficiency in military marching: Studies on stress, fatigue and performance maintenance during foot marches

Marching remains a relevant military task that must be completed efficiently to ensure operational readiness at the destination. The aim of this series of studies is to measure the physiological stress and fatigue during marches under realistic conditions in order to optimise march and supply planning, taking into account preventive medical and performance-oriented aspects.

Despite the increasing mechanisation of the armed forces, the military march remains an essential task for soldiers. However, the foot march is only one part of a military mission and must therefore be completed with as little fatigue as possible in order to be mission capable at the destination.

The parameters combat loads, thermal insulation by clothing and equipment, terrain, climatic influences, distance and speed, in conjunction with personal performance characteristics, determine the individual physiological stress and the resulting fatigue caused by marches. When planning a military operation, these parameters can only be controlled to a limited extent: While parameters such as clothing and equipment are specified by the operation order, climatic factors can only be controlled to a limited extent during the planning phase, e. g. by the chosen time of day. On the other hand, superiors are able to adjust marching speeds when preparing for operations by planning a longer marching time.

Own marching studies with loads showed that when speed was increased by 1.5 km/h, the physiological strain increased

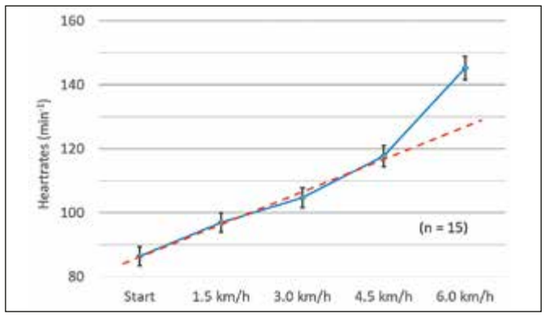

Fig. 1: Step-wise marching test on a treadmill (starting at 1.5 km/h and increasing by 1.5 km/h every 240 s up to 6 km/h with a total load of clothing and equipment of approx. 31.3 kg). The increase from 4.5 km/h to 6 km/h shows a disproportionate and non-linear increase in heart rates (mean value and standard error)

Fig. 2: On-site task analysis with concomitant recording of exercise-physiological parameters during an exemplary foot march of infantrymen with a total load of 32 kg each (clothing, equipment and weapons) at 4.5 km/h and 6 km/h marching speeds

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disproportionately when changing from 4.5 km/h to 6 km/h (Fig. 1 and 2). 6 km/h corresponds to the speed required for the mandatory annual marching test over a distance of 6 km in the German Armed Forces.

Understanding how loads, climate, and speed affect performance and thermophysiology during a march could help superiors plan more effectively and better anticipate the impact of march-related stress on fatigue, exhaustion, recovery, and energy and fluid needs. This study is therefore intended to contribute to the determination of the complex interactions of influencing factors on the extent of physical strain.

To that end, performance, thermal and nutritional physiological parameters as well as cognitive performance parameters are recorded during multi-phase marching tests under almost operational conditions on a treadmill in an environmental simulation chamber in order to compare the effects of different marching speeds (6 km marching distance at 4.5 km/h and 6 km/h respectively) on stress and fatigue.

The marching test is divided into phases (Fig. 3):

i) 6 km marching phase
ii) interval test (simulation of the first phase of a “leap-frogging withdrawal” with 5 sprints at 13 km/h and a 15 s break each)
iii) all-out endurance test (to determine the VO2 peak)

Phases ii) and iii) serve to operationalise the effects of i) with regard to strain and fatigue.

The tests are carried out in an environmental simulation chamber (Fig. 4) with two different temperatures (15 °C and 25 °C) and with two clothing and equipment variants, based on the combat clothing set (total load of 32 kg and 40 kg). The phases described and the parameters recorded are summarised in Fig. 3.

The findings are intended to form the basis of an application-oriented planning aid for the troops, which should enable military superiors to better plan marches from a preventive medical and performance perspective. By testing impedance cardiography for the first time under military stress conditions as part of this laboratory study, the potential of this method for future field studies was also evaluated.

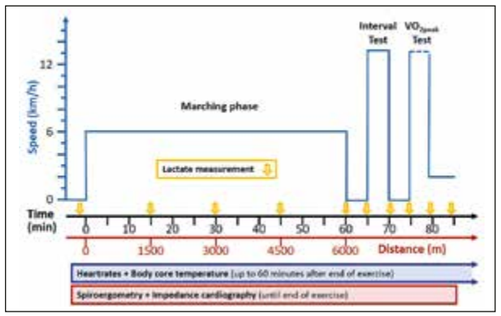

Fig. 3: Illustration of the study protocol including load phases of the load march test at 6 km/h

Fig. 4: Development of the load march test in the environmental simulation chamber

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Routine CT diagnostics leads to radiation-specific gene activation in peripheral blood cells

Computed tomography (CT) contributes significantly to medically induced radiation exposure, which cannot be captured epidemiologically but can be evaluated through radiobiological observation. In this translational *in vivo* study, we were able to confirm the dose-dependent deregulation of cellular processes, which highlights the importance of radiation dose optimisation in diagnostic procedures.

Computed tomography (CT) is an established imaging diagnostic tool in Germany. Its broad range of applications is reflected in the continuously increasing number of examinations. However, despite improved technology and high radiation protection standards, this has led to an increase in medically induced radiation exposure for individuals. Therefore, the potential effects of radiation on the human body, particularly long-term risks such as the development of tumours, should not be ignored.

Earlier *ex vivo* studies demonstrated that even low radiation doses lead to intracellular molecular biological changes. This study aimed to evaluate these findings in a clinical setting with *in vivo* exposure to assess their transferability to the low-dose range typically encountered in medical diagnostics. For this purpose, we combined the expertise of the Bundeswehr Institute of Radiobiology and the two departments of Urology and of Radiology and Neuroradiology of the Bundeswehr Central Hospital in Koblenz.

Blood samples were taken from 40 subjects undergoing microhaematuria diagnostics via abdominal CT, immediately before and after the examination, and incubated for 6 hours at 37 °C. The RNA of the leukocytes was then prepared for genome-wide high-throughput sequencing and analysed using bioinformatics pipelines.

Fig. 1: Next-generation photon-counting CT (Naeotom Alpha) by Siemens Healthineers in the emergency room of the Bundeswehr Central Hospital Koblenz

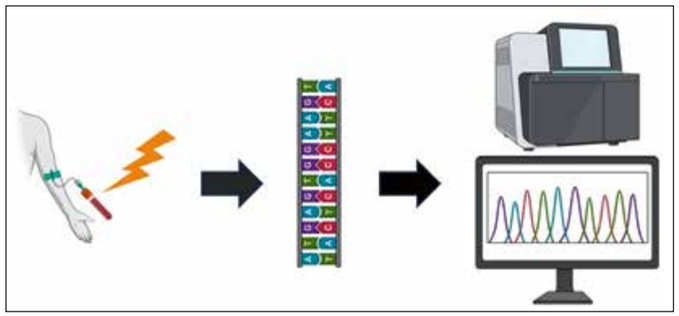

Fig. 2: Schematic representation of the methodology: Blood samples were taken immediately before and after the CT examination. The samples were then processed to enable high-throughput DNA sequencing

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The median applied dose was 6.55 mGy (weight-dependent dose, CTDIvol: 3.75 – 26.95 mGy). All samples taken before CT exposure were part of the “pre” dose group (0 mGy; n = 40), while all samples taken after CT exposure were categorised into the “post” dose group (3.75 – 26.95 mGy; n = 40). Additionally, subjects were divided into three dose subgroups based on their individual radiation dose: “low” (≤ 6.55 mGy; n = 20), “medium” (> 6.55 mGy; n = 16), and “high” (≥ 12 mGy; n = 4).

Given the low radiation doses, interindividual differences dominated the gene expression profiles rather than radiation-induced effects. However, further bioinformatic analyses identified seven significantly upregulated genes following exposure. Six of these seven genes (*EDA2R, AEN, FDXR, DDB2, PHLDA3, MIR34AHG*) were expressed in a dose-dependent manner and are functionally involved in TP53-regulated DNA repair processes, which was also reflected in the analysis of biological signaling pathways. Here, the response to DNA damage, its repair, and cell metabolism were prominent. The seventh gene (*RYR3*) was upregulated in only 3 of the 40 subjects. This suggests that the CT-associated upregulation depends on confounding factors specific to certain subjects’ subgroups; therefore, *RYR3* does not represent a general biomarker for low-dose exposure.

In this study, we successfully reproduced our previous *ex vivo* data *in vivo*, highlighting CT as a suitable model for detecting low-dose radiation exposure in humans within the framework of biodosimetry using biomarkers. The results also emphasise the need to carefully weigh the diagnostic benefits against the associated radiation risks and underline the principle of ALARA (“As Low As Reasonably Achievable”): Patients should always be exposed to the lowest possible radiation dose.

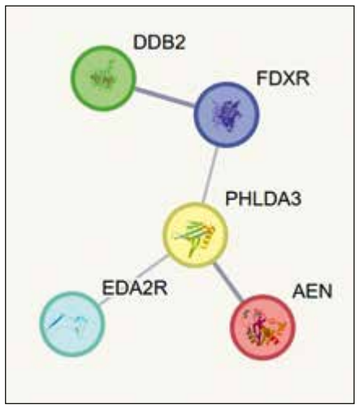

Fig. 3: Representation of the functional relationship of five of the seven identified genes via the STRING database. MIR34AHG, as a long non-coding RNA, was not included. *RYR3* has no direct connection to the other genes. The line thickness represents the significance of the gene interaction.

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Simulator sickness: How long do simulator training sessions affect the flight performance of NH90 pilots?

In a bilateral study, the German Air Force Centre of Aerospace Medicine and the Dutch Organisation for Applied Scientific Research (TNO) are investigating how long a simulator training session affects the vestibular system of NH90 pilots and their ability to fly. This is of great operational importance given the increasing use of simulator training in various military contexts.

Military pilots complete part of their training today and especially in future both in real flight conditions and in a simulator. Simulator training sessions offer numerous advantages: In addition to safely practicing risk situations, they are significantly cheaper in relation to the training time and can generally be made available in larger numbers.

Flight simulators differ in the way they are used and the simulation environment presented. There is a wide range of simulators – from simple flight simulators on individual computer monitors and the use of simple controls, to larger versions, ranging from full-mission cockpits and 180 – 360° screen displays to moving cockpit platforms that simulate possible aircraft movements in all three axes (Fig. 1).
What all simulators have in common is that there is an imbalance between the incoming information from the visual and vestibular systems, which can lead to simulator sickness. The severity of simulator sickness depends on the stimulus intensity of the contradictory information, which is why static simulators that rely solely on visual flight cues often produce the strongest effects.

Fig. 1: Training in the NH90 simulator

Fig. 2: NH90 helicopter in real flight
(source: Bundeswehr / Carsten Schulz)

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The symptoms of simulator sickness vary from person to person and can also last for different lengths of time. Active flying after a simulator flight is therefore only possible after a waiting period. So far, however, there ist hardly any scientific data on how long the symptoms of simulator sickness last and how this affects the ability to fly. It can be assumed that pilots will tend to complete a greater proportion of flight hours at the simulator in future, but at the same time must be fit for flying duty.

The present study was carried out in direct bilateral cooperation between the German Air Force Centre of Aerospace Medicine in Cologne and the Dutch Organisation for Applied Scientific Research (TNO) on German and Dutch NH90 pilots, respectively. The German tests took place at the Transport Helicopter Regiment in Faßberg; the Dutch tests took place at the Training and Simulation Squadron of the Dutch Helicopter Command in Den Helder.

In addition to subjective surveys of the participating active NH90 pilots (Fig. 2) from both countries, laboratory-based examinations were conducted both before and immediately after the two-hour simulator training, as well as at intervals of one, two and a half and five hours, and, on the German side, also after 22 hours on the next day (Fig. 3).

In addition to a test of postural instability with open and closed eyes, the subjects also completed tests on dynamic vision and sustained reaction time (vigilance). The data collected is currently being analysed in close bilateral collaboration. The results of this study will contribute significantly to ensuring pilots' fitness to fly after simulator training and to more accurately determining the required waiting period. This allows mission-specific training contents to be optimised in the simulator, which can then be used in real flight and practiced further after a significantly shorter waiting period, with the aim of increasing the operational capability of pilots in tactical air transport.

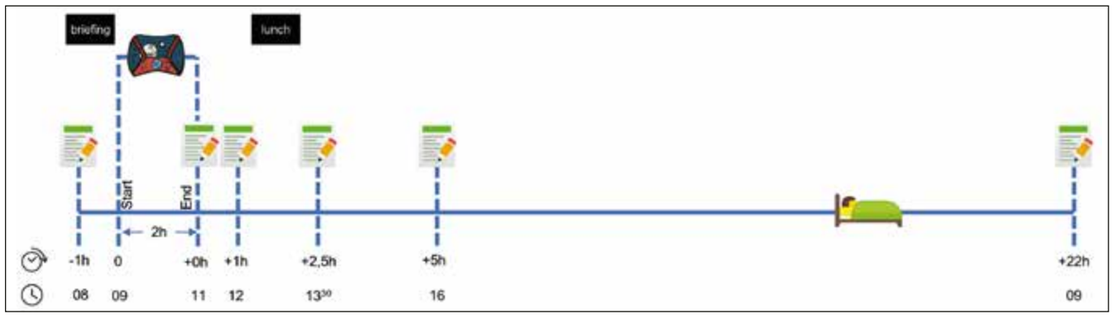

Fig. 3: Study process with measurement times for simulator training

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Should soldiers be considered “military athletes” in certain, very demanding training courses? Findings from the Navy’s “Combat Swimmer Study”

The Navy’s combat swimmer training sets very high standards for the physical and mental resilience of the soldiers. A future understanding of the participants as “military athletes” with the best possible adaptation of the training process to modern training methods can increase the probability of successfully completing the course and avoid dropouts due to minor injuries and infections.

The training to become a member of the Navy’s Maritime Special Operations Forces (MSOF) (Fig. 1) sets very high standards for the physical and mental resilience of soldiers, also in order to prepare them appropriately for dealing with tasks under extreme conditions.

It is thus reasonable to place very high demands on the candidates at the beginning of the extensive training in order to challenge their individual limits and thus to select the best.

One such element is the five-week so-called “swimming pool pre-training” in Eckernförde, which is part of the first section of combat swimmer training.

Even if the “best selection” is one relevant component of this training part, the initial interest of all instructors lays primarily in a high-quality training of the soldiers, which, however, can carry the risk of overtraining / overreaching due to overall physical and mental stress during this period.

The aim of this study was to identify signs of the occurrence of overtraining / overreaching in the soldiers in order to avoid possible dropouts from training in the future. This prospective observational study was conducted on a total of 40 soldiers in combat swimmer training who voluntarily participated in the study. These soldiers completed this part of the training in the regular manner with additional examinations of physical performance, body composition and the status of relevant blood parameters at a total of eight points in time (Fig. 2). T1 – T2 marked the start and end of a six-week sports training immediately before the start of the five weeks of swimming pool training, and examinations were carried out at weekly intervals on T3 – T8. The indoor training included a wide range of training in swimming, apnoea diving (Fig. 3), rebreather diving and day and night exercises as well as other sports at close intervals.

The evaluation of the results showed that the weekly load of the soldiers was between 17,000 and 20,000 MET-minutes (metabolic equivalent task minutes), which corresponds to a daily calorie requirement of 5,500 – 6,000 calories, which is thus roughly the equivalent of running up to one and a half marathons per training day.

Although the physical aerobic performance of all participants was at a very high level at the beginning of the indoor phase (VO_2max = 61.8 ± 6.3 ml / kg / min) and all soldiers were healthy, only 13 soldiers successfully completed the five-week load phase.

The evaluation of blood parameters that are considered to be meaningful for detecting symptoms of overtraining /overreaching showed some significant indications during the course of the indoor training: Testosterone fell from T2: 7.2 ± 1.9 ng/ml to a minimum of T4: 4.1 ± 2.5 ng/ml, while cortisol rose at the same time from T2: 161.2 ± 38.8 nmol/l to T4: 238.3 ± 30.9 nmol/l, and the testosterone /cortisol ratio changed accordingly (Fig. 4). There were also indications of increased sleepiness using the Stanford Sleepiness Scale.

The conclusion to be drawn from the results of the study is that the soldiers’ stress level was in a high athletic range, which was likely to lead to clear signs of overtraining / overreaching in the current training setting, which may have contributed to the relatively low proportion of successful participants. In the future, an increased understanding of the candidates in such highly demanding courses as a “military athlete” with the best possible adaptation of the training process to modern findings of training theory may certainly help to increase the probability of successful completion of the course and, in particular, to avoid “undeserved” dropouts due to minor trauma and / or intercurrent infections.

Fig. 1: Combat swimmers, German MSOF

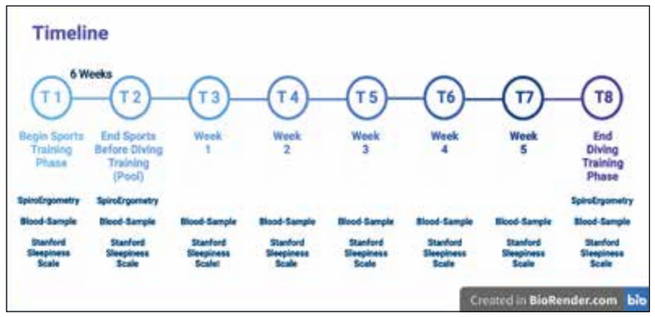

Fig. 2: Timeline

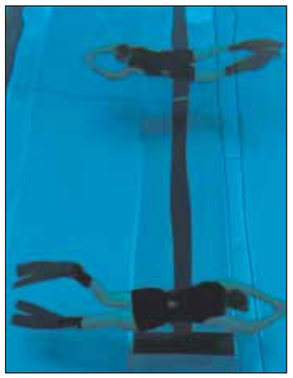

Fig. 3: Indoor apnoea diving training

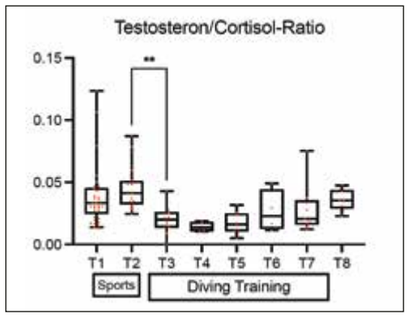

Fig. 4: Testosterone / cortisol ratio

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The PhagoFlow research project: Practicability test of bacteriophage therapy at the Bundeswehr Hospital Berlin

Bacteriophage therapy is a promising approach for the treatment of infections with multi-resistant or difficult-to-treat bacteria. As part of the PhagoFlow research project, the practicability of production and clinical application was tested. This provided important insights for the future of bacteriophage therapy in Germany.

Bacteriophages are viruses that can specifically combat bacteria through lysis. They were first used therapeutically in 1919, but lost importance after the discovery of antibiotics, especially in the western world. However, they remained relevant in the countries of the former USSR. Since the 1990s, bacteriophage therapy for multi-resistant infections has been used sporadically in Germany. The advantage of bacteriophages lies in their specificity towards bacteria, flexibility and adaptability. In military medicine, their potential is particularly evident in the treatment of gunshot wounds and blast injuries, as these are often associated with a high degree of contamination and wound infections. These are often caused by multi-resistant bacteria or bacteria that are difficult to treat. As there is currently no approved bacteriophage preparation in Germany, the aim of the consortium project was to test the practicability of phage production and therapy in Germany.

Isolation, characterisation and selection of the bacteriophages were carried out by the Leibniz Institute DSMZ, while Fraunhofer ITEM developed a manufacturing process for the phage active pharmaceutical ingredients (API) in accordance with the quality standards defined together with the authorities (Fig. 1). The suitability of patients for bacteriophage therapy was tested at the Bundeswehr Hospital Berlin as part of individual treatment trials. Factors such as the pathogen spectrum and the type of infection as well as treatment logistics aspects were considered. After taking pathogen samples (Fig. 2) and sensitivity tests for antibiotics and phages, a decision was made on whether to carry out the therapy. The phages were prepared individually for each patient by the hospital pharmacy in a clean room. The method of application depended on the indication, with a minimum treatment period of ten days being aimed for. The success of the treatment was evaluated clinically and microbiologically.

The DSMZ selected three phages against Pseudomonas aeruginosa from 140 candidates based on host spectrum, genetic properties and lysis efficacy, which were produced by Fraunhofer ITEM for therapeutic use. Almost 20 % of the more than 300 treatment requests were for infections with Pseudomonas aeruginosa (Fig. 3). For the clinical case series, 33 patients were selected for possible bacteriophage treatment, all of them complex cases with mostly unsuccessful previous treatment attempts. In 18 cases, none of the phages showed efficacy in the microbiological pre-test. Treatment was carried out in ten cases. In five cases, the pathogen was demonstrably eliminated, with recurrences occurring in individual cases. In one case, a lasting clinical and microbiological cure was achieved. There were no undesirable side effects in any of the cases.

Even though bacteriophage therapy is a promising treatment option, broad application in everyday clinical practice is not yet possible. There is a lack of infrastructural and personnel capacities for phage production to enable broad application with many different phages in standard care. This requires a clear health policy classification and financing models. The project's own clinical success did not quite reach the level reflected in other publications. It is assumed that this could be due to the limited selection of available phages, but also to the application as a liquid and an application duration that is too short. Complex patient constellations also made therapy more difficult. Through coordinated efforts, therapy could play a central role in the fight against resistant germs in the future.

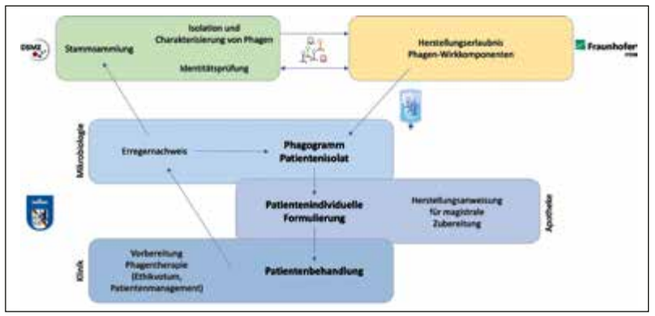

Fig. 1: Overview of the PhagoFlow project structure

Fig. 2: Example of pathogen samples for microbiological testing of susceptibility to bacteriophages

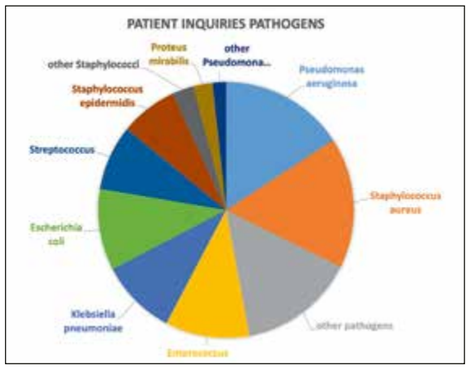

Fig. 3: Evaluation of patient inquiries according to pathogen spectrum

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Evaluation of a new diagnostic system for the detection of malaria parasites in vectors under field conditions

One of the most dangerous tropical diseases of all is mosquito-borne malaria. The Bundeswehr therefore monitors mosquitoes in endemic areas of operation by continuously analysing sample collections. As parasite detection cannot currently be realised on site, our working group is testing the suitability of a corresponding system, which was initially developed for patient diagnostics.

Malaria is an infectious disease transmitted by mosquitoes (= vectors) and caused by members of the unicellular protozoa of the *Plasmodium* genus. With almost 250 million infections and 600,000 deaths per year in tropical and subtropical countries, particularly in Sub-Saharan Africa, it is a major health problem worldwide. Transmission occurs through the infectious blood meal by one of the approximately one hundred competent female mosquito species of the genus *Anopheles*, where the parasite develops into infective stages that can be transmitted to a new human host during another blood meal. The risk of infection for the population in an endemic area therefore depends on (1) the diversity and frequency of competent malaria vectors, (2) the spatial and temporal dynamics of the vectors and (3) the co-presence and frequency of people infected with *Plasmodium* parasites.

Hence, the German Armed Forces carry out vector monitoring in operational risk areas for prevention purposes, i. e. they analyse mosquito collections using fan traps distributed on the premises of military camps. The parasites can be detected using a PCR screening procedure, which, however, can only be carried out after the samples have been sent to Germany. Sample analyses are therefore only possible with a large time delay. A *point-of-care system* for the detection of pathogens in the theatre of operations would lead to a massively reduced reaction time and thus contribute to a significant mitigation of the health risk for soldiers. Our working group has already confirmed the Alethia Malaria Loop-mediated Isothermal Amplification (LAMP) system (Fig. 1) from Meridian Biosciences as a powerful reference tool for patient diagnostics. The current study is now evaluating whether the same system is suitable for parasite diagnostics in vectors under operational conditions.

The development of the malaria LAMP test system's suitability for use is divided into four phases (Fig. 2). Firstly, the standard protocol of the commercially available malaria LAMP kit was modified so that it became applicable for vectors. Next, the *proof of principle* was established by testing on lab-reared vectors that were infected with a rodent-borne malaria species. The final step was to analyse wild catches from high-endemic malaria regions of Central Africa in Gabon, initially under controlled laboratory conditions and later under tropical operational conditions. The RealStar® quantitative malaria PCR (qPCR) from Altona Diagnostics GmbH served as the gold standard for all isolates. Both the lab-bred mosquitoes and the facilities for material collection and diagnostic tests in Gabon were kindly provided by the Bernhard Nocht Institute for Tropical Medicine in Hamburg, a close cooperation partner of the Bundeswehr Hospital Hamburg in the field of tropical medicine.

While the results for lab-bred mosquitoes showed a lower sensitivity (68 %, n = 22) compared to the qPCR reference, the wild-caught analyses showed a higher detection rate (LAMP 7.6 % vs. qPCR 5.1 %, n = 79 pools of 10 mosquitoes, Fig. 3). Individual testing of a subset of positively tested LAMP pools resulted in 5 out of 6 (83 %) confirmed malaria infections, indicating a higher sensitivity of LAMP compared to qPCR, but also a potentially slightly reduced specificity. The results from the field trials in Gabon showed an even higher positive rate (27 %, n=56 pools of 10 mosquitoes each), which corresponds to an estimated infection rate of the mosquito population of 3 to 11 %.

The newly adapted malaria LAMP system is therefore suitable for implementation and is to be tested in future as part of the Bundeswehr's vector monitoring programme in endemic regions.

Fig. 1: The Alethia Malaria LAMP system fulfils all the requirements of a *point-of-care* diagnostic system

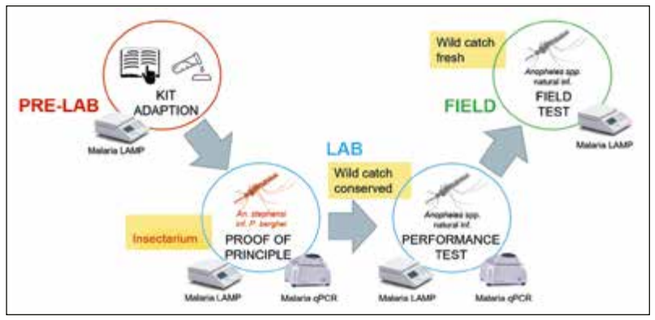

Fig. 2: Workflow for the adaption of the Alethia Malaria LAMP System for diagnostic testing of vectors

General info			
Country of origin	Germany	Gabon	Gabon
Infection status	artifical	natural	natural
Diagnostic laboratory	Germany	Germany	Gabon
# vectors collected	43	1771	551
# vectors analysed	43 (100.0)	789 (44.5) in 79 pools	551 (100.0) in 56 pools
Malaria LAMP			
# pools positive (+ve)	17 (30.9)	6 (7.6)	15 (26.8)
# pools negative (-ve)	24 (65.5)	73 (92.4)	40 (71.4)
# pools invalid (inv)	2 (3.6)	0 (0.0)	1 (3.7)
Malaria qPCR			
# pools positive (+ve)	22 (51.2)	4 (5.1)	n. d.
# pools negative (-ve)	21 (48.8)	75 (94.9)	n. d.
# pools invalid (inv)	0 (0.0)	0 (0.0)	n. d.
Assay performance			
# concordant LAMP +ve/qPCR +ve	15 (34.9)	4 (5.1)	
# concordant LAMP -ve/qPCR -ve	21 (48.8)	73 (92.4)	
# discordant LAMP inv/qPCR +ve	**2 (4.7)**	0 (0.0)	
# discordant LAMP inv/qPCR -ve	0 (0.0)	0 (0.0)	
# discordant LAMP -ve/qPCR +ve	**5 (11.6)**	0 (0.0)	
# discordant LAMP +ve/qPCR -ve	0 (0.0)	**2 (2.5)**	

Fig. 3: Absolute and proportional values (in brackets) of malaria mosquitoes tested with the adapted Alethia Malaria LAMP System compared to the qPCR reference method

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Intelligent military medical capabilities (iMEDCAP) for monitoring, medical care and evacuation of contagious, injured and contaminated personnel

A consortium led by the Technical University of Munich and the Bundeswehr has been working on the development of a system for rescuing and treating casualties from contaminated areas. The focus is on the use of autonomous systems and a telemedical infrastructure for patient care. The overall system will be demonstrated in an exercise in 2026.

In large-scale combat scenarios, it is very challenging to adhere to the tight timelines for optimal casualty care. This becomes even more difficult if areas are difficult to access or are contaminated.

Autonomous vehicles (UxV) have emerged as a disruptive technology in current conflicts, offering new opportunities in the context of casualty care. The iMEDCAP solution will locate, evacuate and monitor injured, contaminated or contagious patients and provide en route medical care.

A consortium of the Bundeswehr, big tech companies, start-ups and research institutions started an EU funded project in 2023 to develop a holistic rescue system. Reconnaissance UAVs will locate the wounded and detect their vital signs over distance.

A UxV is then dispatched to the point of injury. There, the casualty is (semi-)automatically moved to the UxV's patient compartment and monitored remotely using multiple biosensors. Via robot systems, initial diagnosis and treatment can be applied en route. The casualty will then be transported to the next role of medical support, where emergency treatment and, if necessary, casualty decontamination can be provided (Fig. 1).

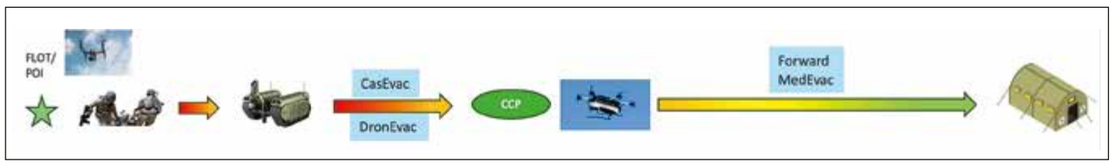

Fig. 1: Integration of UxVs into the military medical evacuation chain (FLOT: forward line of own troops; POI: point of injury; DronEvac: drone evacuation / patient evacuation via an unmanned system and remote medical attendance; CCP: casualty collection point; MedEvac: medical evacuation)

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The centerpiece for patient care is an autonomous patient transport unit (APTU; Fig. 2). The following requirements were defined as key points for the development of the APTU:

1. The APTU must be developed as a self-contained patient cabin that can be operated autonomously.
2. The APTU must be compatible with various means of transportation (ground, air, sea) to ensure a high degree of flexibility. Completely autonomous transportation using Remote Autonomous Systems (RAS) must be possible.
3. Continuous telemedical monitoring of the patients must be guaranteed. Wearables, dedicated medical monitoring systems and external sensors must be integrated as data sources for recording vital signs.
4. Life-saving interventions must be able to be carried out remotely via a robot-assisted surgical and intervention care (RASIC) module integrated into the APTU.
5. The APTU must be able to operate under CBRN threats and have a CBRN detection system.
6. AI-based software should help with patient monitoring, patient flow control and patient tracking.
7. Medical staff in the patient evacuation coordination cell (PECC) must be able to provide psychological support to the patient, monitor all medical data and carry out necessary measures remotely.

The concept focuses on three components within the roles of medical support:

1. Locating the casualty;
2. Automatic evacuation of casualties by UxVs to the nearest medical treatment facility;
3. En route care via remote-controlled medical devices for diagnostic procedures and life-saving interventions.

UxVs can be sent to hazardous areas in large numbers without harming additional personnel. The system of rapid localisation, rescue and initial en route treatment is favourable to meet tight timelines in trauma care and thus to enhance survival rates.

There are already numerous individual components such as UxVs, remote-controlled medical devices and telemedicine applications available. The integration into an overall system is scheduled to be completed by 2027. The final system, including a prototype of the APTU will be tested, evaluated and presented in an exercise scenario using RAS transport by the end of 2026.

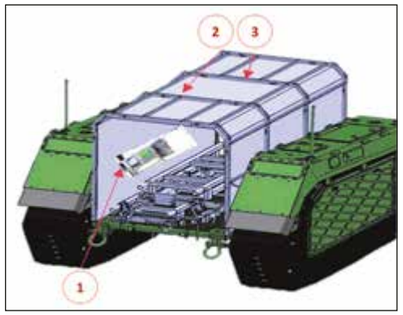

Fig. 2: Representation of a platform-independent patient transport unit mounted on a UGV with holders for medical equipment (1), rails for the intervention robot (2) and an activated charcoal cover (3) to prevent cross-contamination in case of a CBRN threat

iMEDCAP
Funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Comission. Neither the European Union nor the granting authority can be held responsible for them.

Fig. 3: This project has received funding from the European Defence Fund (EDF)

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Afghanistan, Iraq, Mali: Current representative study on Bundeswehr personnel with mission-related mental disorders

How many military personnel are diagnosed with a mental disorder that is attributed to their deployments in Afghanistan, Mali or Iraq? The answer to this question is the task of a large study within the Bundeswehr looking at a total of 112,810 deployed military personnel. The full survey was carried out by the Psychotrauma Centre at the Bundeswehr Hospital Berlin in cooperation with the Bundeswehr Psychological Service, the Bundeswehr Medical Service and the Bundeswehr University Munich, Department of Human Sciences, Institute of Psychology.

Many studies show a significant increase in mental disorders after deployments abroad. This means that mental impairments represent an occupational risk for military personnel. Bundeswehr soldiers who were exposed to a life-threatening event during a deployment have a 6 – 7 times higher risk of suffering from post-traumatic stress disorder, depression or anxiety disorder than their comrades on the same deployment. The risk of relationship breakdowns is also twice as high for them.
The few existing studies on the incidence of deployment-related mental disorders were carried out more than ten years ago and only considered Afghanistan. Two independent studies found almost identical 1-year incidences of 7.3 % and 8.0 %, respectively. Once again, anxiety disorders were identified as the most prevalent disorder.

Employees of the Psychotrauma Centre at the Bundeswehr Hospital Berlin, the Bundeswehr Joint Forces Operations Command and the Bundeswehr University Munich conducted this study to be able to make a representative statement about how many military personnel from Afghanistan, Mali or Iraq were diagnosed with a deployment-related mental disorder.

The aim was to conduct a complete survey of deployments in Afghanistan, Iraq and Mali.
For the calculation, the numbers of all military personnel deployed in Afghanistan from 2001–2021, in Mali from 2013 – 2022 and in Iraq from 2015 – 2018 were determined.
The Berlin Psychotrauma Centre maintains a database of military personnel who present themselves to military psychiatric or military psychotherapeutic facilities of the Bundeswehr Medical Service and who suffer from a mental disorder that can be traced back to their deployment. The mental disorder is diagnosed by psychological psychotherapists and specialists. The connection with the deployment is also addressed. This means that the disorder would most likely not have occurred without the deployment in question, although this does not provide conclusive proof of causality. In addition to the deployment that triggered the disorder, the onset of the symptoms and the first contact with the professional facility are also recorded here.
By combining these data, the cumulative treatment incidence of all military personnel with deployment-associated mental disorders can be determined. This also makes it possible to calculate the latency periods between deployment and the onset of symptoms, or from the onset of symptoms to seeking professional help. However, it should be noted that only military personnel with an ‘official diagnosis’ were taken into account. Therefore, the number of unreported cases is likely to be significantly higher. This calculation does not include those affected who did not seek professional help due to stigma or other reasons, nor those who received a direct referral to external therapists from the military doctor.
The cumulative treatment rate of all military personnel deployed in Afghanistan with a mental disorder is 2.6 %. The main diagnoses are post-traumatic stress disorder (63.2 %), anxiety disorders (25.7 %), depressive disorders (8.3 %) and substance abuse disorders (0. 5 %).
The cumulative treatment incidence of all military personnel deployed in Mali from 2013 – 2022 with a mental disorder is 1.1 %. The most common main diagnoses include post-traumatic stress disorder (45.9 %), anxiety disorders (48.5 %) and depressive disorders (5.7 %).
The cumulative treatment rate of all military personnel deployed in Iraq from 2015 – 2018 with a mental disorder is 3.4 %. Of these, 50.9 % suffer from post-traumatic stress disorder, 32.7 % from anxiety disorders, 7.3 % from depressive disorders and 9.1 % from other mental disorders. The average time from the onset of symptoms to seeking professional help is 1 year, with those affected by post-traumatic stress disorder needing significantly longer at 1.3 years compared to 0.6 years.
Not all affected personnel are statistically recorded to the same extent. There are comparatively few people who suffer from anxiety disorders or depressive disorders. The number of unreported cases is therefore likely to be significantly higher. Future studies should therefore also include referrals to psychotherapists in private practices.

However, the results also show that the deployments have different frequencies of disorders. This should be taken into account when examining those returning from deployments by placing additional emphasis on the most commonly expected mental health symptoms.

Fig. 1: Evacuation operation in Afghanistan: paratroopers at the airport in Kabul / Afghanistan (source: Bundeswehr / deployment camera team)

Fig. 2: Education Cadre Development Institute of the NATO Mission in Iraq (NMI) in Baghdad / Iraq (source: Bundeswehr/PAO)

Fig. 3: Camp Castor during the redeployment of the UN mission MINUSMA in Gao / Mali (source: Bundeswehr/Marc Tessensohn)

Fig. 4: Patrol through Gao / Mali (source: Bundeswehr / Julia Dahlmann)

Fig. 5: Meeting during training support (Capacity Building Iraq) in Erbil / Iraq (source: Bundeswehr / PAO)

Fig. 6: Evacuation operation in Afghanistan: people in need of protection during the evacuation operation in Tashkent / Uzbekistan (source: Bundeswehr / Marc Tessensohn)

4

Military History Research and Military Social Science Research

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

Through its 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 present history of the Bundeswehr. The Centre's research is conducted according to established methods and standards from the disciplines of historical studies and the social sciences and is contingent on the freedom of academia and research as guaranteed by Germany's Basic Law.

Its research results provide the essential foundation for teaching history within the Bundeswehr. This research therefore has an immediate impact on informed citizenship and the historical awareness of Bundeswehr personnel, thereby supporting the Bundeswehr's concept of '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 control and supervision of all collections in the network of Bundeswehr museums.

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Hybrid warfare: Why is a holistic understanding necessary?

Anyone who wants to prepare the armed forces, the state and society for the challenges of hybrid warfare needs a comprehensive understanding of this challenge. It is important to grasp the essential characteristics of hybrid warfare in order to be able to interpret its changing manifestations in a manner appropriate to the situation. Since defence against hybrid attacks requires the cooperation of a large number of different actors – including the armed forces – a common basic understanding is the prerequisite for coherent joint action in defence, resilience-building and counter-response. The aim of this project is to promote such a basic understanding on the basis of a concept aligned with the nature of the phenomenon.

Hybrid warfare in and around Ukraine has confronted Europe with a paradigm shift in security policy since 2014. The escalation of the situation due to Russia's large-scale military invasion of Ukraine on 24 February 2022 led to Germany proclaiming a "turning point" ("Zeitenwende"). It is likely that the future of warfare that the future of warfare will also be characterised to a large extent by hybrid forms. Understanding their parameters and mechanisms of action is therefore a necessary prerequisite for responsible political, social and military action.

Since the complex parameters and indirect, partially concealed mechanisms of hybrid warfare and the associated strategic approaches are sometimes difficult to recognise and to classify, hybrid warfare also poses a particular intellectual and analytical challenge. Not only science but also politics, society and the armed forces must face up to this challenge.

In addition to raising awareness of the challenges posed by hybrid warfare, it is crucial to develop a common basic understanding of this phenomenon. Such an understanding can encourage the necessary cooperation, coordination and coherent, comprehensive action of all relevant actors in defending against and overcoming these challenges. This requires a scientifically based conceptual foundation.

In this connection, it is particularly important to understand the essence of hybrid warfare. This concerns first and foremost the three central characteristics of hybrid warfare:

1. the horizontal blurring of the boundaries of the battlefield in conjunction with the use of non-military centres of gravity for decision-making,
2. the targeted operation in the grey areas of interfaces between war and peace, friend and foe, internal and external security as well as between civilian and military or state and non-state areas of responsibility,
3. the unorthodox combination of means, methods, tactics and strategies.

As the boundaries between war and peace, friend and foe, internal and external security and between civilian and military attack vectors become blurred in times of hybrid warfare, the protection of one's own society, economy and infrastructure against non-military attack vectors (including "weaponised migration", ideological radicalisation, terror and sabotage) is of central importance in addition to a strong military defence.

For the armed forces, the confrontation with hybrid warfare means first and foremost mastering their main military mission (for the Bundeswehr this means national and collective defence) to the best of their ability. Since conventional combat of the highest intensity can form part of an overarching strategy of hybrid warfare, the focus for the armed forces must also be on preparing for this in the context of hybrid warfare.

Beyond this, however, it is also a matter of developing the ability to operate in the 'shadow domain of hybrid operations' and systematically narrowing the spaces for shadow operations in the grey areas of interfaces for hybrid challengers. In this regard, it is important to identify and close authority and responsibility gaps.

Based on the identified characteristics, the following short definition of hybrid warfare can be derived: "Hybrid warfare is a specific form of warfare that delimits the battlefield horizontally and seeks to reach a decision also in non-military fields of action, which operates particularly in the grey areas of interfaces and thus creates strategic ambiguity and which finally challenges the enemy through unorthodox combinations of means and methods." (J. Schmid)

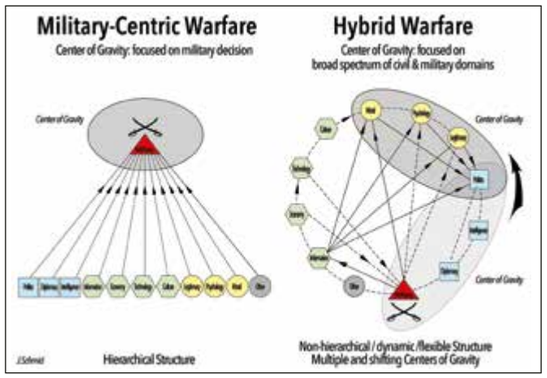

Fig. 1: Horizontal expansion of the battlefield and the use of non-military centres of gravity: Military-centric warfare (left graphic) – as a conceptual counterpart to hybrid warfare – primarily strives for a decision using military means and methods on a military battlefield. Other domains are placed at the service of a military decision, which in turn is expected to achieve the overall political success.
In contrast, hybrid warfare (right graphic) combines and integrates different domains and dimensions as independent battlefields in a dynamic and flexible way. Thereby, a decision can be sought also in non-military centres of gravity. The armed forces can thus become a supporting element of an overall decision in non-military fields of action. In contrast to the hierarchical structure of military-centric warfare, the internal relationships within the framework of hybrid warfare have a flexible, non-hierarchical structure with changing and multiple centres of gravity.

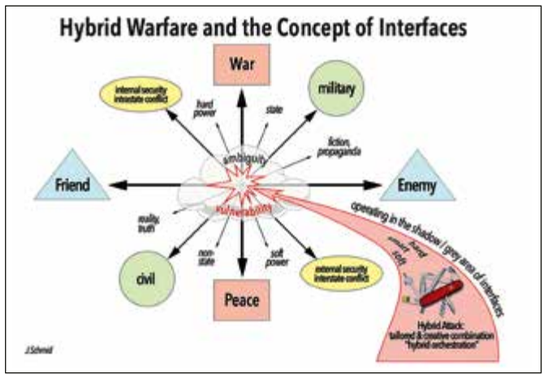

Fig. 2: Operations in the grey areas of interfaces / unorthodox combination of means and methods:
Hybrid warfare is characterised by operating in the grey areas of interfaces. In this regard, a wide variety of instruments, means and methods, tactics and strategies are combined in a precise, creative and unorthodox way. The design of a hybrid campaign can in some ways be compared to the construction of a Swiss army knife. The blade of the knife then represents the military component within the framework of a multitude of other instruments, means and methods.
In contrast to the Swiss army knife, the various instruments can also be used simultaneously or cumulatively in hybrid warfare.

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The Oral History Project of the Bundeswehr Centre of Military History and Social Sciences

In December 2023, the Bundeswehr Centre of Military History and Social Sciences (ZMSBw) launched its Oral History Project. The aim is to systematically record the perspectives of representatives of the German Armed Forces, but also of the ministerial bureaucracy and federal politics for future research and to preserve them for posterity. Not only historiography benefits from the Bundeswehr's Oral History Project, but also the troops themselves.

For the Oral History Project, two employees of the ZMSBw interview active and retired soldiers of the German Armed Forces about their life stories and experiences. Since the two historians work in the research area of operations, which examines Bundeswehr missions abroad, they are particularly interested in the epoch from German reunification in 1990 to the "turning point" (Zeitenwende) in 2022. However, the conversations with the actors of the past are not limited to this most recent period of German military history. And there is certainly no lack of interesting people to talk to. In the first phase, the work initially focuses on decision-makers from the early 1990s because they set the course for the first missions abroad and are already at an advanced age.

The Military History Research Institute and its successor institution, the ZMSBw, have already carried out numerous projects in which contemporary witnesses were given a voice. What is fundamentally new about the current Oral History Project, however, is that the interviews are systematically prepared, conducted and documented. Based on the methods of oral history, the historians are thus creating important sources beyond official documents. What has been successfully practiced for many decades in the armed forces of English-speaking nations in particular is now also finding its way into the Bundeswehr.

The Oral History Project thus puts people at the centre. They function as guides through the complexities of institutional processes and historical events. The interviews can help to reconstruct decision-making processes that led to the creation of official documents, but which are not apparent from them. During the conversation, the contemporary witnesses do not just convey numbers, data and facts – or what they take for it. Rather, they also share their experiences with the recipient. Each interview therefore provides a variety of narratives, perspectives and reflections from several individuals, which ideally complement other sources.

In order to structure the conversations, the researchers created a catalogue of questions that always considers the biographies and assignments of their contemporary witnesses. The interviews, each lasting several hours, are recorded and then transcribed. The latter step is just as time-consuming as the editing of the transcripts. As soon as such a text is available, the interviewees will receive it. While they can make minor corrections, the spoken word generally is what counts.

As soon as the written approval has been received, a file is created from all documents. In addition to the transcript and the release declaration, it includes the correspondence, the audio file of the interview and further documents. The file is then handed over to the Federal Archives (Military Archives Department) in Freiburg im Breisgau, where it is given a shelf mark and a granted protection period of 30 years, which is mandatory for thematic files. This ensures that every visitor to the archive can use the material after expiry of the protection period. Only employees of the ZMSBw are able to do this in advance.

In this way, the researchers produce unique sources that are of great value for historical research and the Bundeswehr. The interviews conducted so far already show the great potential they hold for future research projects. They provide information for numerous studies on the troops' internal perspective, some of which would not be possible without them. Taken as a whole, they even form a valuable basis for the Bundeswehr's history of mentalities. Last but not least, the project presented offers the ZMSBw a unique opportunity to establish itself as a Centre of Military Oral History in Germany.

Fig. 1: Interview for the Oral History Project of the ZMSBw (source: Bundeswehr / Nimpsch, 2025)

Fig. 2: Files of the Oral History Projekt of the Bundeswehr (source: Bundeswehr / Nimpsch, 2025)

Fig. 3: German UN soldier with young Cambodian women in Phnom Penh (source: Bundeswehr / Modes, 1993)

Fig. 4: Federal Minister of Defence, Volker Rühe (right) and Chief of Defence, General Klaus Naumann at the press conference on the UNOSOM II mission in Somalia (source: Bundeswehr / Modes, 1993)

Fig. 5: Tank commander of the German Operational Brigade of the KFOR troops in Kosovo (source: Bundeswehr / Modes, 1999)

Fig. 6: ISAF mission in Afghanistan: German soldier near Mazar-e-Sharif (source: Bundeswehr / Heinrichs, 2013)

5

Geoscientific Research

The Bundeswehr Geoinformation Service is tasked with scientific findings in the geosciences, developing them for further use, and pursuing its own projects with the aim of supporting the armed forces and the Bundeswehr as a whole in accomplishing their mission while also averting damage to materiel and personnel.

One important research area is the general influence of the atmosphere on service personnel, military equipment and ultimately the overall conduct of operations. Although such influences can vary in degree, they always play a key role in operations. This is nothing new. Clausewitz explains as follows: “As there are certain circumstances which attend the combat throughout, and have more or less influence upon its result, therefore these must be taken into consideration in the application of the armed forces. These circumstances are the locality of the combat (ground), the time of day, and the weather.” (Major General Carl von Clausewitz, 1780 – 1831, “On War”, Volume 2). There is no better way to describe the essential aspects of what the Bundeswehr refers to as geoinformation support.

The projects presented this year clearly demonstrate the diversity of the field of meteorology. They range from fundamental work on modelling the atmosphere and coupling these models with the Earth and the oceans, to investigating the influence of atmospheric conditions on the use of sensors and effectors, and providing individual soldiers with quality-assured meteorological information that is relevant to their assignment.

What is most significant, however, is a noticeable trend that fulfils the requirements of modern combat management: Both command personnel and military users must have direct access to the most up-to-date, requirements-driven and, above all, usable information, parameters and predictions without the necessity for expert consultancy. The next few years will see a paradigm shift in this regard, also due to the use of artificial intelligence.

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Earth system and sea state model to improve forecast quality

An Earth system model (atmosphere-ocean coupling) and a new sea state model are being developed at the Bundeswehr Geoinformation Centre (ZGeoBw) in cooperation with the German Meteorological Service (DWD) to provide optimum meteorological and oceanographic (METOC) support for all armed forces. The article summarises the planned approaches, the realised initial milestones and provides an outlook.

A new forecast system is currently being developed as part of a ZGeoBw research project. It consists of an Earth system and a sea state model and aims at making an important contribution to maritime status reports. The resulting improved forecasts are required by the German Navy and its NATO partners in operational, crisis and exercise areas in day-to-day operations (24/7). Current and previous models and procedures are commonly based on uncoupled atmosphere and/or ocean models due to high model complexity, limited computing resources and the prevailing state of knowledge. The new two-way coupled models provide the opportunity to enhance operational consulting. This is particularly important for special naval systems, such as AUVs (autonomous underwater vehicles) and UAVs (unmanned aerial vehicles), as well as various subsequent applications, e. g. for sonar performance and dispersion forecasting. However, all users in the armed forces will benefit from the improvement in METOC forecast quality.

In cooperation with DWD as contractor, a coupled Earth system model on the weather scale (ICON-ESM-W) is being developed in an eight-year project. This model consists of the main components ICON atmosphere (ICON-A), ICON ocean (ICON-O) and the sea state model (ICON-WAVES). In addition to the technical implementation of the coupling (Fig. 1) and the parameterisation and conservation of physical quantities exchanged between the model components and the oceanic data assimilation, the objectives of the project are the establishment of an observation-based verification for evaluation, the development of an experimental test environment and a routine control system.

Furthermore, two possible ways of regionalising the ICON-O model are being implemented and tested, which improve the quality of METOC support in the areas of interest. On the one hand, this is done in the form of a separately executable model with one-way coupling (ICON-O-LAM) and, on the other hand, through a refinement integrated into ICON-O (Fig. 2) with two-way coupling (ICON-O-ZOOM). Based on ICON-O-ZOOM, future selected model areas are to be routinely calculated in higher resolution (Fig. 3). If required, further relocatable model areas can be calculated with ICON-O-LAM in higher spatial and temporal resolution.

In addition to more accurate weather forecasts, sea state forecasts are particularly important for naval units. The ZGeoBw research project ICON-WAVES focuses specifically on the simulation of surface waves in the ocean and their interaction with the atmosphere (Fig. 4). Due to the flexibility and extensibility of ICON, ICON-WAVES can be integrated into the Earth system simulation both globally and regionally (LAM), making it possible to improve both weather and seasonal forecasts, especially in regions where the interactions between wind, waves and ocean currents are particularly strong (e. g. off the French coast around Quessant near Brest or off South Africa in the region of the Agulhas Current in the Eastern Cape). This is of utmost importance for safe maritime navigation.

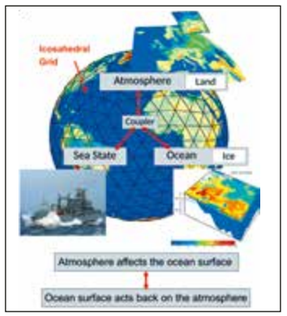

Fig. 1: Schematic structure of the Earth system model based on the ICON (icosahedral grid) model incorporating the sea state model (ICON-WAVES). The YAC coupler exchanges the relevant variables between the ocean component ICON-O (including ice) and the atmosphere and land component (ICON-A, and TERRA / ICON-Land) (source: ZGeoBw III 4 (1))

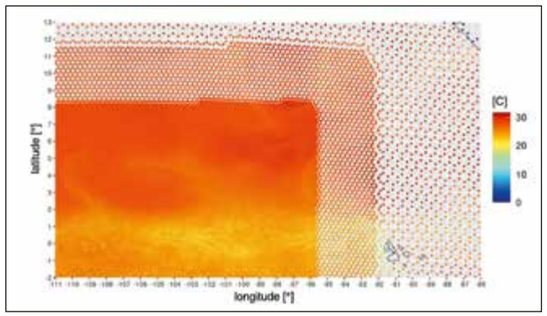

Fig. 2: Representation of the ZOOM grid in the area of local refinement based on the sea surface temperature in the East Pacific / West Coast of South America region. The outer region corresponds to 40 km resolution, followed by an area of 20 km, which merges into a refinement level of 10 km. The finest resolution represents the high dynamics, visible in the surface structures, near the Galapagos Islands (source: ICON-ESM-W project)

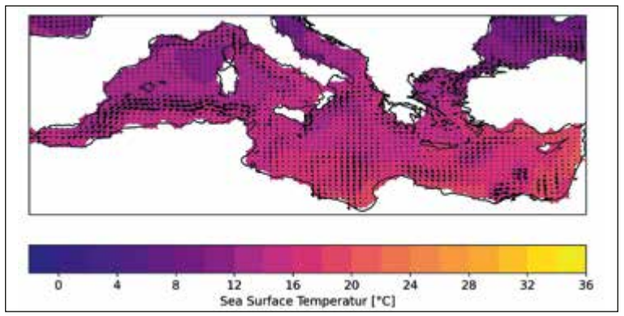

Fig. 3: Modelling of the surface temperature (colours) and currents (arrows) in the Mediterranean (source: ICOM-ESM-W project)

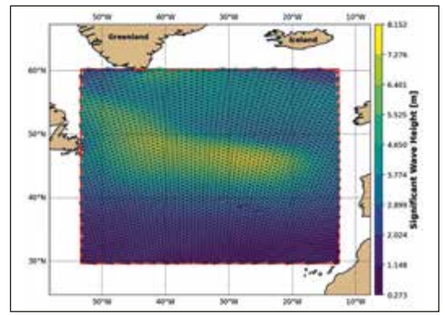

Fig. 4: The figure shows an ICON-WAVES forecast of the significant wave height for the North Atlantic as a function of longitude and latitude in the LAM. The resolution given by the average spacing of the triangular ICON R02B06 grid shown is 40 km (source: ZGeoBw FPe 5533)

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IT service: Meteorological information for small UAS

Weather is a key factor when it comes to flights of unmanned aerial systems (UAS). Particularly the use of small UAS is steadily increasing such that the development of digital tools for self-briefing becomes inevitable to support missions with high-quality weather information and to reduce the immense workload of the weather forecasters.

To implement UAS as "key technology for future war", the Chief of Defence of the German Armed Forces has set up a drone task force. As a result, the decentralised acquisition of small commercially available drones with an expected financial volume of up to 1 billion Euros is planned for the services from 2025. As part of the preparation for drone flights outside the field of vision, meteorological consultancy is required. Pilots of drone flights within the field of vision are required to retrieve meteorological information independently (Fig. 1). Due to the absence of appropriate tools for self-briefing, it is common practice to request meteorological consultancy also for drone flights within the visual range.

To fill this gap, the Bundeswehr Geoinformation Service (GeoInfoDBw) intends to enable drone pilots of small UAS (Fig. 1) to retrieve meteorological information independently by providing appropriate digital tools in the near future. In a first step, the Bundeswehr Geoinformation Centre (ZGeoBw) has developed an IT service on behalf of the Army Concepts and Capabilities Development Centre, which provides meteorological information particularly for the drones ALADIN and MIKADO that are employed by army, air-force and navy. For this purpose, a METOC (meteorological – oceanographical) procedure has been developed which runs at the German Meteorological Computing Centre in Offenbach am Main. Here, the German Meteorological Service (DWD) and GeoInfoDBw jointly operate a high-performance computing facility at which the numerical weather prediction models are run.

The resulting forecast data provide the data basis for the weather forecasts that are issued by both institutions at national to global scales. Goal of the newly developed METOC procedure (Fig. 2 for scientific details) is to extract the key information indicating danger for flight security of the drones ALADIN and MIKADO from the high-dimensional forecast data generated by numerical weather prediction. For example, it is checked if wind and temperature forecasts in the vertical flight zone exceed the operating limits of the drones or if hazards such as thunderstorms or icing are likely to occur.

To provide a user-friendly presentation, a traffic light representation which comprises the colours green, red and yellow is derived. This allows to see at a glance at which locations and time slots the weather situation is expected to become unfavourable for drone flights. Since the final decision about the feasibility of a flight is left to the drone pilot, the traffic light colours red and yellow come in combination with the meteorological factors that have led to the specific colour at a certain place and time – this is what is referred to as "meteorological information" in the narrower sense.

Once the data have been derived by the METOC procedure, they are provided as geographical maps in the so-called weather portal – a web page of ZGeoBw that is accessible from the intranet of the German Armed Forces (Fig. 3). In the near future, meteorological information can be accessed there for self-briefing on a 24/7 basis, both for Europe and at a higher spatial resolution for Germany. At a later stage, data will also be provided based on numerical weather prediction models that ZGeoBw runs for the operational areas world-wide.

To facilitate a comprehensive, goal-oriented development of the overall system, close and agile cooperation between the development team and the sponsor, the Army Concepts and Capabilities Development Centre, as well as exchange with the weather forecaster team from the Air Manoeuvre Training and Exercise Centre in Celle and the training pilots from the Army ISR School in Munster have proved successful.

Fig. 1: The 2nd company of 3 reconnaissance support battalion practises flight operations at very short range with the drone ALADIN at the garrison training area in Wendisch Evern (Lower Saxony) (source: https://ynside.extranet-bw.de/de/aktuelles/mediathek/audios-videos-galerien/woche-im-bild-kw-22-5437324)

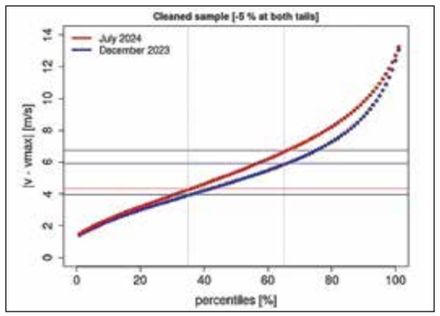

Fig. 2: To identify threshold values for the intensity of turbulence, e. g. weak, moderate and strong, percentiles of gust spread are assessed. In aviation meteorology, gust spread is used as a proxy for turbulence (source: ZGeoBw)

Fig. 3: The webservice. Presented is a traffic light forecast depending on the drone type, which states if the weather situation is expected to be favourable for drone flights. It is possible to choose the drone type, the point of time as well as the numerical weather prediction models for Europe (ICON-EU) or the one for Germany (ICON-D2), both operated by DWD (source: ZGeoBw)

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Approaches to the further development of a weather briefing tool for night vision goggles

The use of image intensifier or night vision goggles (NVGs) contributes to an increased level of safety and of capabilities for night flight operations of helicopters. The persisting weather briefing tool assessing NVG performance no longer fulfills all operational requirements, which is why this research project aims to improve the briefing tool for NVGs.

In daily use, ranges of most electro-optical systems are limited by environmental conditions. In case of NVGs, the range is strongly limited by the meteorological visibility and the amount of residual light, but factors like vegetation, the content of chlorophyll, soil moisture and fauna are also playing significant roles.

For that reason, a weather briefing tool for weather forecasters predicting NVG ranges was developed in the 1970s and 1980s. Its core functionalities have remained the same, and they are still being used by the Bundeswehr Geoinformation Service (GeoInfoDBw) in order to brief pilots on expected NVG ranges. In essence, the tool consists of a set of empiric mathematical functions, which take the amount of residual light and meteorological range as input variables. Most parameters and correction factors were determined during measuring campaigns, however, the parameter set is limited to the perception range of forest areas and fields.

Generally, the algorithm works very reliable for NVGs of the so called third generation and for navigational tasks within a typical central European forest and field landscape, however, its applicability is limited to those areas and cannot be extended easily for different environments or more modern NVG technologies.

For this reason, we are developing a new briefing tool to predict NVG ranges utilising a more future-proof, flexible and model-based approach, which is not equally dependent on measuring campaigns. Such models already exist in form of software applications and are able to predict the whole light path from a source through atmosphere, optics, its perception by a human and, finally, the resulting range.

On the downside, such software is rather impractical and therefore not suitable for daily use by forecasters, however, it could be used to derive parameters for a limited or simplified set of cases.

Another aspect which has not been considered yet is light pollution. Worldwide satellite and light propagation datasets are available and could be rather easily integrated as an additional light source. However, the extremely high spatial variability of artificial light pollution levels raises a challenge on the design of briefing products to assess the expected variability along a chosen route.

At the current early stage, the necessary consolidation of requirements for a new or improved briefing tool is still pending. Only when the necessary information has been acquired, the right method and data can be chosen and implemented for the particular user demands.

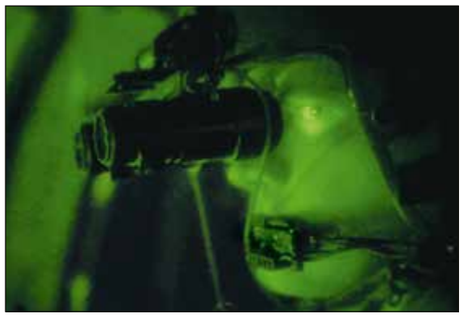

Fig. 1: NVGs are usually clipped on the pilot's helmet. The field of view is strongly limited (source: Wikimedia Commons)

Fig. 2: View through NVG BONIE-M (source: www.bundeswehr.de)

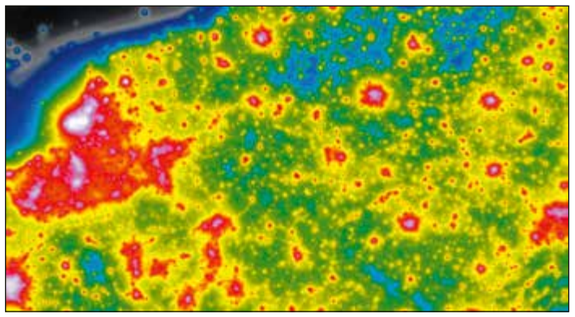

Fig. 3: Simulated zenith luminance over Germany through light pollution. Blue shades mark areas with low, red and pink shades with very high light pollution levels (source: www.lightpollutionmap.info).

6

Cyber and Information Technology Research

On the one hand, research in the field of cyber and information technology is guided by civilian and disruptive innovations such as artificial intelligence. However, it must also consider the specific characteristics of current and future conflicts, which are becoming increasingly hybrid. The research mainly covers the areas of cyber security, information operations, military communications and applications in the field of command and control support.

Two examples from the wide range of research activities are presented in this chapter: the intelligent emulation of cyber attacks in cyber ranges for exercise purposes, and the optimisation of network service infrastructure and security in tactical coalition networks.

The aim is to employ as much civilian technology as possible, which can be adapted for military use as required. It is clear that comprehensive automation is crucial to all areas of defence research.

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FIST: A project for optimising network service infrastructure and security in tactical coalition networks

As part of the Federated Information Sharing over Tactical Networks (FIST) II project, the Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE), together with IABG, developed extension proposals for strategic and tactical IT infrastructures for future coalition operations to support initiatives such as NATO Federated Mission Networking (FMN) in various areas.

In the area of infrastructure, it was shown that the reduction of control efforts for Software-defined Tactical Networks (SDTNs) is necessary, leading to the development of an adaptive assignment of Software-defined Network (SDN) controllers. This divides the network into clusters to increase robustness against failures and enable efficient load balancing. A multi-controller setup was introduced to implement software-based clustering, depending on the control effort within the network. Another topic is the involvement in the standardisation of the mobile tactical domain within the framework of FMN. The Fraunhofer FKIE is directly involved in the NATO Tactical Edge Syndicate in developing specifications for upcoming FMN spirals. The standardisation of interfaces for digital voice with push-to-talk is currently one of the most important topics. Possible procedures were tested for interoperability as part of the NATO Coalition Warrior Interoperability eXploration, eXperimentation, eXamination eXercise 2024 (NATO CWIX 2024).

In the area of information services and Service Management & Control, a new transmission method for sensor data from the Internet of Things (IoT) was developed. It was shown that the compressed MQTT connection is more resistant to disturbances.

In the technology field of security, concepts for preventive network security were developed to support the FMN IWG Tactical Edge Syndicates. This involves additional protection of confidential information with NINE and STaC-IS, which go beyond the encryption mechanisms of radios. In the field of reactive network security, improvements were made for the security management in multinational military operations.

A concept was designed for training an AI-based system to improve the detection of cyber attacks, based on federated learning and training data distributed among partner nations. Reinforcement learning was used to explore how optimal response strategies to cyber attacks in tactical networks can be learned.

A secure, browser-based access to the SOA & IdM RuDi platform was an outcome in the context of application security. Furthermore, the control of data exchange between security domains, based on Information Exchange Gateways (IEG) and security labels in accordance with ADatP-4774/47748 standards, was extended for other protocols, such as XMPP. In parallel, Data Centric Security with the ACP 240 standard was investigated, which provides an interoperable way to securely exchange data between nations.

The necessity of interoperable communication systems or IT infrastructures in coalition operations was the motivation to evaluate the developed solutions over several years at CWIX. For this purpose, an extensive testing infrastructure was built (Fig. 1 to 3). The focus of the tests was on areas such as Dynamic Link Exchange Protocol (DLEP), tactical voice based on STANAG 5634, network awareness, and coalition routing. Detailed interoperability investigations with the SOA & IdM RuDi platform were also conducted, focusing on service usage via browser, secure XMPP across domain boundaries, Service Management and Control (SMC), and Friendly Force Tracking (FFT).

Through successful tests, FIST II has made a significant contribution to the verification of FMN Spiral 6 and the exploration of future spirals.

Fig. 1: Test infrastructure for the evaluation of interoperable communication systems at CWIX

Fig. 2: Setup of tactical handheld radios at CWIX

Fig. 3:Setup of tactical vehicle radios at CWIX

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Intelligent emulation of cyber attacks in cyber ranges for training purposes

Cyber ranges provide practical training environments for security personnel to defend against emulated cyber attacks. Adversary emulation tools automate this resource-intensive emulation but often rely on predefined scenarios. This study explores how cyber attacks can be automated without human interaction or fixed scenarios in such exercises.

To better prepare against real cyber threats, the defence of production networks can be trained in cyber range exercises. An exemplary topology of a cyber range is shown in Fig. 1, which includes a Windows Active Directory domain with a Windows Server as the domain controller and two Windows 10 workstations, an Ubuntu log server, and a Kali Linux machine acting as the adversary. Manually replicating attacks in such environments is very resource-intensive, requiring specially trained personnel and a lot of time for both preparation and conduct of attack scenarios. Adversary emulation tools partially automate the conduct of an attack, for example, using scripts or predefined attack scenarios. However, their use often still requires a certain level of expertise, and the repeated use of predefined scenarios can result in a reduced learning effect of an exercise. Driven by this challenge, this study investigates how cyber adversary activities in exercises can be automated, eliminating the need for human interaction or predefined scenarios.

An analysis of related work revealed that the cyber security platform MITRE Caldera stands out from other work due to its modularity and the use of planning engines that allow for the emulation of complex adversarial behaviours. Thus, as a result of the work conducted so far, a new planning engine for Caldera has been developed – the Bounty Hunter. In the context of an exercise, the objective of the Bounty Hunter can be configured, which is then autonomously pursued. To achieve the objective, the emulated adversary makes decisions based on reward values that are recursively calculated from the defined objectives for all available attack steps. For this reward calculation, the Bounty Hunter utilises connections between attack steps, which are established based on gathered and required information. Fig. 2 illustrates an example of the connection between the attack steps. The steps leading to the configured objective have high reward values (490 or 700), while steps that do not lead to the objective have low standard values.

The steps executed during an exercise using the novel planning engine are illustrated in Fig. 3. In this example, the emulated adversary is given the objective to compromise a Windows Active Directory domain through a Kerberos Golden Ticket attack – a scenario that was built based on an APT29 campaign as part of this study. At the beginning of the exercise, an autonomous initial compromise is performed using network scans and the exploitation of discovered vulnerabilities. Once the target is compromised, the adversary begins executing commands on the target system. In this case, an autonomous privilege escalation is performed to subsequently read locally cached passwords from memory. The adversary then collects additional information about the active domain. At this point, the emulated adversary has autonomously gathered all the information needed to execute the objective step, carries it out and then stops the activities.

The results of this study so far show that cyber adversarial activities can be automated in cyber ranges using the newly developed Caldera plugin Bounty Hunter. During the training exercise, no human interaction is required and no predefined scenarios are utilised. As a result, new scenarios are automatically generated for each exercise, preventing boredom among participants due to already known attack processes. Current work within this study focuses on integrating detection and success probabilities of adversarial activities.

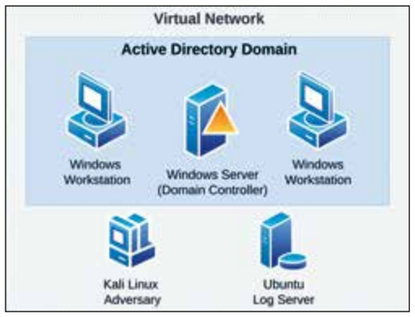

Fig. 1: Exemplary topology of a cyber range

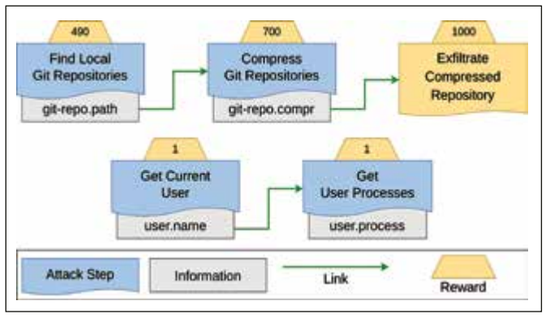

Fig. 2: Linked attack steps using gathered and required information

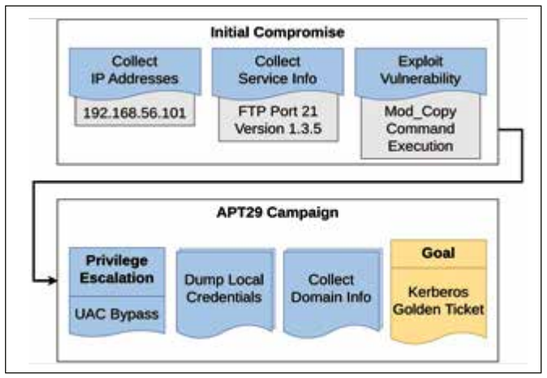

Fig. 3: Execution flow of an attack scenario using the novel Bounty Hunter planner

7

Bundeswehr-Related Research at the Bundeswehr Universities

The Bundeswehr universities in both Hamburg and Munich conduct a broad spectrum of research that is also relevant to the areas of security and defence, including research in the fields of cyber and information technology, the humanities and social sciences, military medicine and military psychology, the geosciences and engineering.

Both universities take a highly interdisciplinary approach. For this reason, the Bundeswehr University in Munich has long had a number of research centres and institutes at its disposal. The data required for research relevant to security and defence can be acquired most comprehensively through cooperation projects. Helmut Schmidt University / Bundeswehr University Hamburg is currently undergoing a strategic process of profile development that also involves defining research priorities in security and defence. Both universities have been reliable partners of the FMoD for years and maintain numerous well-established research collaborations with the FMoD and Bundeswehr agencies, national and international research institutions, the security and defence industry, and the civilian sector.

Consequently, both universities are able to successfully combine engineering research with research aimed at competence-building and shaping the organisational structures and work of the future. In the long term, the demands and opportunities of digitalisation and artificial intelligence will come to play a central role in all of these research fields. In this regard, we have a very broad understanding of the topics pertaining to security and defence.

Since 2020, complementary research has also been conducted at the Bundeswehr Centre for Digitalisation and Technology Research (dtec.bw), which is run by the two Bundeswehr universities under the ministerial responsibility of the Head of the FMoD's CIT Division as ministerial CIO, and is currently funded by the European Union through NextGenEU. Dtec.bw has been a major success for both Bundeswehr universities. The research findings obtained so far in the 66 dtec.bw university research projects will hopefully contribute to improving the Bundeswehr's independent, self-determined and reliable accomplishment of its constitutional duties in the digital world. This is becoming particularly evident thanks to the keen interest in the research results shown by Bundeswehr agencies and the multiple collaborative undertakings with Bundeswehr agencies within individual dtec.bw projects. In its institutional evaluation of dtec.bw, the German Science and Humanities Council found some of the research results achieved to be of an exceptionally high standard. They recommend that the university research carried out by dtec.bw be geared towards the Bundeswehr's digitalisation requirements to an even greater extent.

This disciplinary diversity of university research, particularly in the fields of security and defence, is exemplified by the articles included in this report.

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AI-driven anomaly detection and diagnosis for complex systems: From the International Space Station to military applications

The "(K)ISS" project develops AI-based solutions for anomaly detection and diagnosis in complex systems. Using the ISS as an example, it introduces advanced technologies with potential for space and military applications. An innovative MLOps platform facilitates the efficient implementation of AI algorithms, promising improvements in the efficiency and safety of technical systems.

As modern technical systems become increasingly complex, the challenge of rapid and precise fault analysis grows despite rising sensor density. This is particularly relevant in space and military applications, where high reliability under extreme conditions is crucial.

To address these challenges, the Bundeswehr universities initiated a project in collaboration with Airbus Defence and Space and Just Add AI from Bremen. The goal was to develop innovative solutions for anomaly detection, diagnosis, and reconfiguration (Fig. 1). The International Space Station served as the primary application example, with transferability to other complex systems – including military applications – being a central objective from the outset.

The methodological foundation of the project was the combination of machine learning and symbolic AI to develop a comprehensive assistance system. Neural networks emerged as a particularly important technology for anomaly detection, while a hybrid approach combining machine learning with logic was pursued for diagnosis. The developed solutions (Fig. 2) are characterised by their interpretability, transferability, and modularity, making them attractive for a wide range of applications.

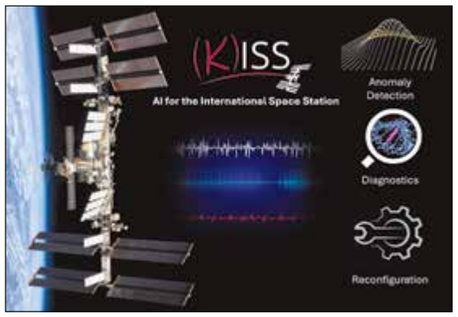

Fig. 1: The (K)ISS Project

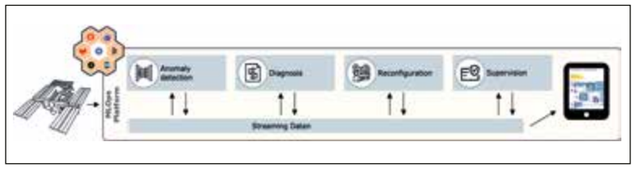

Fig. 2: Overview of modular AI services in the (K)ISS project

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Another focus was on developing an MLOps (Machine Learning Operations) platform that supports the entire lifecycle of AI applications (Fig. 3). This platform not only enables efficient implementation, deployment-to-production, and modular coupling of algorithms but also evolved into an independent research subject. It was designed independently of specific use cases, won an Airbus innovation award, and was presented at several professional conferences. The platform forms the basis for founding the startup prokube.ai GmbH, which is now taking over the further development and marketing of the MLOps platform. It offers cross-industry application possibilities and supports deployment in private data centres and the Cloud as well as in completely isolated (air-gapped) environments without connection to external networks, making it particularly attractive for security-critical applications.

The technologies and concepts developed in the project make an important contribution to increasing efficiency, flexibility, and safety in complex technical systems. The project results are already planned for use in the ISS successor project and future space missions. Beyond the concrete application perspective in space flight, there is also considerable potential for military applications to improve performance and reaction speed in critical situations. In the Bundeswehr, such an assistance system can be used in existing systems to optimise maintenance processes for autonomous systems such as unmanned aerial vehicles as well as land and water vehicles. Moreover, there are opportunities for AI-based analysis and diagnosis in supporting complex combat decisions and improving multi-domain integration.

Due to its success, the project has been extended by two years to continue and deepen the promising research and development in this important field. The extension addresses new research questions, particularly the transfer of developed methods to other complex systems such as the Orion Multi-Purpose Crew Vehicle (MPCV). The (K)ISS Project is funded by dtec.bw – the Bundeswehr Centre for Research on Digitalisation and Technology. dtec.bw is financed by the European Union – NextGenerationEU.

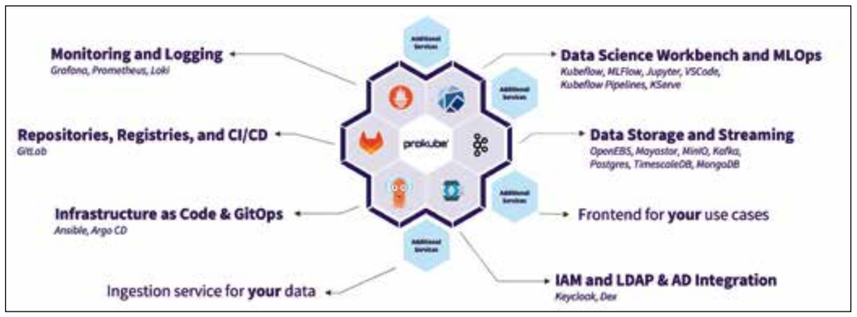

Fig. 3: MLOps platform and its core features

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Close-quarters battle – Predictors and training effects in non-specialised soldiers and police special forces

Close-quarters battle (CQB) is a key skill for special forces. This study (N = 35; n = 18 police special forces) examined predictors of CQB performance and training effects. An anticipatory stress response correlated positively with performance, while extraversion showed a negative correlation. The training significantly improved tactical performance in both groups.

Increasing urbanisation and the rising prevalence of asymmetric conflicts are shifting military engagements more frequently into urban areas. A significant proportion of the global population already resides in cities, with further urban growth expected in the coming years. This trend makes urban operational capabilities a critical factor for military and security-related actors, since urban conflicts present new tactical challenges and opportunities. Urban environments offer irregular and regular forces various advantages, such as enhanced surveillance, the use of underground infrastructure such as tunnels, and the disruption of resource concentration by opposing forces. At the same time, the task of distinguishing civilians from combatants in urban conflicts poses a considerable challenge. In such scenarios, technological advantages are often less decisive, while the training and skills of deployed forces are crucial for success.

A key competency in urban operations is close-quarters battle (CQB). These micro-tactical approaches rely on speed, precision, and the use of spatial geometry, requiring a high level of adaptability and rapid decision-making. Originally developed for special forces, CQB has become essential for regular infantry units, particularly in urbanised conflict scenarios. It also plays a critical role in law enforcement. Special units use these tactics for counterterrorism, apprehending armed offenders, and rescuing hostages.

The complexity of CQB places significant demands on training and individual capabilities, making its implementation time-consuming and costly. However, mastering these tactics is indispensable for ensuring civilian safety and meeting legal requirements.

A sample of N = 35 participants (n = 18 police special forces) completed a CQB training and pre- and post-training CQB performance tests. Performance was assessed through standardised eye-tracking analysis (Fig. 1) and video-based evaluations by two experts. Stress responses were measured during CQB (heart rate) as well as before and after CQB (salivary alpha-amylase and cortisol).

The training significantly improved the performance of both specialised and non-specialised forces ($F(1,15) = 11.372$, $p = .004$, $\eta^2P = 0.431$; Fig. 2), particularly in tactical behaviour, while response time and gaze behaviour showed no improvements. Stress responses decreased after the training ($F(1,32) = 6.647$, $p = .015$, $\eta^2 = 0.048$; Fig. 3 and 4), and anticipatory stress response was positively associated with CQB performance in the pretest ($\rho = .512$, $p = .005$). Additionally, extraversion negatively predicted CQB performance ($\beta = -.40$, $p = .035$), and the mean 2D:4D ratio strongly correlated with gaze behaviour ($r = .45$, $p = .007$), tactical behaviour ($r = .41$, $p = .019$), and attentional ability ($\rho = .57$, $p < .001$).

The findings demonstrate that a compact CQB training can effectively enhance performance and reduce stress. Gaze behaviour proved to be a valid indicator of CQB expertise, offering valuable insights into participants' competence levels. An increased anticipatory stress response was found to enhance performance, while extraversion and the 2D:4D ratio emerged as important predictors for aptitude diagnostics.

Potential applications include the development of compact CQB courses tailored for both novices and experienced personnel. Performance facets such as tactical behaviour, weapon handling, gaze behaviour, and response time serve as practical evaluation templates. In particular, gaze behaviour can be utilised for personnel selection and training evaluation, enabling targeted enhancement and development of CQB capabilities.

Fig. 1: Photo of the eye-tracking recording from a CQB scenario

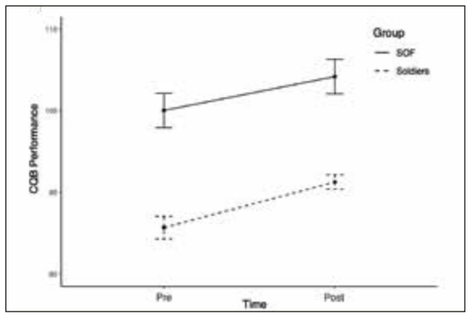

Fig. 2: Effect of CQB training on overall CQB performance between police special forces and non-specialised soldiers

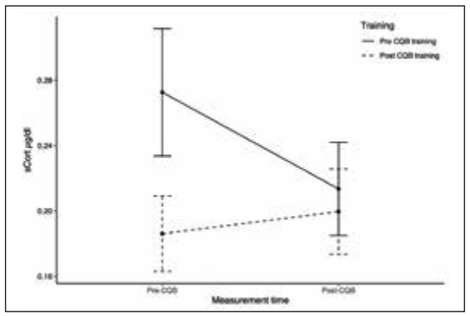

Fig. 3: Salivary cortisol concentration before and after the CQB scenario pre- and post-CQB training

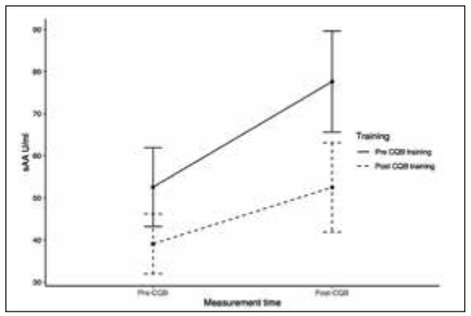

Fig. 4: Salivary alpha-amylase concentration before and after the CQB scenario pre- and post-CQB training

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Physiological and psychological stress reactions in soldiers during virtual combat scenarios

Soldiers have to make complex and sometimes existential decisions under extreme stress. Research into physiological and psychological stress reactions in virtual reality is intended to contribute to a better understanding of how soldiers experience stress in order to further optimise military training and thus improve the combat readiness of the German Armed Forces.

Life-threatening situations, extreme climatic conditions, noise, uncertainty, and high physical strain are inherent components of armed conflicts and characterise the operational reality of many soldiers. In order to optimally prepare soldiers for real combat deployments, a profound understanding of the individual perception and processing of physical and psychological stress is essential. The Smart Health Lab (SHL) at the Bundeswehr University Munich (UniBw M) aims to expand this understanding through an interdisciplinary approach that integrates research methods from sports biology, psychology, and computer science.

The depiction of realistic combat scenarios poses a particular challenge due to high personnel, material, and time requirements. The SHL therefore uses a virtual training platform which makes it possible to generate diverse, immersive combat scenarios in virtual reality (VR) and adapt them flexibly and resource-efficiently for various research projects (Fig. 1).

Moreover, the laboratory equipment of the SHL enables a comprehensive assessment of physiological and psychological parameters. Data collection through psychometric measures and wearable sensors is increasingly complemented by the analysis of stress hormones (e. g., cortisol, alpha-amylase) in a newly established wet lab (Fig. 2). To investigate the impact of external stressors on physiological and psychological parameters, several studies have been conducted, in which soldiers from the UniBw M completed various virtual scenarios (Fig. 3). Stressors such as ambient noise, enemy pressure, and physical exertion were deliberately varied.

The current study results suggest that VR combat scenarios effectively induce stress in soldiers, with performance being negatively affected by increasing intensity of applied stressors. However, the results also indicate significant interindividual differences in stress experience among soldiers. Furthermore, a gradual increase in the intensity of stressors does not necessarily lead to stronger stress reactions. Regarding the stressor “enemy pressure,” both intense combat actions and long combat pauses, as well as reconnaissance activities in urban environments, were identified as particularly stressful (Fig. 4). Future studies will therefore examine the impact of individual factors such as VR experience, training level, and personality traits on stress perception. Additionally, analyses of blood glucose levels and stress hormone release will provide further insights into the physiological mechanisms of stress response.

In the long term, the SHL research projects aim to enhance VR scenarios with adaptive content, where the assessment of stress responses will allow for flexible adjustments to the scenarios, providing individualised training for Bundeswehr soldiers and thereby improving their combat readiness.

Fig. 1: Soldier in the virtual reality training platform

Fig. 2: Analysis of saliva cortisol samples in the wet lab

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Fig. 3: Virtual scenario from the participant’s perspective

Fig. 4: Virtual scenario with a casualty situation

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Residual load-bearing capacity analysis of bolted joints after blast loading for the safety assessment of critical infrastructure such as bridges

To ensure safe passage for military and civilian vehicles after blast loading, this project investigates the residual load-bearing capacity of strategically important bridges. A specially developed test rig for fundamental research experimentally and numerically analyses the loading of bolted joints. For this purpose, typical bolts used in modern steel construction were tested in an explosion tunnel.

Given current geological developments, the protection of critical infrastructure is becoming increasingly important. Until now, research has primarily focused on damaged reinforced concrete components, as this material dominates the high-rise and bridge construction sectors in crisis regions. In high-tech countries, however, steel constructions play a central role due to their high performance, making it increasingly important to assess their continued use after explosion impacts.

Capability building in national and alliance defence requires the protection of critical infrastructure, especially of steel constructions after explosions, which is why this project was developed in collaboration with the BAIUDBw, Dept. Infra. Military and civilian vehicles must be able to safely pass traffic routes and bridges in crisis situations. Building on the ongoing “BRASSCO” project at the Bundeswehr University, which focuses on quick classification for bridges, the challenge now lies in rapidly assessing the residual load-bearing capacity of damaged structures to make informed decisions about their continued use and on how to make them secure.

To address this critical issue, numerical and experimental tests were conducted to understand the behaviour of bolted joints under high dynamic loads. The main motivation for the studies was to collect data for assessing failure scenarios and to develop and calibrate numerical calculation models. The fundamental structural behaviour under high loading rates was investigated in 2024 through a specially designed test rig (Fig. 1) at the Bundeswehr Technical Centre 52 (WTD 52) in Oberjettenberg.

Bolted joints made of various materials with different diameters and both preloaded and non-preloaded screws were tested. The test variants varied in terms of load, distances, preload, and strength (Fig. 2). The blast tests were conducted in the so-called small blast chamber of WTD 52, where the test frame with the specimens (bolted joints) was exposed to a controlled explosion. This developed testing procedure is loosely based on the shock tube test in accordance with the glass building standard, where glass panels are tested against pressure waves.

The combination of experimental and numerical methods confirmed that bolted joints undergo significant deformations and failure mechanisms under blast loading (Fig. 3). It also showed that high-strength steels perform better under these extreme conditions compared to conventional steels. The numerical simulations also provided valuable insights into stress distribution within the bolted joint, which will now be further examined with the data measured in the experiments (Fig. 4).

Since this study mainly generated fundamental insights, there is enormous future potential for this field of research. The goal of future work is to develop a comprehensive guideline that describes the effects of blast loading on steel structures. This includes, for example, the development of innovative protection systems for critical infrastructures, specifically to shield them from blast loads – such as using energy-absorbing components. Another focus will be on refining existing models and investigating larger bolted joints to better understand their behaviour under extreme loads. To validate these models, there are plans to carry out open-field tests on scale models or even full-sized components. Additionally, efforts will be made to expand and strengthen international collaborations to promote knowledge exchange and benefit from global developments.

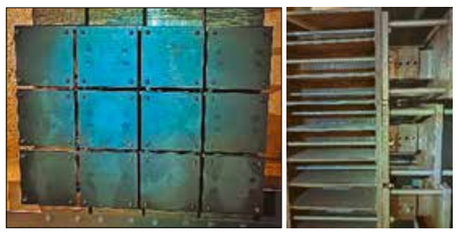

Fig. 1: Test setup for investigating screw connections under explosive load

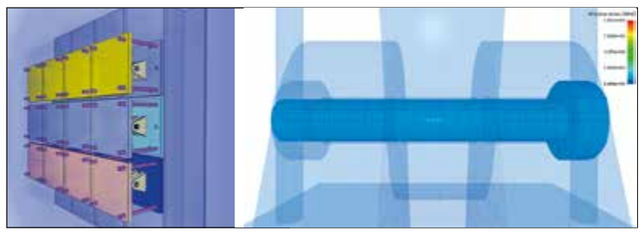

Fig. 2: FEM model of the whole test frame (left) and, as an example, the screw connection M16 not prestressed (right)

Fig. 3: AScrews removed from the test specimens after the explosion with diameters M12 (left) and M16 (right)

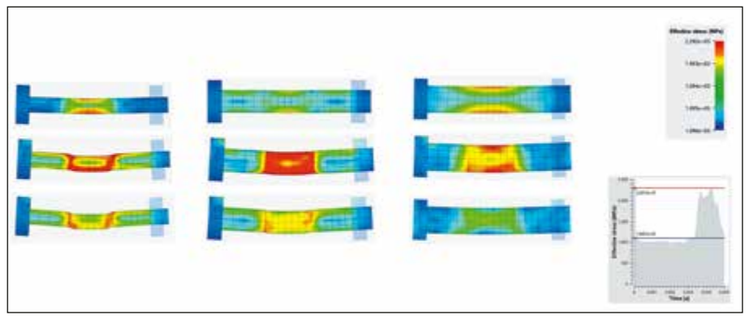

Fig. 4: FEM model of the screw connection under explosion load M12, M16 and M20

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Artificial intelligence: Acceptance and use in private and professional environments

In a pilot study, knowledge of and attitudes towards artificial intelligence (AI) as well as the current and future use of AI-based tasks and tools among students and managers were examined. The study was conducted by the Department of Work, Organisational and Business Psychology at Helmut Schmidt University/Bundeswehr University Hamburg (HSU) in cooperation with the Armed Forces Office.

Artificial intelligence plays a central role in many professional areas and is leading to new opportunities, but also to social debates about opportunities, risks and ethical aspects. Tasks that used to take a lot of time can now be completed with significantly less effort. More and more people are using AI in their daily lives, be it through voice assistants such as Siri or Alexa, personalised recommendations on streaming platforms, or smart navigation systems. AI facilitates many processes and is increasingly being integrated into a wide range of areas of work and life, which is why the topic is also highly relevant in the German Armed Forces.

In spring 2024, the Department of Work, Organisational and Business Psychology at HSU conducted a pilot study on the acceptance and use of AI systems together with the Armed Forces Office. The initial goal was to develop a questionnaire instrument to identify both situational and individual factors that either facilitate or hinder the use of AI.

Additionally, the study aimed to determine which AI applications are already widely accepted and used and, conversely,

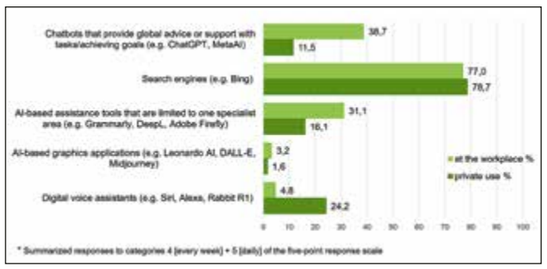

Fig. 1: Frequency of use of AI-based tools

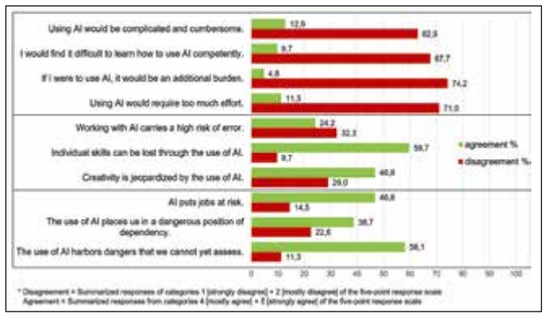

Fig. 2: Perceived effort and risks of AI

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where there are still reservations, a lack of knowledge or unfavourable framework conditions.

To answer these questions, a total of $N = 62$ people were surveyed online in a pilot study, of which $n = 24$ were students at the university of the German Armed Forces and $n = 38$ were managers from various industries. In addition to questions about individual use of AI-based applications, personal attitudes towards AI, and perceived advantages and disadvantages, the survey also examined the conditions of AI use as well as the attitudes of others in the participants' professional environment. Furthermore, participants were asked to assess their future intention to use AI, both in general and in specific application scenarios.

The results of the pilot study indicate that AI is already widely used both professionally and privately, with the specific tools varying among users (Fig. 1). Most respondents find AI interesting and useful, but also express concerns about ethical issues, security risks and the impact on the labour market (Fig. 2). Compared to the surveyed managers, the students show higher values in use, competence and acceptance of AI, which is likely related to the younger age of the student sample (Fig. 3). Overall, it can be seen that a high perceived usefulness supports the willingness to use AI, while a strong perception of risk or a perceived high effort tends to inhibit this. Additionally, workplace conditions and opinions from the professional environment also have a significant influence on current and future use (Fig. 4).

To strengthen the acceptance of AI in the work context, user-friendly technologies should be provided and supportive framework conditions established. Managers should receive targeted training in order to act as role models. Clear guidelines for secure use and data protection are essential to minimise concerns. Future research should further explore the reasons for low acceptance and usage based on a broader data basis, taking a differentiated look at various areas of work and application. The findings should be expanded and deepened in further studies.

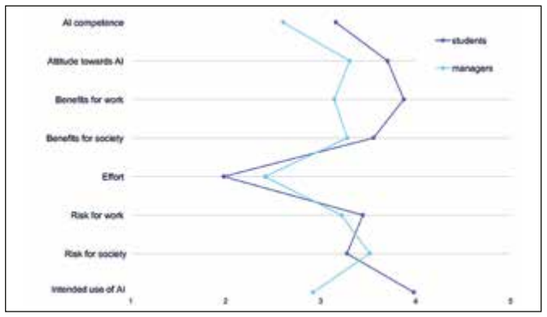


Fig. 3: Comparisons between samples

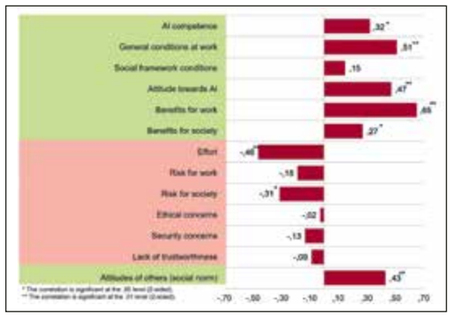
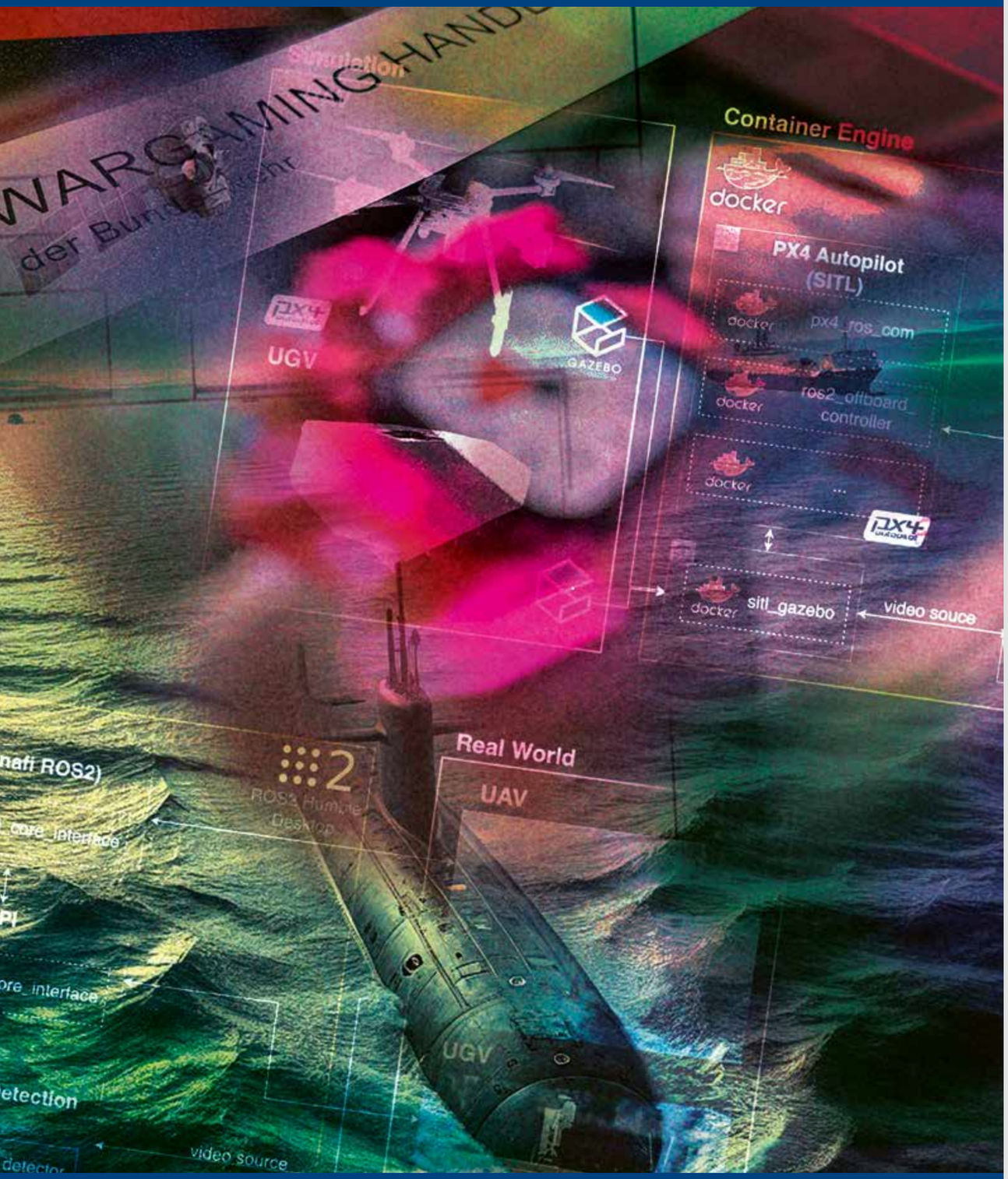


Fig. 4: Correlations with the intended use of AI


Container Engine
docker
PX4 Autopilot
(SITL)
px4_ros_com
ros2_offboard
controller
...
sitl_gazebo
video souce
UGV
GAZEBO
Real World
UAV
UGV
ROS2 Humble
Desktop
video source

8

Appendix

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