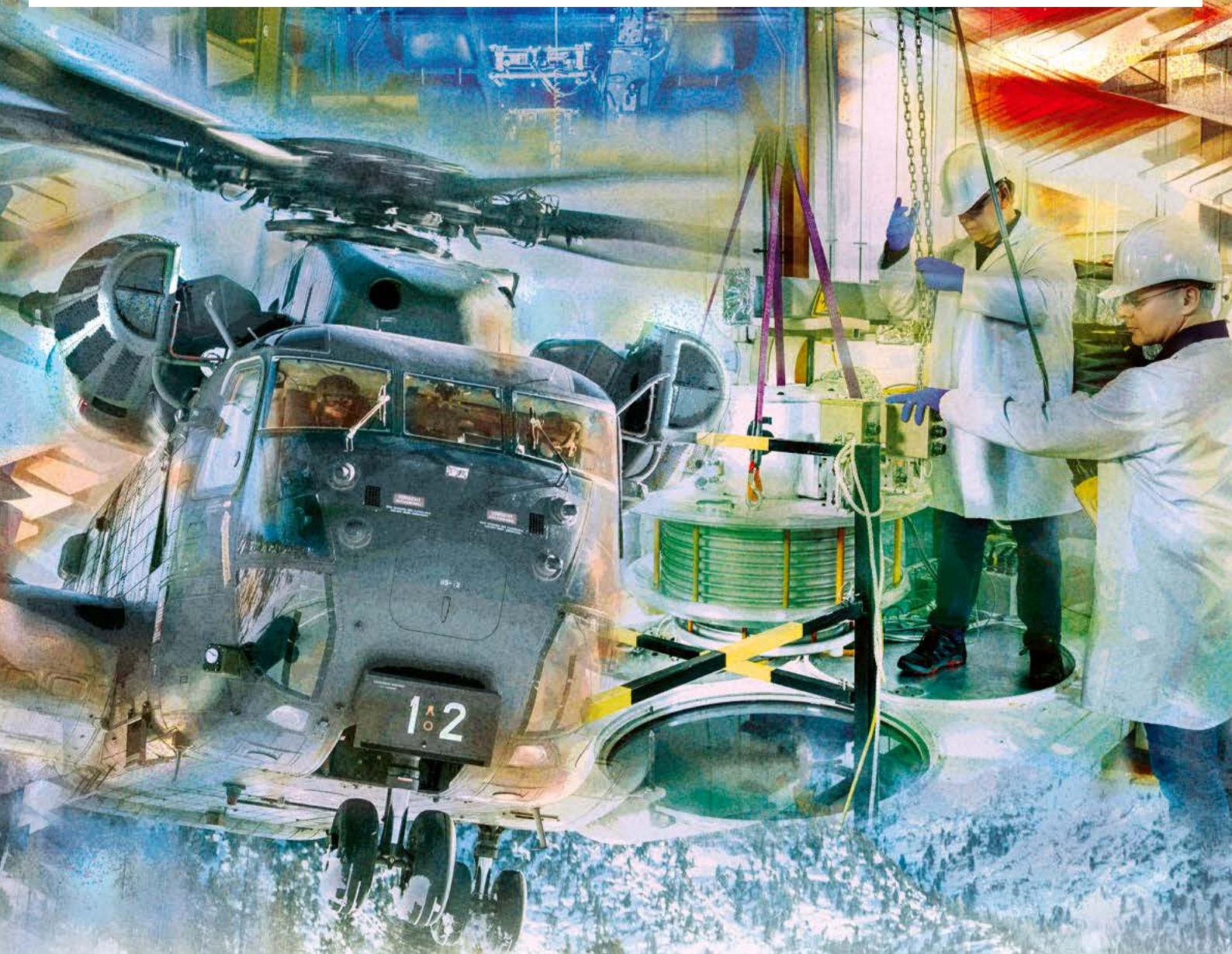
Federal Ministry
of Defence

Military Scientific Research Annual Report 2022

Defence Research for the German Armed Forces



BUNDESWEHR

Federal Ministry
of Defence

Military Scientific Research Annual Report 2022

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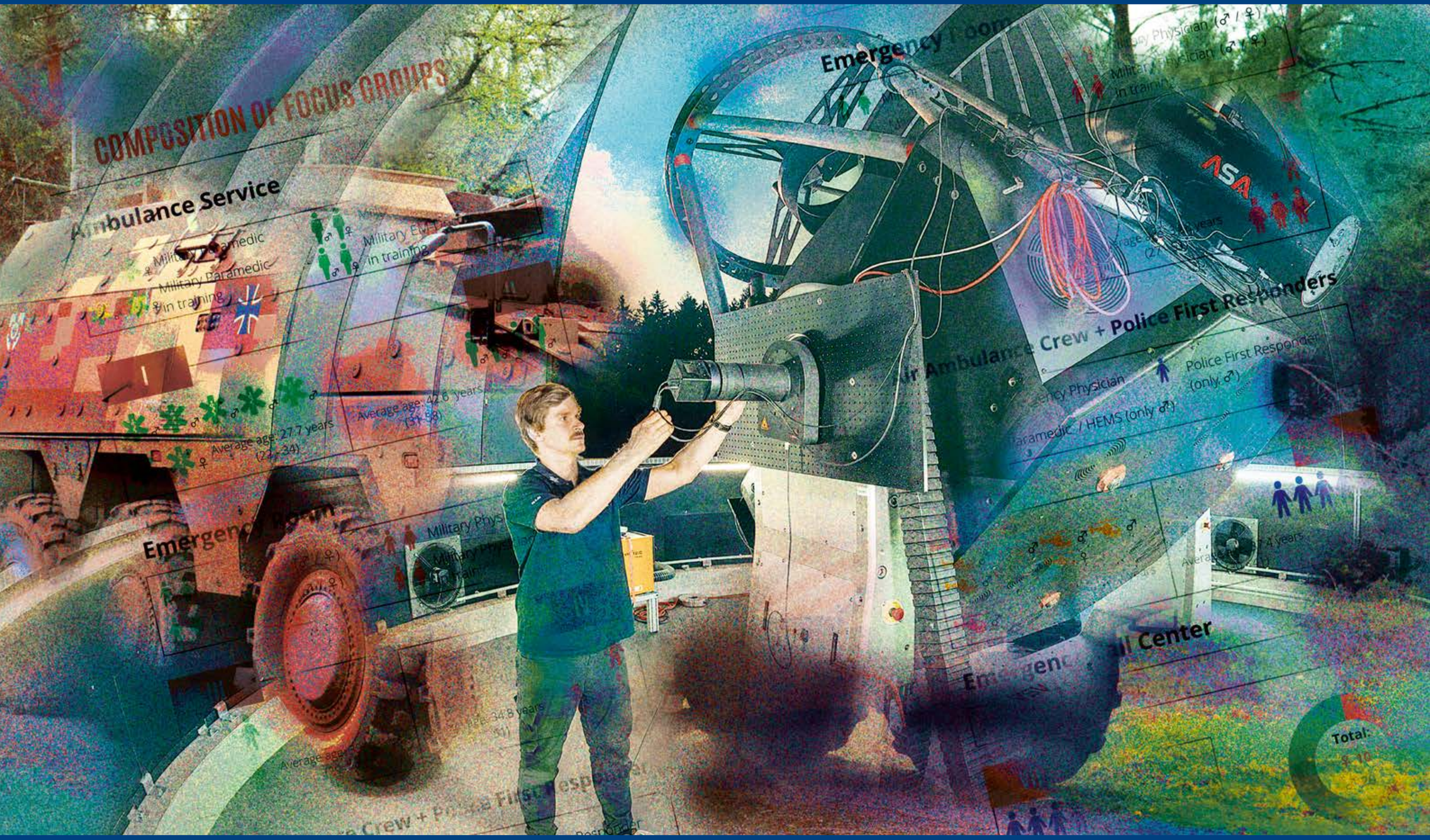
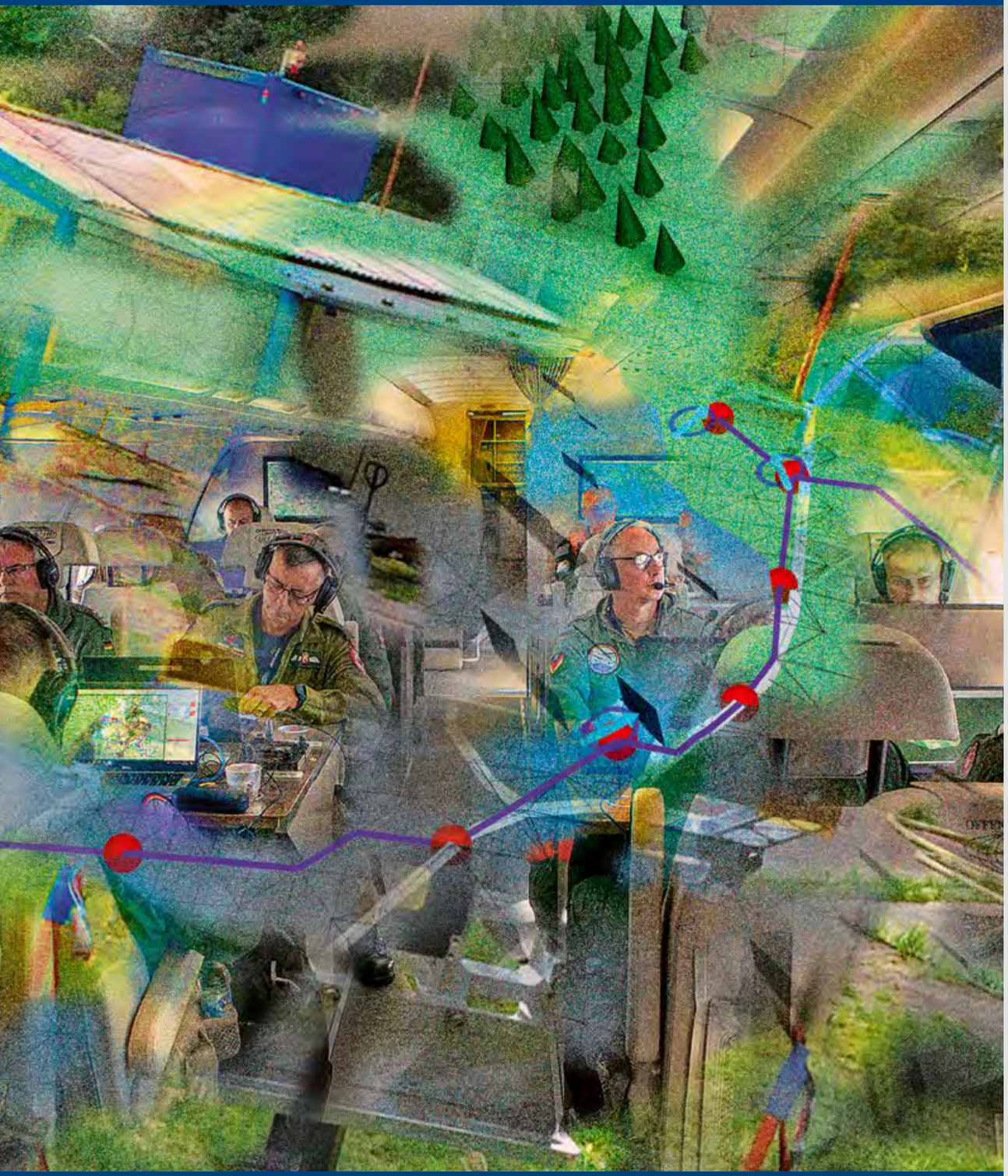

COMPOSITION OF FOCUS GROUPS
Ambulance Service
Military Paramedic
in training
Average age: 27.7 years
(24 - 34)
Military EMT
in training
Average age: 42.6 years
(34 - 68)
Emergency Room
Military Physician (♂ / ♀)
in training
Average age: 34.8 years
(31)
Ambulance Crew + Police First Responders
Emergency Physician
Paramedic / HEMS (only ♂)
Police First Responder
(only ♂)
Average age: 37.4 years
Emergency Call Center
Total:



Ministerialdirigent Alexander Schott

Unterabteilungsleiter A III und Forschungsbeauftragter
Bundesministerium der Verteidigung

Defence Research for the German Armed Forces

Russia's invasion of Ukraine in contravention of international law has shaken the very foundations of the European peace order and put our national and collective defence capability to the test. As Chancellor Olaf Scholz has said, this represents a watershed moment, a turning point in history for Germany – one that will also affect all areas of the Bundeswehr. The efforts required to ensure and maintain a fully operational Bundeswehr go far beyond the special fund that has been made available in the budget and the goal of accelerating the procurement of defence materiel. Our security environment and our responsibility to European and transatlantic security require comprehensive and permanent national contributions to the defence of the Federal Republic of Germany and our allies.

Defence research and its focus areas of
- defence technology,
- military medicine and psychology,
- military history and the social sciences,
- geosciences and
- cyber and information technology

play an important role in anticipating and meeting future requirements.

The importance of technological superiority in today's conflicts is evident in Ukraine's ongoing successful resistance to attacks by Russian armed forces and paramilitary units.

In order to meet the challenges of this watershed moment, available high-tech equipment must be fielded to our troops more quickly. We must also work to maintain and increase the conceptual and technological advantage of our armed forces, however, to ensure that we can project a deterrent effect as a peacekeeping measure. That, ultimately, is the goal of our defence research efforts.

Ensured by a strong foundation of constantly advancing defence research, the ability to analyse and assess trends and technology forms an essential basis for a wide range of decisions, from the right selection and use of safe and effective defence materiel to the careful and qualified medical treatment of casualties as well as aspects of the conduct of operations.

Robust defence research rightly focuses on immediately ensuring the sustainable operational readiness of the Bundeswehr, yet it is also essential for Germany's strategic capacity and ability to take action on matters of security policy. The war in Ukraine has exposed the vulnerability of supply chains and the problems associated with a dependence on armaments from other states.

Defence research provides a considerable contribution to reducing such dependencies and to maintaining and enhancing the technological sovereignty of Germany and Europe. While it

are our partners, the German research landscape and German industry who ensure our sovereignty with scientific and technological advances, their knowledge and products often would not exist without defence research.

Defence research conducted on behalf of the Federal Ministry of Defence cannot achieve all of this alone, however. For it to comprehensively accomplish its tasks, it must cooperate with the civilian scientific community in Germany and with international partners. On the international stage, bilateral and multilateral cooperation are equally important. Such multilateral cooperation, for example in the context of the European Defence Agency and NATO's Science Technology Organization, ensures that scientific problems can be approached from a position of burden-sharing and pooled expertise. In bilateral cooperation with strong partner nations, we must join forces to more effectively achieve our goals even despite limited funds and scientific capabilities.

If anything, Russia's invasion of Ukraine has strengthened the ties between us. International cooperation has been intensified and reservations about German civilian researchers working together with their colleagues in defence research have been overcome. The importance of the latter is highlighted in the 2023 Report on Research, Innovation and Technological Performance in Germany by the Commission of Experts for Research and Innovation, which recommends that the strict separation of military and civilian research that exists in Germany be overcome to facilitate synergies.

The contributions in this 2022 Annual Report on defence research for the German Armed Forces will provide some insight into the diverse range of current research projects. The topics covered in this report are at the cutting edge of science. Three contributions, for example, focus on the detection of (and defence against) hypersonic missiles, a topic that is extremely relevant at the moment.

The ERNST small satellite project to study space-based methods for detecting rockets and hypersonic missiles is particularly noteworthy. It has already achieved such a high level of technological maturity that its launch is planned as part of a demonstration of technology in cooperation with the US Space Force in 2024.

Aside from such prominent topics, there are also many contributions on less high-profile issues. Nevertheless, images of Russian tanks getting stuck in mud and being recovered by Ukrainian tractor drivers for their own army have shown just how important some of the less high-profile topics can be, including terrain trafficability, which is essential for the safe deployment of own forces and for assessing enemy axes of movement. The contribution on this very subject included in this report thus makes for interesting reading.

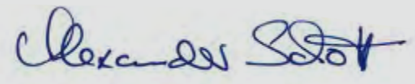
Aside from these examples, the 2022 Annual Report includes many more important contributions from the five fields of defence research which illustrate how the watershed moment that is the war in Ukraine is reflected in defence research.

Over the coming years, our main focus will be on ensuring that the results of defence research can be fielded more quickly through closer cooperation between researchers and users. This way, we can reliably and sustainably ensure our technological advantage. We must keep in mind that any technologies currently in use in Ukraine can be captured, analysed and shared.

As a result, potential adversaries will eventually also have these technologies at their disposal. This requires even greater effort on our part to rapidly operationalise new technologies and to guarantee our technological and operational superiority for the future. We can only do this together with the German research community and our international partners.

Together we will be able to rise to the particular challenges and tasks of defence research for the Bundeswehr. Defence research in Germany in cooperation with its users will continue to contribute to enhancing the Bundeswehr's operational readiness, technological and operational superiority and, last but not least, its fitness for the future. I am confident that, together, we can achieve this goal.

With best regards



Alexander Schott, 25 July 2023

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Access directly by clicking on the item

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Defence Technology Research

The Russian invasion of Ukraine had a strong impact on defence technology research in 2022.

The war has allowed us to objectively assess the value of our technology in combat against an adversary with Russian material and operational principles.

Ukraine's successful resistance, which is partly the result of superior Western weapon systems, has also demonstrated the fundamental necessity and importance of defence research. The weapon systems that today are highly praised by the defenders of Ukraine are the products of military research conducted over past decades. These products include technology that has been developed in all stages of defence technology research (preliminary and applied basic research as well as prototypical technology demonstrators) in Germany or by our partners in the EU and NATO.

The analysis and assessment capabilities acquired in defence research and technology are currently asked for the implementation of the special fund. Even when commercial off-the-shelf products are purchased in order to accelerate procurement for the Bundeswehr, the question remains, "What is the right product both now and in the future?"

This question, however, can only be answered on the basis of defence research and its analysis and assessment capabilities. Maintaining this expertise is just as important as developing new technologies. Furthermore, these analysis and assessment capabilities are necessary to identify new threats at an early stage, to define requirements for new technologies, and to evaluate prospective weapon systems.

At the same time, every system we give to Ukraine potentially diminishes our technological advantage. Every unit that we provide may be captured and analysed. As a result, we must step up our efforts in defence technology research in order to develop new technologies together with our international partners and thus maintain a sufficient technological edge.

Both the war in Ukraine and the COVID-19 pandemic have highlighted the vulnerability of our supply chains and the importance of European technological sovereignty. Research in defence technology also makes a significant contribution to securing supply chains and enhancing technological sovereignty.

In summary, defence technology research has become more important since the Russian invasion of Ukraine and faces a large number of tasks. Nevertheless, selected researchers from the field of defence technology have taken the time to present their findings from 2022. Their work is presented on the following pages.

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Position selection assistant: Terrain evaluation to support operational planning and battle management

Terrain evaluation is deeply rooted in the decision-making process of the land forces. However, it costs valuable attention and time for map reconnaissance and terrain walks. Time, in particular, is a scarce asset in the preparation of combat. Automated terrain evaluation can relieve the military leader and accelerate decision-making.

In the decision-making process of the land forces, the craft and art of the military leader combine to arrive at a sensible decision. From the mission analysis to the decision, many influencing factors have to be considered which are divided into the categories of opponents / other actors, friendly forces, geospatial factors, civilian situation, information environment and other factors.

At Fraunhofer IOSB, geospatial factors were assessed as particularly suitable when approaches for the development of assistance functions were examined. Studying the map in detail is often tedious, time-consuming and requires little creativity. The potential for automation is therefore high. In addition, the map can provide only part of the available terrain information in an abstract form. A machine, however, makes it possible to evaluate additional and more detailed information. For example, elevation information is only roughly represented by contour lines on maps, while digital displays sometimes provide resolutions below one meter. Here, there is potential to relieve the user and to accelerate the decision-making process.

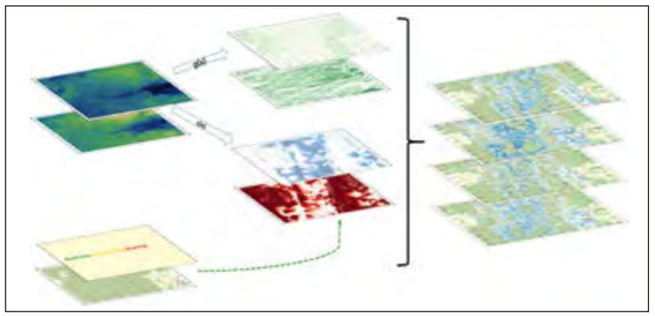

Fig. 1: Operating principle: From available geodata (first column), the terrain is evaluated with regard to individual parameters (second column, results in map form). These are then weighted and combined according to the situation and weapon system parameters (third column)

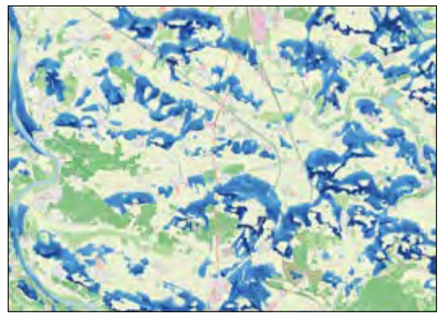

Fig. 2: Position value map (SWK): Potentially good positions are marked in blue. The darker the blue, the greater the probability of finding a good position

Based on this insight, the position selection assistant (Stellungswahlassistent, SWA) was developed. The SWA calculates, for a selected terrain, where suitable positions for the armoured forces are likely to be located (Fig. 1). The extension to other branches is to be examined in follow-up projects. Among other things, each terrain element is assessed as to whether it offers the opportunity to act on terrain ahead or to provide cover from enemies. Based on this, a kind of heat map (position value map, Stellungswertkarte, SWK) is generated which enables the planner to focus on specific areas when making further decisions (Fig. 2).

Together with Rheinmetall Electronics GmbH, the previous development on behalf of the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support was continued with a view to evaluating and improving the existing functionalities and adapting them to possible applications. With the support of the German Army Headquarters, it was also refined in a spiral development process with testing and feedback by the user. In this process, Rheinmetall was primarily responsible for the interface to the user and to the systems introduced.

Initial process evaluation trials were conducted with two comparison groups that had to develop a “preliminary operation plan”. One group was equipped with the position value map (SWK) in addition to the topographic map (Fig. 3). By using the SWK, the time required could be reduced from approx. 60 minutes to approx. 10 minutes.

During further evaluation at the Army Tactics Centre (ATC), the results were confirmed in terrain inspections conducted together with the user. It became clear that the positions were selected correctly based on the parameters used. The fact that not all positions found are equally suitable is mainly due to assessments that are associated with specifically human skills or influenced by parameters that have not yet been considered, such as approach and departure routes. Nevertheless, the position selection assistant (SWA) makes it possible to reduce the number of necessary terrain inspections. The experts at the Army Tactics Centre preliminarily estimated the time advantage thus gained at approx. 30 minutes per level of command.

From the contractors’ perspective, the agile development practiced with direct user participation proved to be particularly useful in the implementation of the project. The evaluations of the position selection assistant (SWA) have convinced us that its use can accelerate the decision-making process and will be of advantage to the troops. We intend to continue this in the further improvement of the position selection assistant and functional extensions, for example to the operational planning assistant (OPlA). In this way, the user will be able to benefit from the results of applied research as soon as possible.

Fig. 3: Digital meets traditional: A position value map (SWK) printed in red on an overlay is superimposed on a topographic map for operational planning. Result of a map exercise for evaluation

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Efficient video image exploitation by gaze-based interaction and artificial intelligence

Video image exploitation is an essential capability for modern reconnaissance and surveillance systems. Automatic image exploitation procedures such as multi-object tracking and screening, in combination with gaze-based interaction and voice input, provide efficient support for imagery analysts. Studies have shown a significant performance improvement and workload reduction.

Today, imagery reconnaissance and surveillance increasingly include video image exploitation. Platforms such as LUNA, HUSAR, Heron, Tornado or Fennek are equipped with optronic sensors and provide imagery from which the mission-relevant information must be extracted.

Image exploitation requires a continuously high degree of concentration of the imagery analysts and is a very demanding task. This applies in particular to live video image analysis. Modern video exploitation systems such as the ABUL system (automated image exploitation for unmanned aerial vehicles) developed at the Fraunhofer Institute for Optronics, System Technology and Image Exploitation (IOSB) are available for support. ABUL offers various functions, such as image optimisation, image stabilisation, procedures for change detection, motion detection, object detection and object tracking.

Due to their high performance, state-of-the-art AI methods based on deep artificial neural networks are used, in particular for detection and tracking procedures. Object detection can work on video streams as well as large single images, e. g. to support screening tasks (finding and, if necessary, counting objects) (Fig. 1). The object detection procedures also form the basis for multi-object tracking, which provides trajectories of moving objects (Fig. 2) in video data and is of interest both for conventional full motion video (FMV) and for wide area motion imagery (WAMI, video imagery with large scene coverage often including a large number of objects).

The objective of the research work was to further develop selected image exploitation methods and interaction through eye tracking and voice input in order to reduce the workload and to enhance the performance of imagery analysts.

Gaze-based interaction is implemented using a video-based eye-tracking device that captures the user's gaze position on the monitor (Fig. 3). The gaze position is naturally suitable for pointing purposes, since the user visually fixates the interaction location before performing the interaction. In contrast to traditional mouse input, looking for and manual repositioning of the mouse cursor are not required, which significantly reduces the perceptive, cognitive and manual effort. In user studies on experimental systems for interaction with multi-object tracking and vehicle screening (target object selection, zooming and shifting of images), gaze-based interaction was more effective and faster than interaction based on mouse input. The availability of automatic screening results significantly increased the number of correct target selections.

Voice input provides further relief. A prototype system has been realised which allows controlling the integrated recognition assistance system (based on RecceMan®) using voice commands to enter distinguishing features of a vehicle to be identified (Fig. 4). The underlying AI software "KALDI" (based on deep neural networks) receives user input commands like "apply track vehicle" and forwards them to the recognition assistance system, which determines the possible vehicle type based on this information. Voice control works in a very robust manner, even with different users.

Future work will focus on the detection of partly occluded static objects that are more difficult to detect by human analysts and on optimising persistent tracking of moving vehicles that are temporarily occluded.

Fig. 1: AI-based object detection in the ABUL video exploitation system. The imagery shows the detection of aircraft, passenger cars and trucks (image section: XView, cf. Lam, Darius, et al. "xview: Objects in context in overhead imagery." arXiv preprint arXiv:1802.0785 (2018))

Fig. 2: AI-based multi-object tracking in wide area motion imagery (WAMI) showing automatically recognised trajectories for moving vehicles (WAMI image section: Hensoldt, cf. Sommer, Lars, Wolfgang Krüger, and Michael Teutsch. "Appearance and motion-based persistent multiple object tracking in wide area motion imagery." Proceedings of the IEEE/CVF International Conference on Computer Vision. 2021)

Fig. 3: Experimental system equipped with a Tobii 4C eye tracker below the video exploitation monitor. The pointing operation is accomplished using gaze and allows, for example, selecting the position of relevant objects (e. g. vehicles). Object marking as well as zooming and shifting of images are actuated at the gaze position using various keys of the computer keyboard

Fig. 4: Recognition assistance with AI-based voice input: The recognition features arranged around the target object can be entered into the system for target object determination by means of voice commands while keeping the visual attention on the target object

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The first small satellite for the Bundeswehr: Missile detection with the 12U-CubeSat ERNST

With the completion of the 12U-CubeSat ERNST, the first small satellite mission for the Bundeswehr will begin in November 2023. ERNST will demonstrate the potential of CubeSats, which are small, standardised and cost-effective satellites, in an ambitious application: the detection of rockets and hypersonic weapons with a cryogenically cooled camera system.

The ERNST satellite mission is breaking new ground in several respects. ERNST is not only the first CubeSAT to be examined for its potential for Bundeswehr applications. It is also the first space system exclusively developed by Fraunhofer, which for many years has contributed to innovations at the component and subsystem level in many areas of space travel. ERNST also sets new technical standards. Above all, it will demonstrate a complex, cryogen-cooled infrared application in a CubeSAT of only 12U in size. “U” stands for “unit” and defines the size of CubeSats. One unit corresponds to a cube with an edge length of 10 cm. A 12U satellite thus has external dimensions of 24 × 24 × 36 cm^3 and a total weight of less than 20 kg.

The main payload is an infrared camera system which will be used to demonstrate missile detection measures developed at Fraunhofer IOSB. The satellite will observe the earth’s surface in various short- and medium-wave infrared ranges in order to ensure the reaction time required for early warning and the initiation of interceptions. The combination of different spectral ranges allows the satellite to rapidly and reliably detect the infrared signature of a rocket or missile during its various operating phases, such as boost and glide phases. The stationing of ERNST in an orbit close to the earth will ensure a high signal-to-noise ratio. In order to increase observation and integration time along the 96-km-wide recording strip in the event of rocket detection, the satellite will swivel along its trajectory and pursue the target. THE ERNST mission will not only collect reference data of the earth’s background in the relevant wavelength ranges, but will also characterise the signature of a rocket launch and demonstrate its tracking.

For the compact payload, we have combined commercially available defence products that have been specially adapted and verified for measurement and space applications. These include optics, a Stirling cryo-cooler, an infrared detector module, and a pyrometer. Proprietary developments of Fraunhofer EMI include a filter wheel and a data processing unit. The components are accommodated on an optical bench manufactured by EMI. An optimised topology gives the component a bionic appearance while ensuring the necessary mechanical and thermal stability for the payload. In addition, there is a three-dimensional radiator that emits considerable thermal loads on a much smaller surface than usual radiators.

Additional payloads on ERNST include a camera used for georeferencing as well as a radiation monitor developed by Fraunhofer INT. The latter measures the total dose of radiation received by the satellite as well as the influence of protons and neutrons by using electronic storage elements that are coordinated and shielded in different ways.

In addition to the concrete objectives of missile detection and radiation monitoring, ERNST will demonstrate the effectiveness of small satellites for military applications. This class of satellites has significantly lower costs, higher risk tolerance and a high time coverage when constellations are used. The most powerful CubeSAT products available were tested for the satellite bus. If they were not commercially available, they were developed at Fraunhofer EMI. An example of the latter is the brake sail that ensures rapid de-orbiting at the end of the mission.

After completing and integrating the flight hardware, we are preparing ERNST for its scheduled launch in November 2023 as part of a cooperation project with the US Space Force.

Fig. 1: 12U-CubeSat ERNST in orbit in future

Fig. 2: Main payload: a special camera with a filter wheel as an infrared imager

Fig. 3: ERNST de-orbit subsystem: stowed system (left) and sequence of a deployment test

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SimIB internal ballistics software family: Designing the next generation of Bundeswehr tube weapons

Guns are an important weapon in current and future land systems. Against this background, Fraunhofer EMI is developing simulation programs for government and industry in order to design and evaluate new guns and their ammunition with regard to increased performance requirements and safe handling.

After the end of the Cold War, the operational profile of the Bundeswehr was characterised by the transition from national and collective defence to operations abroad. This transition was reflected in the equipment used by soldiers. Large guns, especially for tanks and artillery, became less important because of the technical superiority over adversaries in asymmetric conflicts. This attitude has changed considerable since the annexation of Crimea by the Russian Federation in 2014, and especially since the invasion of Ukraine and the subsequent turning point in Germany security policy in 2022. Effects on traditional battlefield targets, such as heavy armoured vehicles with high levels of protection, have quickly become the focus of attention again.

Since modernisation measures have not been taken for many years, we can no longer assume that our weapons are superior. Modern software tools for design and evaluation are required in order to improve the performance of existing systems and to develop new, more powerful guns and ammunition. These tools must be based on current scientific knowledge and must be able to predict internal ballistic processes. Against this background, Fraunhofer EMI is working on developing a family of modern internal ballistics programs called SimIB (Simulation tool for Internal Ballistics). SimIB will replace the programs that have been used since the 1980s and 1990s and will in future be the standard software tool in Germany for such calculations.

The first stage is the SimIB-0D software. This is a calculation tool based on STANAG 4367 and has been successfully used by the German government and industry since 2015. A wide variety of functions are available that allow the modelling of traditional guns of all calibres. Dual chamber systems for grenade launchers and mortars as well as small arms can be modelled.

Since equation solvers are separated from SimIB, it is possible to use a high-level programming language such as Python to control SimIB and optimise propulsion. The aim of such optimisation is usually to achieve a high muzzle velocity for the projectile. This approach allows us to evaluate new propellants without complex tests. A common gun safety feature is the ability to set maximum gas pressure. SimIB can take this into account as an additional constraint for optimisation.

The SimIB-1D version is currently being studied. It allows us to model gas-dynamic features of the internal ballistics process. The flow of hot propulsion gases and the behaviour of the propellant bed in the barrel can thus be analysed.

The ignition of the propellant bed is particularly important for large-calibre systems, such as large artillery guns and tank guns, which are designed to accelerate projectiles to velocities of 1500 m/s or more. If the design is incorrect, pressure waves can build up in the chamber that can cause powder grain fracture. In a worst-case scenario, this can have disastrous consequences for material and personnel. These safety requirements can be analysed by simulations with SimIB-1D. The current version of this tool is able to calculate basic charge structures. The software will be continuously extended so that it can offer the functions of SimIB-0D. An extension for multidimensional calculations in 2D/3D is in preparation.

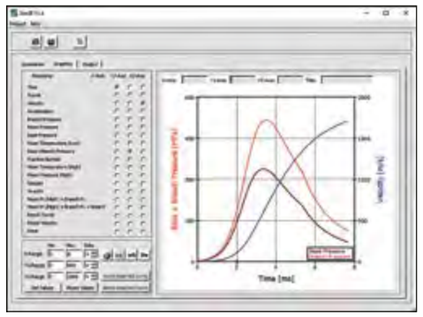

Fig. 1: SimIB-0D user interface

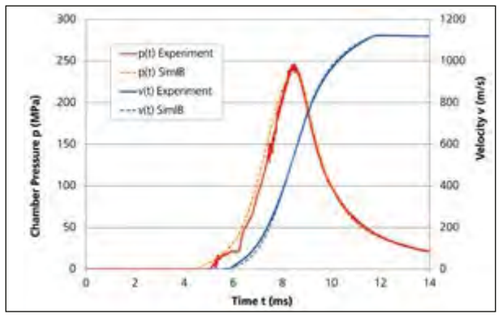

Fig. 2: SimIB-0D – comparison between calculated and experimental pressure and velocity curves

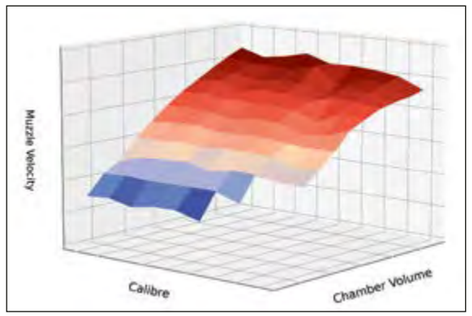

Fig. 3: SimIB-0D-based parameter study

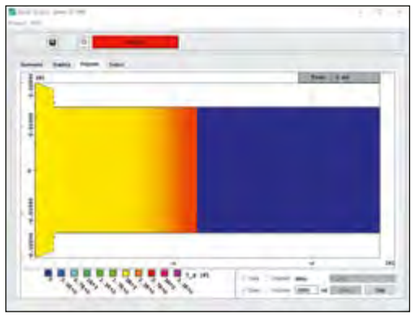

Fig. 4: SimIB-1D – spatial representation of gas temperature behind a projectile

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Passive radar with Starlink satellites

The deployment of new satellite constellations such as Starlink opens up promising opportunities in the field of passive radar. The use of their signals, which are available continuously around the world, will lead to improvements in comparison to other satellite systems. Fraunhofer FHR is validating this new technology with the SABBIA 2.0 demonstrator.

Reductions in satellite launch costs have recently led to a rapid increase in the number of broadband communication satellites deployed in low earth orbits (LEO) at altitudes of less than 2000 km. Among these new satellites, the Starlink constellation represents a major development. It currently offers global network coverage with more than 3000 satellites at an altitude of approximately 550 km.

The characteristics of these new satellites make them highly relevant for passive military radar applications: they ensure global, permanent and all-weather coverage including oceans, poles and remote areas; they are highly reliable in the event of natural disasters or physical attacks; they have strong bandwidth signals (around 240 MHz per transmitted channel) for a ground range resolution up to 0.65 m; they have higher received power on the Earth's surface, which improves the signal-to-noise ratio and maximum range compared to other satellite systems such as Digital Video Broadcasting Satellite (DVB-S) or Global Navigation Satellite Systems (GNSS); they have a predictable transmitter movement which enables radar imaging applications; and they have transmitter redundancy, which provides a resilient and spatially diverse illumination of the ground.

In addition, the opportunistic use of existing transmitters offers the usual advantages of passive radar systems: no frequency allocation is required, development costs are usually lower, covert operation is possible, they are more robust against jamming, and they are better at detecting stealth targets.

Due to these promising possibilities, we examined the suitability of Starlink signals for passive use in the frequency band 10.7 – 12.7 GHz. This allows the development of passive radar systems with ground-based receivers for target detection and imaging. The system architecture (Fig. 1) includes a high-gain reference antenna that tracks the selected Starlink satellite in order to receive a copy of the transmitted signal and a surveillance antenna that is pointed toward the observation area in order to receive echoes from targets.

This architecture can be extended with additional reference channels to simultaneously exploit several satellites with different angles of incidence or with additional surveillance channels in order to apply polarimetric or interferometric methods.

An experimental demonstrator (Fig. 2) was built which extends the corresponding capabilities to the passive radar system SABBIA 2.0 of Fraunhofer FHR. This powerful and modular system can flexibly use Starlink or DVB-S signals on the basis of ad hoc developments in commercial antennas that can be controlled mechanically or electronically. In addition, the system integrates GNSS and inertial sensors that enable operation on moving platforms.

The demonstrator was used to conduct several field tests (Fig. 3) in which Starlink signals were received and characterised (Fig. 4). This new technology is thus being validated not only for target detection and classification but also for permanent remote detection applications such as avalanche detection and infrastructure monitoring.

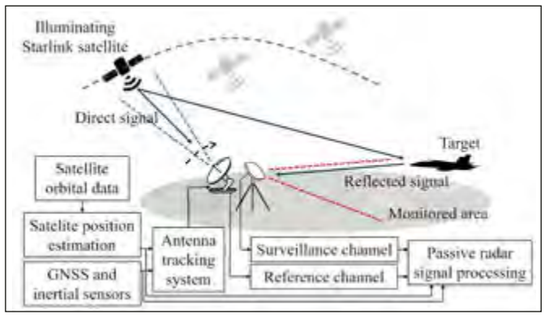

Fig. 1: Passive radar system architecture based on the opportunistic use of Starlink signals

Fig. 2: SABBIA 2.0 passive radar demonstrator with commercial antennas from EPAK (right) and Kymeta (left)

Fig. 3: Field test at Frankfurt airport

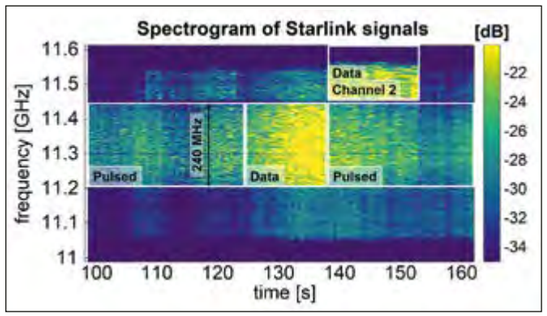

Fig. 4: Spectrogram of Starlink signals received

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Metamaterials for antennas with electronic beam steering

The scanning range of array antennas is physically limited. This range could be extended in the long term by means of electronically reconfigurable metamaterials.

Product developers seek as many degrees of freedom as possible in development and design. Metamaterials could increase the number of these degrees in future. Unlike conventional materials, their electromagnetic properties can be adjusted by the developers themselves. Properties that do not occur in nature are also possible.

Among other things, metamaterials could provide additional degrees of freedom in the development of antennas. But how can military radar systems be improved with metamaterials? This question was investigated by Fraunhofer FHR together with the Spanish company Tafco Metawireless SL and the Spanish Universidad Pública de Navarra in the METALESA II project for the European Defence Agency (EDA).

In this project, Fraunhofer FHR is focusing on conformal array antennas, which consist of numerous smaller antenna elements whose radiating surface is curved. Normally, the beam direction of such antennas is adjusted electronically but the beam scanning range is limited.

In the METALESA II project, which is short for “Metamaterials for Active Electronically Scanned Arrays”, researchers at Fraunhofer FHR are working on expanding the scanning range and improving the performance of curved antennas. The researchers intend to use electronically reconfigurable metamaterials to further change the phases of the radiated wave fronts and thus to extend the scanning range. The electromagnetic phase properties of these special metamaterials can be controlled by applying DC voltages to the varactor diodes integrated into the metamaterial unit cells.

But to what extent can such reconfigurable metamaterials change the phase of radar radiation? And how high are the losses that result? The researchers examined these questions in various experiments. To do this, they fabricated and measured two large metamaterial prototypes using printed circuit board technology.

In one experiment, they mounted the reconfigurable metamaterial PCB in front of a transmitting antenna and investigated radiation behaviour with a receiving antenna. The results are very promising. Phase changes of up to 170° are possible for both horizontal and vertical polarisation. Losses were low, in the range of 1 to 2 dB.

In a next step, the researchers designed and built two prototypes. The first prototype consisted of a single reconfigurable metamaterial circuit board illuminated by a single antenna element, while the second prototype consisted of several reconfigurable metamaterial circuit boards in a faceted configuration, and excited by a curved antenna array (Fig. 1 and Fig. 2).

It was successfully demonstrated that a reconfigurable metamaterial excited by a single antenna element or a small array can perform a lens operation combined with dynamic beam scanning. A scanning range of ± 60° in the azimuth plane with a 3 dB increase in the gain for both polarisations was achieved with the use of only a 1 mm layer of reconfigurable metamaterial structure (Fig. 3 and Fig. 4). The curved antenna array prototype also performed well. An improvement of the antenna array gain by 1 to 2 dB was achieved for horizontal polarisation in the scanning range from 70° to 90°.

These results are important, especially for small platforms such as drones. In future, the new technology will make it possible to use a light, cost-effective system with just a single antenna instead of an array antenna and still achieve high gain and adjust the direction of view of this antenna electronically.

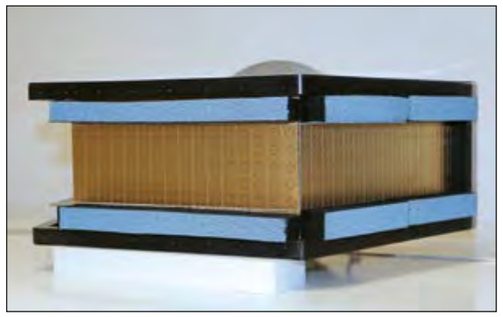

Fig. 1: Reconfigurable metamaterial layer for array antenna

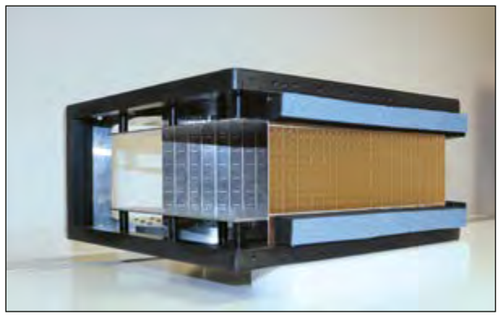

Fig. 2: Conformal array antenna with reconfigurable metamaterial layer

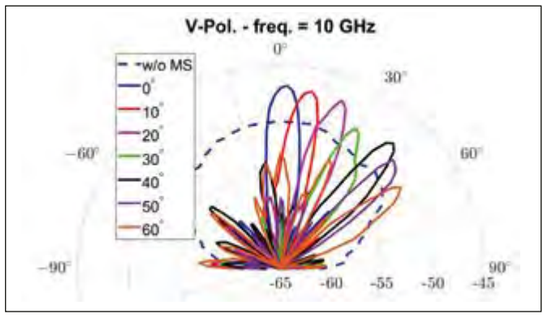

Fig. 3: Radiation patterns at different scanning angles in the azimuth plane with and without reconfigurable metamaterials (vertical polarisation)

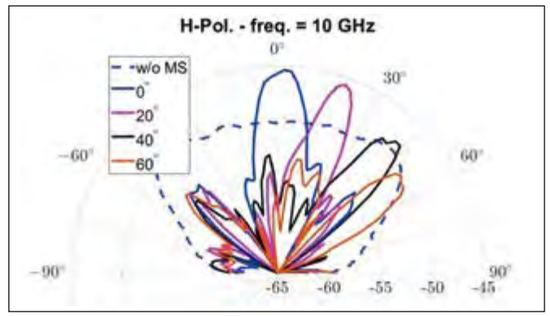

Fig. 4: Radiation patterns at different scanning angles in the azimuth plane with and without reconfigurable metamaterials (horizontal polarisation)

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Automated planning to support dismounted infantry through UGVs

Unmanned vehicles will transport infantry soldiers in the future. The utility of embedded robots in the field can be further enhanced by additional capabilities. This usually requires automated mission planning. A solution for using robots as mobile radio relays to increase range was investigated in the project Accompanying Transport.

The development of all-terrain unmanned vehicles capable of performing transport tasks for infantry (Fig. 1) has progressed to such an extent that the introduction of such systems will be possible in the near future. Supported by sensors, the vehicles will move automatically in suitable terrain and therefore will not require permanent monitoring. This means they can be used for additional tasks besides escorting. Examples include reconnaissance and surveillance as well as the evacuation of wounded or the use of multiple robots as radio relays for the mobile networking of forces – the latter will be considered in more detail here. These types of tasks for robot swarms or teams require automated mission planning, since manual coordination of vehicles in dynamic operational situations is too time consuming. For mobile radio networking, a new planning procedure was developed at Fraunhofer FKIE as part of the Accompanying Transport Project, which was supervised by WTD81 GF340. The procedure continuously adjusts target positions and routes of the mobile relays in such a way that the radio link between infantry squads is maintained for as long as possible. Fig. 2 provides an example of this.

Fig. 1: Mobile robots for material handling

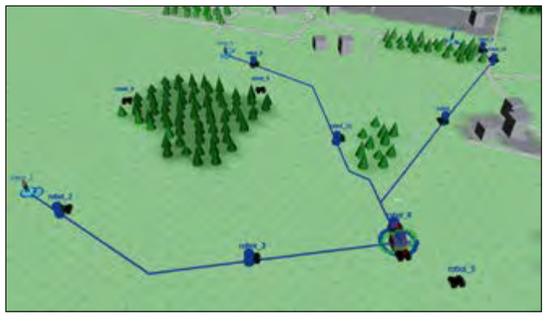

Fig. 2: Scenario in which three squads (cyan) move with transport robots in terrain. They are connected to each other and to the base by relay robots

The algorithm combines methods of combinatorial optimisation for vehicle navigation with those for relay placement in a novel way. Inputs to the algorithm include a digital route network and terrain model, radio prediction models for the deployed equipment, and the known positions of the squads to be networked. This task is unique in that, in addition to optimising relay positions, their rapid accessibility by mobile robots must also be taken into consideration. Since the robots can move not only on paths but also off-trail in drivable terrain, a complete and simultaneous optimisation of relay placements and travel paths is not possible in real time for reasons of complexity. Instead, a two-step approach was chosen which first determines a drivable path network between the target positions and then computes optimised relay positions, which are limited to positions on these paths.

First, the method uses a fast optimisation algorithm to extract from the digital map the minimum possible network of drivable paths that connect all the radio nodes in question. Fig. 3 shows an example of this. To calculate the relay positions, it then uses a prediction model to determine for each node in the reduced network which other nodes are reachable by radio. This gives a network of all possible radio links (Fig. 4), from which a fast combinatorial optimisation procedure is used to determine the relay positions through which all nodes can be connected. Fig. 5 shows the result of such a calculation.

The algorithm was evaluated in a simulation for multi-robot systems. It also provides good solutions for teams of more than ten robots in fractions of a second. In combination with an optimal allocation procedure of relay positions to the robots, relays can therefore be repositioned or redeployed even while the soldiers are moving. On a small scale with two radio participants, the simulation results were confirmed in experiments with real robots.

Although the two-stage procedure cannot guarantee optimal solutions, it quickly finds good and comprehensible plans. Due to its modular design, it can also be easily transferred to other applications. Subsequent work will investigate how the method can be adapted from relay planning to reconnaissance tasks for swarm robots by replacing the radio models with suitable sensor models.

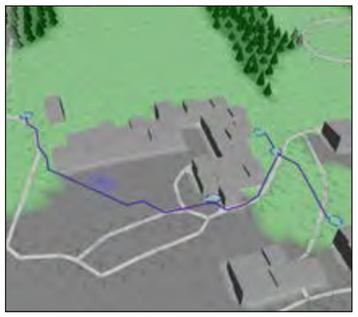

Fig. 3: Five participants connected by the shortest network

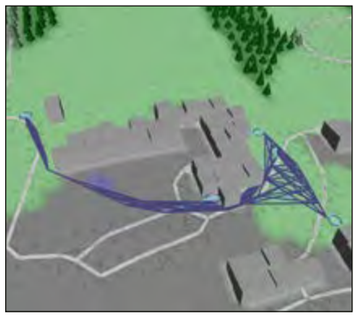

Fig. 4: Possible pairwise radio links between points on the path network based on a propagation model

Fig. 5: Calculated positions of the relay robots

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Efficient high-voltage GaN transistors for radar applications

Operating GaN transistors at a higher voltage than what is possible with commercially available devices allows us to generate superior output power on a smaller chip area. With the help of these components developed at Fraunhofer IAF, more powerful radar transmitters in L, S, C and X band can be built. The form factor of the systems does not have to be changed for this purpose.

In order to detect even small objects with radar at great distances, we require not only a high antenna gain of the receiving and transmitting antennas but also a sufficiently powerful transmitter amplifier. Owing to their superior electrical and thermal properties, GaN transistors are capable of delivering significantly higher output power per chip area than silicon- or gallium-arsenide-based devices. Their full potential can only be exploited, however, if they are operated at a much higher voltage than 50 V or 65 V, which is common in commercially available devices. Fraunhofer IAF is therefore developing high-voltage GaN components for radar applications which are designed for use at a voltage of 100 V.

The use of these new transistors provides a number of advantages at systems level. The high supply voltage means lower DC current consumption for an amplifier of given output power, which allows us to use smaller and lighter power supply units. In addition, DC routing is simplified since the lower absolute current allows us to use cables with a smaller diameter. The increased power per chip also makes it possible to increase the output power of the transmitter while the size of the transmitter remains the same. This means that the detection range of the radar is enhanced. It also has a positive effect on costs, since fewer chips are required to achieve a given transmitter output power. A photograph of a 400 W device for S-band (2 – 4 GHz) applications is shown in Fig. 1.

The high supply voltage also helps the circuit designer to design amplifier matching networks with low losses. The greatly increased load-line resistance, or output resistance, facilitates the design of more compact networks, in particular when using transistors with very high output power. Trimming the size of the networks leads to lower losses, which helps to boost system efficiency.

Increasing the output power per chip area also results in higher dissipation and thus puts additional thermal stress on the devices, which reduces their projected operational lifetime. For this reason, it is necessary to further increase the energy efficiency of the transistors and to optimise thermal properties through a suitable layout and improved process technology. Both of these aspects, efficiency enhancement and thermal optimisation, were successfully demonstrated. By implementing specific process changes, a 40 % reduction in output capacitance was obtained compared to first-generation devices. This achievement directly translates to very high power-added efficiency (PAE) values of 84 % at 2.0 GHz and 66 % at 7.2 GHz. These values represent world records in terms of efficiency of 100 V GaN transistors at these frequencies. The maximum output power density was as high as 15 W/mm.

New transistor layouts also make possible more efficient heat dissipation of the devices due to better utilisation of the heat-spreading properties of the substrate material. Compared to conventional layouts, thermal resistance is reduced by around 20 %. This is equivalent to an increase in lifetime by more than a factor of 10.

A hybrid power amplifier (IMFET) based on two 100 V GaN transistor chips (Fig. 2) delivers an output power in excess of 140 W and a PAE of 46% at a frequency of 7.2 GHz (Fig. 3). The housing offers space for up to four transistor chips of the same size. Appropriate implementation would allow a substantial increase in output power of more than 250 W per amplifier.

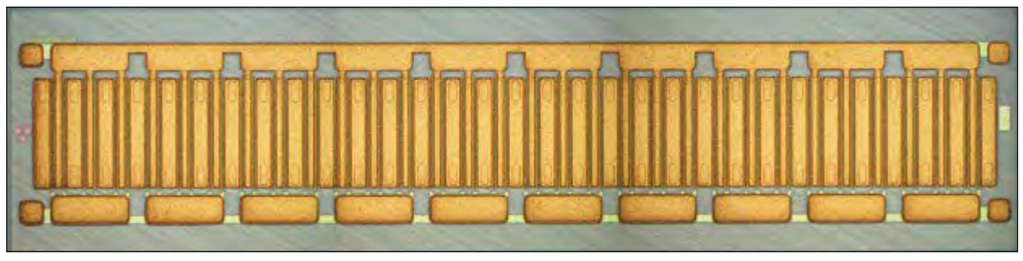

Fig. 1: Micrograph of a 100 V GaN transistor with an output power of more than 400 W at S-band frequencies (2 – 4 GHz)

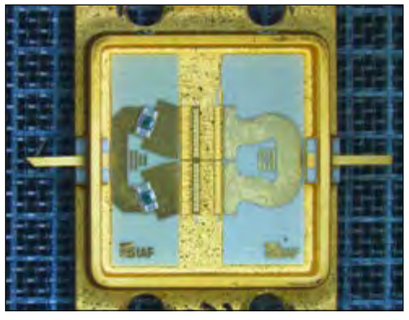

Fig. 2: Micrograph of an in-package-matched power amplifier (IMFET), based on 100-V GaN transistors, delivering more than 140 W at a frequency of 7.2 GHz

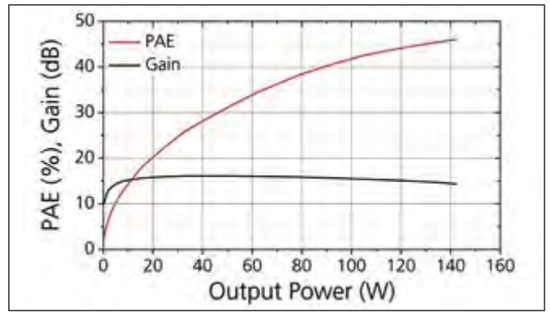

Fig. 3: Measured output power, PAE and gain of an in-package-matched power amplifier (IMFET) based on 100 V GaN transistors at a frequency of 7.2 GHz

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Towards a single-photon camera for active imaging in short-wave infrared

Laser-active imaging systems for use under difficult visual conditions and for non-line-of-sight imaging require cameras capable of detecting individual photons. The spectral range of short-wave infrared is best for this purpose. This necessitates research on InGaAs-based single-photo detectors.

Light detection and ranging (LiDAR) imaging systems for ambient and range sensors are a key component of autonomous navigation systems for land, sea and air vehicles in changing and poor visibility conditions. In recent years, non-line-of-sight (NLOS) has become the focus of military LiDAR applications. What this means is that the indirect field of view is considered in order to explore hidden scenes behind obstacles (Fig. 1).

The physical basis of LiDAR systems is the measurement of the time between transmitted and backscattered pulses. A highly sensitive photodetector is required in order to ensure a sufficiently long range. Single-photon avalanche diodes (SPAD) operated in Geiger mode provide the highest sensitivity.

Compared to the visible spectral range, short-wave infrared (SWIR) at wavelengths between 1 – 2.5 µm offers better penetration of particles in the atmosphere such as smoke, fog, dust, etc. as well as the availability of lasers that are safe for eyes and reduced solar background radiation. The III/V semiconductor material InGaAs is ideal as a detector material in SWIR. High-resolution InGaAs/InP SPAD detector arrays

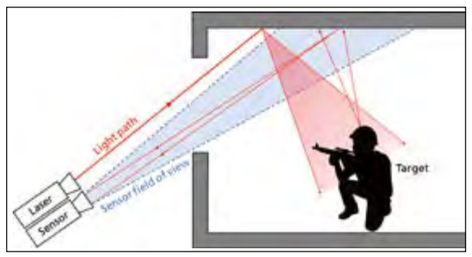

Fig. 1: NLOS imaging (according to F. Christnacher et al., Adv.Opt. Techn. 8 (6), 403–414 (2019))

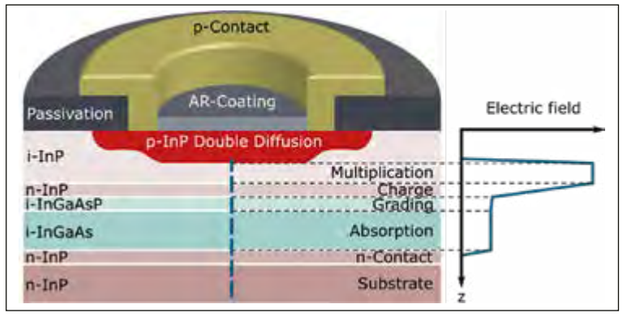

Fig. 2: Not-to-scale cross-section of a single-photon detector with an electric field strength profile

are the core component of these and future LiDAR imaging systems in SWIR.

A key technology for the fabrication of InGaAs/InP SPADs is the diffusion of dopant zinc through a lithographically patterned diffusion mask to produce a spatially confined p-type region. The geometry of the diffusion profile has a decisive influence on the shape of electric field strength in the active zone of the SPAD. For the best possible SPAD properties, a doping profile in the form of a double trough is created by sequential, double diffusion.

Fig. 2 shows a cross-section of a traditional InGaAs/InP SPAD. The double diffusion trough profile is highlighted in red. The main functional layers in the vertical layer structure comprise the intrinsic (i) InGaAs absorber for single-photon absorption and the i-InP multiplier for internal amplification of the photocurrent. The remaining layers, which are considerably thinner, are for electrical contacting, for grading the band edges between InGaAs and InP, and for controlling electric field distribution, which is shown in the right half of Fig. 2. Field strength can be adjusted depending on the choice of layer thicknesses and dopants. For zinc diffusion, a new method of selective epitaxial overgrowth was developed at Fraunhofer IAF. Based on this method, a corresponding double-diffusion profile was realised for the first time (Fig. 3).

Electro-optical measurement data of the InGaAs/InP SPADs fabricated at Fraunhofer IAF show a curve of the dark current and photo current over the applied bias voltage and the resulting gain in linear operating mode, which is customary for avalanche photodiodes (Fig. 4). In the inset, quantum efficiency below the breakdown voltage of the SPAD is shown vs. the wavelength, demonstrating the ideal suitability of detector material in active illumination using a laser with a wavelength of approximately 1550 nm. These initial characterisation data were measured at 240 K, which corresponds to a typical operating temperature for InGaAs/InP SPADs achievable by thermoelectric cooling.

Based on these results, concepts for optimising the device characteristics of SPADs and their implementation in focal plane arrays are now being investigated. These focal plane arrays will form the core of a future SWIR single-photon camera.

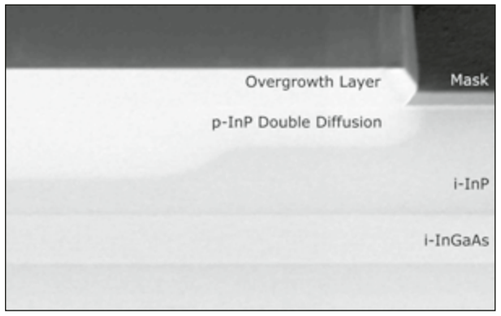

Fig. 3: Scanning electron micrograph of a cross-section of an InGaAs/InP single-photon detector immediately after the second zinc diffusion

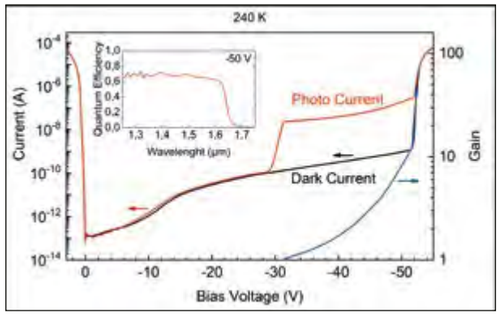

Fig. 4: Diode characteristics and spectral responsivity below breakdown voltage

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Active twist rotors for modern helicopters

The German Aerospace Centre (DLR) is developing components for future helicopter rotors. This new technology will improve the aerodynamics of helicopters with a view to reducing noise and vibration and improving fuel efficiency. One of the fields being investigated is the active twist rotor.

The pitch angle of helicopter rotor blades, which must be continuously adjusted during the flight of a helicopter, is controlled by means of a swashplate and control rods, which make it possible to change the pitch angle of all blades simultaneously (collectively) or sinusoidally once per revolution (cyclically). The precise, locally variable control of each individual blade pitch angle can be achieved using individual blade control. This makes it possible to reduce noise and vibration and improve fuel efficiency. The active twist rotor can contribute to this, but the integration of actuator technology subjected to tensile stress is a challenge.

Active twist rotors are the subject of current research and consist of a passive rotor blade structure combined with piezoelectric actuators that are integrated into the structure of each rotor blade and can change the twist of the entire blade. A new rotor blade design has allowed us to reduce loads and to generate a uniform strain distribution in the actuators. Damage can thus be prevented and the durability of active rotor blades increased. This represents the basis for the specific and efficient use of active twist technology.

The goal is to achieve a deformation of ± 2° twist at the blade tip. In 2017, a blade was designed and manufactured at DLR that takes into special account the demands on actuators. In addition to various structural and material modifications, a new type of actuator layout was also used. The integration of a large number of pressure and strain sensors and their cables poses a major challenge and requires efficient use of available installation space. Various computed tomography images were evaluated to validate manufacturing methods and also specific rotor blade properties.

Whirl tower tests on a rotor blade demonstrated that strength could be preserved and that the actuator concept is robust enough while achieving blade tip twists of ± 2° at the relevant control frequencies 2/rev, 3/rev and 4/rev. A complete blade set with 4 rotor blades and one spare blade has already been manufactured and successfully qualified in individual blade tests. This set of blades is now ready for further system qualification tests and will subsequently demonstrate the improved aerodynamic properties in a wind tunnel.

Fig. 1: Investigation of an active twist rotor blade in a whirl tower

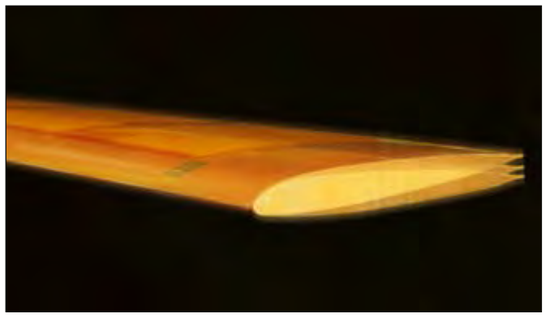

Fig. 2: Blade tip movement of an active twist rotor blade

Fig. 3: New actuators and pressure sensor section

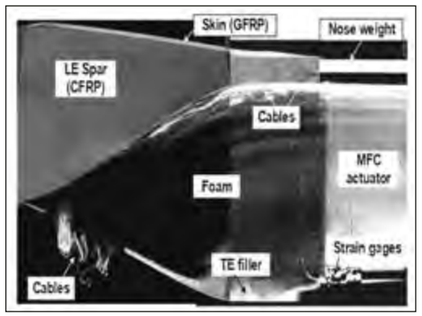

Fig. 4: Enlarged view of CT scan images around blade root regions

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Information fusion of various remote sensing sensors

Despite improved data collection methods, optical and radar remote sensing data is evaluated on a sensor-specific basis in the two-dimensional space. Combined processing of this data in the three-dimensional space may result in a significant national capability gain in the field of Earth observation. The DLR Institute of Optical Sensor Systems and the DLR Microwaves and Radar Institute are conducting research on this information fusion.

We have recently been confronted with a rapidly increasing number of challenges in the global situation that are not only almost impossible to solve but also difficult to analyse. These new challenges involve complex ecological, social and political processes that require a very precise and specific information basis to be able to assess situations correctly.

If a building has been damaged, it is important to know up to which floors it is still intact. The requirement to accurately estimate the physical damage is a challenging task because of the data situation, which includes data that may originate from various sources and sensors. The most well-known data source considered is the electro-optical (EO) sensor, which ensures that image data can be easily evaluated due to its high resolution and intuitive interpretability. In addition, high-quality information in the form of 3D models can be derived from multiple EO images taken from different perspectives. However, significant information gaps may occur since this is a passive imaging system that is dependent on the presence of sunlight. These gaps can be closed be the use of active radar sensors, which provide 24-hour availability and can be operated

Fig. 1: Aircraft-based EO image of Berlin, taken in August 2017, as orthoprojection

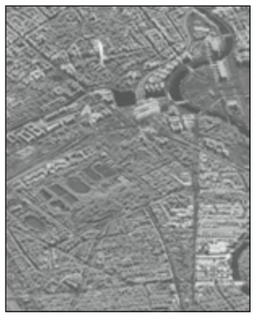

Fig. 2: Satellite-based SAR image over Berlin, taken in August 2017 by the TerraSAR-X satellite

Fig. 3: The fused information of the aircraft-based electro-optical and satellite-based SAR image

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almost independently of weather conditions. Synthetic aperture radar (SAR) imaging systems, in particular, provide distance-independent high-resolution and large scene coverage at the same time.

Despite improved data collection methods, this data is evaluated on a sensor-specific basis. In order to obtain a complete picture of the change, the separately examined information must be combined in a multi-sensor network. In the field of information fusion between EO and SAR data, the different imaging geometries are the challenges to overcome. Conventional EO images are usually projected vertically onto a digital surface model (true-to-scale true orthophoto, Fig. 1), whereas SAR images have an oblique geometry parallel to the flight axis (side-looking radar, Fig. 2). The information management of the very large amounts of data is another challenge. All information must be read, processed and stored within a reasonable period of time. To ensure optimal performance, first the imaging geometry of a high-resolution SAR image is fused with a 3D model and then the EO texture is added (Fig. 3).

Information fusion provides significant added value with regard to the interpretation of the scene. For instance, Fig. 4 shows an SAR signature of a chimney that can hardly be seen due to the SAR-specific imaging effects. The chimney is also barely visible in the EO image due to its relatively small diameter (Fig. 5). After the information from these images has been fused, however, the entire scale of the chimney can be seen very clearly (Fig. 6).

These promising results form a good basis for future development in the field of automated information extraction. This includes, for example, three-dimensional change detection and the mapping of these changes in a fused situation picture.

Fig. 4: SAR signature (TerraSAR-X) of a chimney that can hardly be seen due to SAR-specific imaging effects (Berlin, August 2017)

Fig. 5: Optical image (aircraft-based electro-optical image) of the chimney shown in Fig. 4 (Berlin, August 2017)

Fig. 6: Fused information of Fig. 4 and Fig. 5 results in the clearly visible signature of a chimney

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Automated air-to-air refuelling

Air-to-air refuelling is of great strategic and tactical importance in many military operations. At the same time, it is still one of the most challenging and critical manoeuvres for pilots. To improve the effectiveness of missions involving air-to-air refuelling and increase the safety of the pilots of the receiver aircraft, the air-to-air refuelling process is to be increasingly automated. Automation is also a prerequisite for air-to-air refuelling of future unmanned aircraft.

Air-to-air refuelling is the process in which an aircraft transfers fuel to a second aircraft or helicopter in flight. It is a highly challenging task that is often a key element of military operations. Automation of this manoeuvre would not only be a great help for pilots but is also essential to enable air-to-air refuelling of unmanned aerial systems in the future. As part of the F(AI)^{2}R project (Future Air-to-Air Refuelling), the DLR works on developing various methods for automated air-to-air refuelling of manned and unmanned aircraft, testing them in a simulator and, in some cases, during flight tests and finally evaluating them. Research has so far focused on the "probe-and-drogue" method, during which the refuelling probe of the receiver must connect to a refuelling basket (drogue) on the end of a hose trailing from the tanker.

The spectrum of support options for air-to-air refuelling ranges from pilot assistance systems and semi-automation to the complete automation of the refuelling manoeuvre. A modification of control laws in the receiver can already facilitate aircraft control for the pilot during the coupling procedure and thus reduce the duration and risks of air-to-air refuelling.

For higher levels of automation in air-to-air refuelling missions, relative navigation between receiver and tanker but also between probe and drogue will play a key role. Electro-optical sensors such as infrared cameras and LiDAR systems are considered for this purpose, as they do not require GNSS or an active data link. For fully automated air-to-air refuelling, the receiver needs an additional on-board mission control system that monitors the entire refuelling procedure and triggers the transitions to the required control modes.

The evaluation of automation procedures is based on flight-mechanical simulation models of the participating aircraft (tankers and receivers), the refuelling system and aerodynamic interactions. A model of the Future Military Transport Aircraft (FMTA), a generic military transport aircraft similar to the A400M, is used as the tanker (Fig. 1). Representative models of a combat aircraft, a transport helicopter and a UAV were developed as receivers. A complex model of the refuelling system with all its essential components was developed to be able to realistically represent the interaction of drogue and probe and conduct a refuelling mission in its entirety within the simulation.

Aerodynamic interaction, in particular the effect of the flow field behind the tanker (Fig. 2) on the receiver and the aerodynamic effect of the receiver's bow wave on the drogue, is another important aspect of air-to-air refuelling that is taken into account in the simulation. The overall model can then be used in the DLR flight simulators, such as the Air Vehicle Simulator (AVES) or the Military Aircraft Research Simulator (MARS-FIT), to have pilots conduct tests of the newly developed and implemented automation methods and assistance systems and evaluate them (Fig. 3).

Active control of the refuelling basket (drogue) is also investigated as a new concept. Technologies for this purpose are developed at the DLR and tested as scaled versions using UAVs in flight tests. Wind tunnel tests were conducted in the low-speed wind tunnel in Braunschweig (operated by DNW, German-Dutch Wind Tunnels) to determine the coefficients and derivatives of an aerodynamic model, which is required for the development of drogue control laws (Fig. 4). A controlled drogue can be used to mitigate disturbances caused by turbulences and to stabilise the drogue in its position, which significantly reduces the load on the receiver during the coupling task.

Fig. 1: Air-to-air refuelling simulation involving two Future Military Transport Aircraft (FMTA)

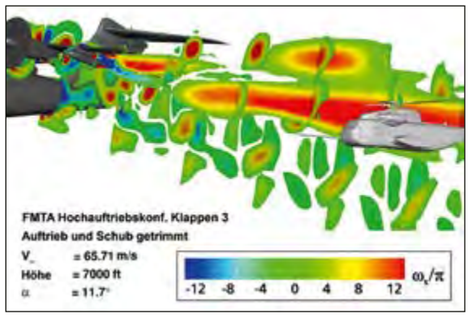

Fig. 2: Refuelling position of a transport helicopter in the vortex field behind the FMTA

Fig. 3: Test of an assistance system for air-to-air refuelling of combat aircraft using the Microsoft HoloLens

Fig. 4: Wind tunnel measurements on the scaled, controllable refuelling drogue

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Radar signature identification and evaluation of military aircraft

During the development of military aircraft, it is particularly important to consider their radar signatures in the early design phase to increase the probability of survival of future (unmanned) jet aircraft. Radar signatures can be reduced for certain aspect angle ranges both by the selected construction material itself and by its arrangement.

A numerical simulation of the radar signature serves as an aid for the development engineers of state-of-the-art military aircraft to find areas that are critical for detection while considering different flight configurations (Fig. 1). Knowledge of radar signatures is also necessary for the early detection, tracking and identification of airborne threats and for engaging them. With regard to hypersonic missiles, it is also necessary to take into account plasma formation along the front edges (Fig. 2).

Radar signatures can be obtained by high-precision measurements of (possibly scaled) models in an anechoic chamber (Fig. 3) or through computer-based simulations. Simulations use exact procedures such as the method of moments or the fast multipole method or even significantly faster and resource-saving asymptotic procedures such as physical optics or ray tracing methods, taking into account edge scattering and multiple reflections.

In addition, a distinction is made between source-based methods, which determine the current density distribution across the object surface as the source of the backscattered radiation (Fig. 4), and field-based methods, which determine the electric fields between neighbouring volume elements.

The commercially available FEKO software by the Altair Engineering company, which also allows the different methods to be used in combination, was used to calculate the signatures shown here.

The radar cross section (RCS) is a measure of the energy scattered towards the receiver. Monostatic radar systems with transmitters and receivers at the same location are the most frequently used sensor for the detection and reconnaissance of military aircraft. The RCS value can be specified for each pair of azimuth and elevation angles under which the aircraft may be observed in the sky.

Bistatic or multistatic radar systems with transmitters and receivers that are located far away from each other are becoming increasingly more important, despite their higher complexity and costs, because they may serve as an effective tool to detect stealth aircraft. Bistatic RCS is characterised by four degrees of freedom (angular positions of the receiver and the transmitter). In Fig. 5, the position of the transmitter is fixed.

Altogether, research on radar signatures opens up an enormous potential to keep the service life of military aircraft at a high level.

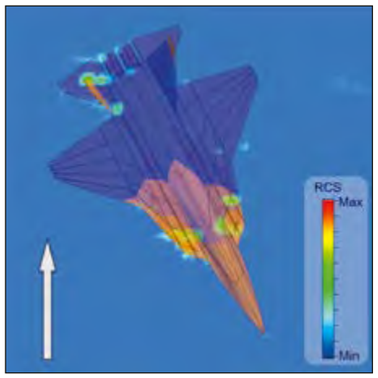

Fig. 1: Scattering centre localisation by Inverse Synthetic Aperture Radar (ISAR), arrow indicates viewing direction

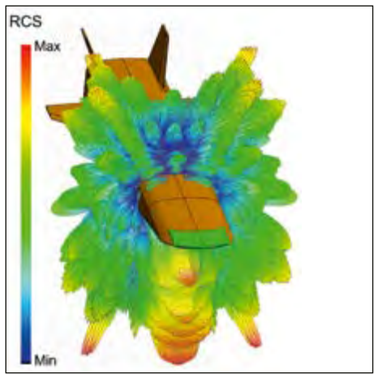

Fig. 2: Monostatic RCS distribution of a hypersonic missile, taking into account plasma formation

Fig. 3: Measuring facility for the experimental determination of the bistatic radar cross section (RCS), measuring frequency range: 75 to 110 GHz. The device to be measured (scaled aircraft) is highlighted by a red circle

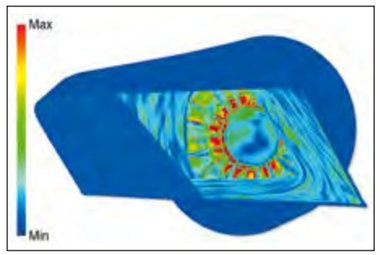

Fig. 4: Current density distribution of a jet engine with a curved inlet channel as the source of backscattered radar signals

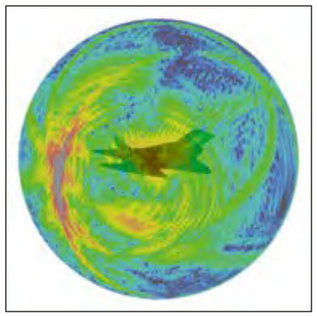

Fig. 5: Bistatic radar signature, position of transmitter directly in front of the aircraft, 4° below the nose

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Examination of unsteady aerodynamics of a remote carrier during the wing sweep process

A numerical examination of the aerodynamics and flight mechanics of a remote carrier (RC) with sweep wings was performed in this study. For this purpose, a simulation environment was created that can also be used to investigate generic airdrop manoeuvres of such RCs, e. g. from an A400M. The study showed that the wing sweep process has a major influence on the trajectory of the RC during the airdrop.

Within the framework of the Future Combat Air System (FCAS), remote carriers are to operate together with combat aircraft and have mission times as long as possible. Long mission times can be achieved by airdropping the RC from a carrier aircraft (Fig. 1) close to the target area. For this scenario, RCs with sweep wings are advantageous because they have smaller loading dimensions and lower aerodynamic drag during transport. During the airdrop, however, it must be ensured that the wing sweep process does not lead to critical flight conditions with regard to aerodynamics and flight mechanics.

It must also be taken into account that mass moments of inertia and the centre of gravity vary during the wing sweep process. In the study presented here, a simulation environment was created with the DLR's inhouse tools to numerically examine the aerodynamic behaviour of RCs with sweep wings. In addition to considering the wing sweep process when determining the aerodynamic coefficients, the simulation environment also allows the integration of a flight mechanical tool. This makes it possible to simulate the free fall of an RC during the airdrop and the transition to the flight phase.

Fig. 1: Example of a remote carrier being dropped from a military transport aircraft. This shows the launch of a DT25 from the A400M, which was carried out as part of the UAV Launcher project initiated by Airbus (Source: Airbus)

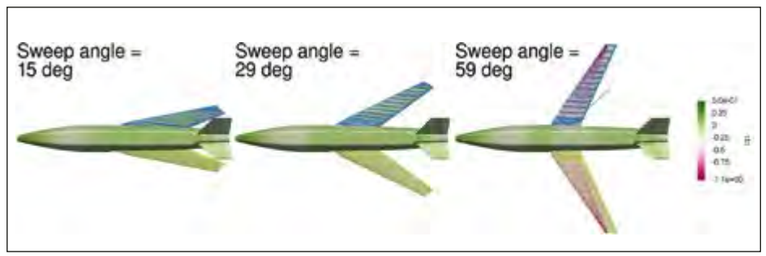

Fig. 2: Development of the flow at the RC as a function of the wing sweep angle for a Mach number of 0.85 and a fixed angle of attack of 1°. This shows the surface pressure distribution and the wall shear stress lines

This simulation environment was successfully applied for the first time with the generic GRC2B-2 RC. This design of a transonic RC with sweep wings comes from the DLR's FK2020+ missile project. The RC is characterised by wings that are positioned one below the other. In flight configuration, these have a positive sweep of 31° or a sweep angle of $\varphi = 59°$.

Fig. 2 shows how the flow at the RC and in particular at the wings during transonic airspeed (Mach = 0.85) develops in relation to φ. Based on the shown surface pressure distributions and the wall shear stress lines, it can be seen that, for small φ (< 30°), the wings contribute only slightly to the overall lift, as is to be expected. The pressure level at the top surface of the wing is relatively high and falls within inflow range. Any further increase of φ leads to a significantly lower pressure level at the top surface. As a result, the lift of the wings and the associated pitching moment increase considerably. An analysis of the wall shear stress lines for the final state at $\varphi = 59°$ shows that the characteristic wing configuration causes the flow in the area of the wing root to develop asymmetrically with respect to port and starboard. This also has an effect on the roll and yaw attitudes of the RC.

The relation between aerodynamics and the wing sweep angle also affects the flight mechanical behaviour. The trajectory of the RC in free fall after being airdropped clearly depends on whether the RC has sweep wings or whether the wings are already in their end position (flight configuration) from the start of the airdrop. This was demonstrated by means of coupled simulations. Fig. 3 shows the position and attitude of the RC at 0.5 seconds after the airdrop determined in the simulations. At this point, the wings of the RC with sweep wings have just reached their end position, which means that both RCs are in the same geometric state but have different aerodynamic backgrounds. The effects of the sweep process are obvious. As a result of its initially lower drag and the lower lift generation of its wings, the RC with sweep wings has less spatial offset to the initial state at t = 0 s and its roll attitude is also clearly affected by the wing sweep process.

Data on the aerodynamic and flight mechanical behaviour of an RC is of major importance during the design phase of an RC or airdrop device and for the definition of airdrop scenarios. This also applies to the consideration of possible recovery manoeuvres. Using the newly created simulation environment, this data can now be generated numerically.

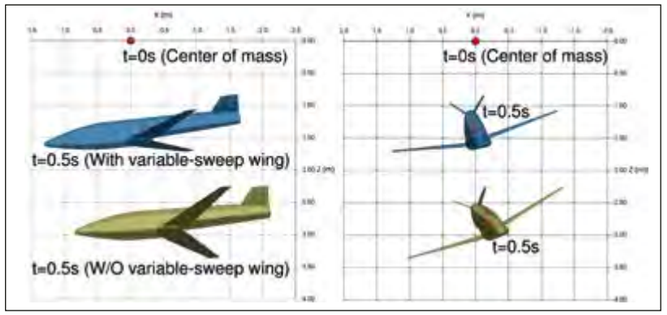

Fig. 3: Influence of the wing sweep process on the position and attitude of the RC in free fall 0.5 s after airdrop (initial conditions: Mach number = 0.85, angle of attack = 1°)

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Verification of cameras for use under the Open Skies Treaty

Even in challenging times, arms control instruments still need attention. In 2022, new digital camera systems were certified for the Open Skies Treaty. Sensors in the thermal infrared spectral range are to follow in the coming years. The basic scientific, technical and procedural principles for this purpose must be developed.

Even in times of crisis, it is necessary to keep arms control instruments intact. This includes the Treaty on Open Skies concluded in 1992. In 2022, Romania and Germany took important steps to enhance the relevance of this treaty by successfully certifying new camera systems. In addition to new cameras, the Federal Republic of Germany also certified a new platform, the Airbus A319 OH, and thus has the most modern aircraft for this task at its disposal.

The Open Skies Treaty allows its signatories to fly over foreign territories and take aerial photos within mutually agreed parameters. In order to assure all participating states that these parameters will be complied with, a high degree of transparency is key. For this reason, traceability and verifiability were emphasised as early as in the conception phase of the platform and the camera systems.

The verification of sensors and their data products is a central task of the certification process. Sensor settings such as focal length, focal distance and lens aperture must be unalterable so that performance parameters cannot be changed during later missions. Inspectors of the contracting states must be able to easily and reliably compare the characteristics of the camera systems with the documentation provided previously.

In October and November 2022, specialists from 23 contracting states gathered near the Cologne / Bonn Airport to verify the characteristics and workflows of the new camera systems with regard to their compliance with the Treaty. They were able to thoroughly examine both the Romanian Antonov An-30B and the German Airbus A-319 OH and check their respective sensors both on the ground and during in-flight operation.

To answer specific question with regard to sensors, data processing and the characteristics of the data products, both experts from the sensor and platform manufacturers and scientists of the German Aerospace Centre (DLR) were present. The support provided by scientists of the DLR Institute of Optical Sensor Systems was made possible by a contract with the Bundeswehr Verification Centre.

The Open Skies Treaty also permits the use of cameras for the thermal infrared spectral range, which have already been installed in the A319 OH aircraft. Procedures for the certification of these sensors must be developed and coordinated with experts from the contracting states so they can also be certified for use under the Treaty at a later stage. The Open Skies Consultative Commission (OSCC) will then be able to make decisions on how such certifications are to be conducted.

Scientific support is essential for the development of verification methods for thermal infrared cameras that are comprehensible and acceptable for all contracting states. Due to the specific characteristics of infrared radiation, conventional instruments for the verification of digital aerial cameras cannot simply be used without adaptations. For instance, new calibration targets need to be developed. The Bundeswehr and the DLR will continue to cooperate on this matter in the coming years.

Fig. 1: The Romanian and the German aircraft during ground inspection

Fig. 2: Inspectors on board the Airbus A319 OH during an inspection flight (Source: Dagmar Benner)

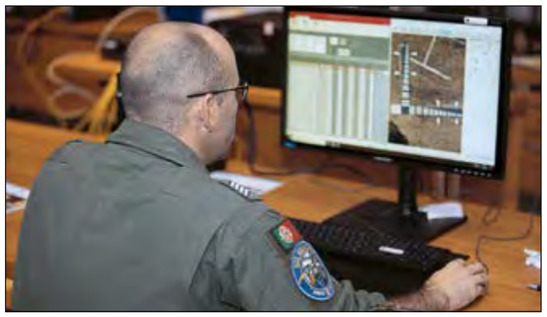

Fig. 3: An inspector evaluating the images of the calibration target (Source: David Porschen)

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The DLR's Johannes Kepler Observatory: A unique ground station for the laser-optical evaluation of the space situation

In addition to the detection of orbital objects, laser-optical methods make it possible to make further important contributions to reconnaissance such as the analysis of object dynamics, material composition and object structure. Based on its design, the German Aerospace Centre's Johannes Kepler Observatory is the most powerful observatory in the European Union and can make important contributions to the evaluation of the space situation.

The safe operation of satellites in Earth orbit is threatened by a steadily increasing object population. The majority of orbital objects consists of inactive satellites, upper stages or fragments generated during regular operations and as a result of collisions and explosions. These objects will remain in Earth orbit for many decades before natural orbital decay leads to re-entry. Especially small parts with dimensions ranging from a few centimetres to a few decimetres are mission-critical and pose a particular threat to satellites due to their large numbers. The orbits of these mission-critical objects are known only to a small extent and with insufficient accuracy.

High-precision orbit determination with accuracies in the meter or sub-meter range is feasible by using time-of-flight laser techniques (Satellite Laser Ranging). Such precise orbit determination is a prerequisite for reliable approach and collision warnings and for planning efficient collision avoidance manoeuvres. Detecting these diffusely scattering small debris objects requires a pulsed laser transmitter with correspondingly high transmission power or high-pulse energy. Another prerequisite is the availability of a receiving telescope with a large aperture, typically more than one metre in diameter, to detect the relevant object sizes with dimensions in the decimetre range.

In addition to (inactive) space debris, the number of active satellites has also increased significantly, in particular due to the operation of satellites in mega constellations such as the Starlink satellite network. A general object reconnaissance or status analysis of active satellites, accordingly, does not only require precise orbit monitoring but also the analysis of the structure and dynamics of satellites. These tasks can be addressed by laser-optical or passive optical methods in the visible or infrared spectral range and are a central topic of research at the DLR's Johannes Kepler Observatory. The research observatory for satellites and space debris of the German Aerospace Centre (DLR) is named after Johannes Kepler, who is considered the co-founder of modern astronomy.

The main instrument of the Johannes Kepler Observatory is a reflecting telescope with a primary mirror diameter of 1.75 metres with four Nasmyth ports and a pre-configured Coudé path. In the future, the Coudé path will provide the option of coupling a laser into the telescope and using it as a transmitter. Its agile mounting allows the tracking of objects in low Earth orbit.

The observatory is located at the Innovation Campus in Empfingen, an access-controlled site with low light pollution in the Northern Black Forest region at an altitude of 520 metres, around 60 kilometres southwest of Stuttgart. Its building height is 15 metres and it has a rotatable slit dome with a diameter of 7.5 metres. High-resolution cameras and a grating spectrometer are provided for analysing the object dynamics, material composition and structure of orbital objects. The mount allows tracking speeds of up to 10 °/s. This allows object tracking in low Earth orbit. Initial test campaigns demonstrated the highly accurate optical tracking of small objects of CubeSat sizes.

In the future, bistatic campaigns with a deployable laser container and the Kepler Observatory are planned, in which the laser container serves as transmitter and the Kepler Observatory as receiver.

Fig. 1: Current representation of catalogued objects in low Earth orbit (Source: NASA Orbital Debris Program Office)

Fig. 2: Laser-optical ground stations at the Empfingen site: Deployable laser container in the foreground and Johannes Kepler Observatory in the background

Fig. 3: Reflecting telescope and mount inside the dome of the Johannes Kepler Observatory

Fig. 4: Telescope mount with receiving telescope (left) and transmitting telescope (right) on the lifting platform of the containerised ground station (STAR-C: Surveillance, Tracking and Ranging Container)

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OTTER: Maritime situational awareness

The more our dependence on space-based capabilities increases, the more important it becomes to protect this critical infrastructure and to be able to rapidly expand and replace it. In this context, the Responsive Space Cluster Competence Centre of the German Aerospace Centre is building a technology base and conducting demonstrations. The first microsatellite mission – OTTER – will contribute to maritime situational awareness.

In close cooperation with industry, users and research institutes, the Responsive Space Cluster Competence Centre (RSC³) of the German Aerospace Centre, which is funded by the Federal Ministry of Defence, is conducting a microsatellite project called OTTER (Optical Traffic Tracking for Responsive Space). The challenge is to establish an initial capability for the RSC³ to conduct research on responsive space capability gaps. The mission from kick-off to flight readiness of the satellite is scheduled to be six months. It will provide a baseline for identifying requirements in all phases of the satellite development process, so that necessary capabilities can be made available more quickly in the event of a military emergency. In addition, it will foster knowledge for establishing suitable research infrastructure at RSC³.

The operational objective of the project is to detect cooperative targets at sea and visually confirm their position by means of an Automatic Identification System (AIS) receiver and visual camera after the satellite has been successfully deployed in space (Fig. 1 and 2). Mapping AIS signals to visual imagery of an area of interest will enable detection of uncooperative targets (Fig. 3). The OTTER project involves a fusion of multi-sensor data from space with air-, land- and sea-based (surface and underwater) data to provide added security value in terms of interoperability and resilience. The RSC³ is currently engaged in national and international exchanges with the DLR Institute for the Protection of Maritime Infrastructure, the German Navy Headquarters (Flotilla 1), and industry on the issue of AI-based data exploitation. In the context of NATO, the RSC³ will cooperate with the Centre of Excellence for Operations in Confined and Shallow Waters and the Centre for Maritime Research and Experimentation.

In this way, the mission is fulfilling a current research requirement, namely the expansion of the maritime situation picture from orbit for the wide detection of conspicuous vessel behaviour. Illegal interference with infrastructure at sea, such as the sabotage of the Nord Stream gas pipelines in the Baltic Sea, can thus be clarified, as can oil spills, illegal fishing and smuggling. The following insights have already been gained from the OTTER project. An ECSS approach (European Cooperation for Space Standardization) to mission planning requires too much documentation and too much time to quickly meet a need. New lean management and automated documentation processes must be used in future. The procurement under EU procurement law in November 2021 took several months.

It is thus necessary to stockpile modular, open and ready-to-use satellite systems of different weight classes. These must be flexible for payloads requested at short notice. Ad-hoc rocket launches are necessary for the responsive delivery of payloads. This is where microlaunchers, sea-based and air-based launch services will play a role in the future. With OTTER, the RSC³ was able to win a free ride on ISAR Aerospace's maiden flight in a payload competition organised by the German Aerospace Centre (Fig. 4). This will offer a separation into a 250 km to 350 km elliptical orbit, which will be circularised at an altitude of 400 km using electric propulsion to provide a lifespan of about 4 years. With a launch planned for mid-2023 and the satellite ready to fly by the end of 2022, the system can be tested.

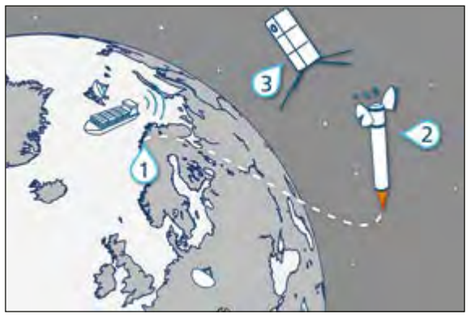

Fig. 1: Concept of operations for OTTER :
1) Launch of ISAR Aerospace Spectrum Rocket from Andøya, Norway
2) Separation in low, elliptical orbit 250 km – 350 km
3) Recording of AIS signals and optical images from ships

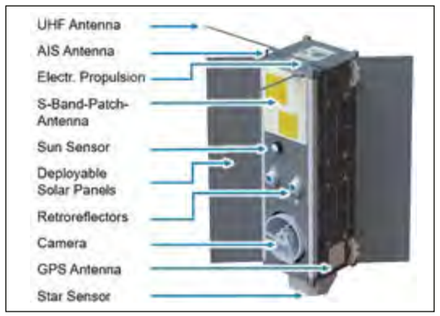

Fig. 2: OTTER satellite

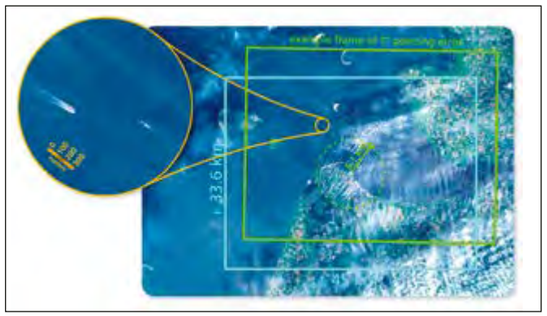

Fig. 3: Image of Cuxhaven taken by Sentinel 2A (Level-1C, true colour image, 10 m ground sampling distance); rectangles show OTTER's image size at an orbit altitude of 350 km; example frame of 1° pointing error. A magnifying glass increases the size of two ships with a length of approx. 100 m and 200 m

Fig. 4: Winners of the payload competition for the maiden flight of ISAR Aerospace's Spectrum rocket: the Responsive Space Cluster Competence Centre in Trauen, Germany

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Signature measurements of ground-based rocket engine tests with a small infrared satellite

Unlike ballistic missiles, hypersonic missiles are difficult to detect in good time by ground- and sea-based reconnaissance. Space-based reconnaissance enables detection with greater advance warning times. The first step towards detection is the measurement of signatures of missile engines. This goal is pursued by the Responsive Space Cluster Competence Centre (RSC³) in the HERMELIN project.

Infrared detectors, which react to the thermal radiation of rocket engines and their exhaust jets, are the most important sensor technology for the space-based reconnaissance of rocket launches and their trajectories with satellites. Satellite-based IR sensor technology is also already being successfully used for monitoring vegetation and forest fires. Satellites can be used for the first demonstration of rocket detection from space, provided their ground sampling distance is finer than that commonly used for vegetation observation. Since these higher-resolution satellites have so far only been in orbit individually as technology demonstrators, a rocket flight or test must be precisely timed with the overflight of a corresponding satellite. Not only test flights of rockets, such as those of the MORABA mobile rocket base, but also ground-based burn tests can be used for signature measurements. The latter regularly take place at the engine test site in Trauen for the development of hybrid rocket engines.

The RSC³ has carried out a pilot test as part of the HERMELIN project in order to regularly accompany these tests in future with appropriate sensor technology and thus to record the signature of the engines. A burn test of the newly developed VISERION hybrid rocket engine was synchronised with the overflight of a small satellite for forest fire remote sensing. In order to obtain additional data for calibration, the experiment was recorded on the ground with an identical model of the satellite's IR camera (Fig. 1). Due to the much shorter distance, these ground-based images offer a higher level of detail and a negligible influence of the atmosphere for the modelling of missile signatures. At the same time, satellite and ground-based images can be directly compared.

A 20-kg satellite was chosen for the spaceborne survey. Due to its low cost, this class of satellites is better suited for setting up a constellation, which is essential for continuous and seamless Earth remote sensing.

The challenge of observing rocket engine tests with satellites can be summarised in three points:

- The engine tests represent independent experiments that are carried out for the development of the engine.
- Satellite overflights determine a time window of only a few minutes for the test. Furthermore, in most cases only one time window per day is available and not every pass offers a good angle of view.
- Weather represents an external influence, since measurement from space requires cloudless skies.

Strong time constraints thus arise for the team carrying out the engine test. However, no additional changes must be made and the potential for synergy is high.

In the HERMELIN project, the RSC³ coordinated the teams involved in order to schedule a test of the VISERION engine during a period with the best possible passes of the satellite. The IR signature of the engine was successfully measured from the ground on 29 September 2022 (Fig. 2 and 3). Unfortunately, no signal could be picked up from space due to cloud cover during the satellite pass.

Further efforts will be undertaken to observe the upcoming engine tests in 2023. Predictions of a favourable time window and experiment schedules must, however, be further optimised. The RSC³ is already preparing the Trauen test site to make an important contribution to upcoming missile early warning satellites.

Fig. 1: View of the test stand with cameras for the visual (left) and infrared spectrum (right) in the foreground

Fig. 2: Engine exhaust jet in the visual spectrum

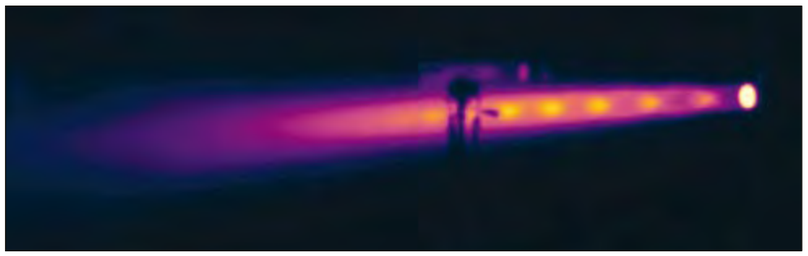

Fig. 3: Engine exhaust jet in the infrared spectrum; taken on the ground with the same camera used by the satellite

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Artificial neural networks for predicting the behaviour of explosive reactive armour

Various traditional approaches such tests or numerical simulations can be used to design effective explosive reactive armour (ERA) to counter a specific threat. The use of artificial neural networks (ANN) was tested at the German-French Research Institute of Saint-Louis (ISL) in order to predict the dynamic response of different ERA configurations.

Explosive reactive armour has been developed since the 1960s and is still of great interest as a protection system against kinetic energy penetrators and shaped-charge warheads. Especially with the evolution of new threats, ERA solutions must be taken into account in the design of solutions for the protection of mobile platforms. The performance of ERA against a specific threat is determined by several parameters such as dynamic material properties, geometry, the type of explosive, the hit position, the impact angle, etc.

Depending on the threat and the application, a number of different designs of ERA must be considered in order to find the best solution, i. e. the solution with the lowest mass for the various conceivable threat scenarios. An evaluation of the best solution becomes difficult and time consuming especially when ERA must be effective against a variety of threats.

Traditional approaches to designing effective ERA include experiments, analytical modelling, and numerical simulation with finite element codes. These approaches, however, lack precision because of simplifications and imprecise material models or are time and cost intensive. The best solution is often found by a trial and error approach.

Artificial neural networks (ANN) are an artificial intelligence (AI) technique that is currently being successfully applied in many engineering domains, especially where large data sets must be evaluated or complex systems with large parameter spaces must be analysed. This is the case with ERA-threat interactions.

Studies at ISL have shown that artificial neural networks can predict the response of ERAs with different configurations, i. e. plate materials, thicknesses, and initiation points. Training data was based on precisely calibrated numerical models. The ANN was able to predict the velocity and deformation of ERA plates for different configurations with a high degree of precision and in very short times depending on the quality of the data used. The results were validated in experiments with x-ray measurements.

While a numerical simulation with finite elements can take several minutes to hours, an ANN can provide the result for a certain configuration within a fraction of a second. As a result, a number of different configurations can be tested in order to find an optimal solution.

In a next step, it will be tested whether ANN are also able to predict the effectiveness of different ERA configurations with respect to their mass efficiency in order to find the optimal configuration. In addition, ANN could be used for vulnerability analyses in tactical tools, where a number of different scenarios must be evaluated in a short time.

This work was presented at the International Symposium on Ballistics in Reno, Nevada, in 2022 and was awarded the Louis and Edith Zernow Award for the best advancement in fundamental ballistics.

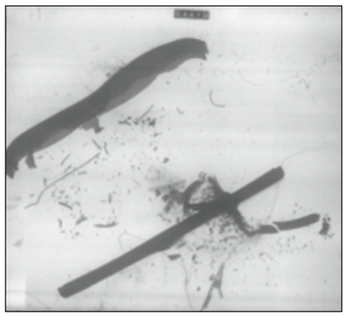

Fig. 1: Experimental result of an ERA against an APFSDS projectile, single exposed flash X-ray image

Fig. 2: Numerical simulation of an ERA against an APFSDS projectile

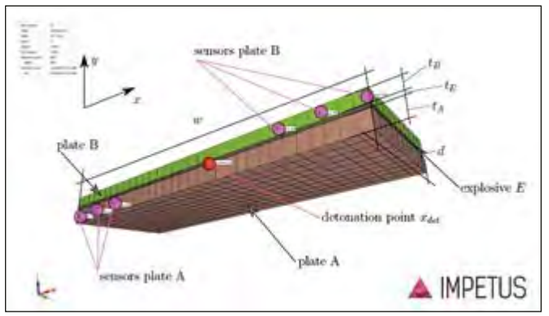

Fig. 3: Numerical model for training an artificial neural network

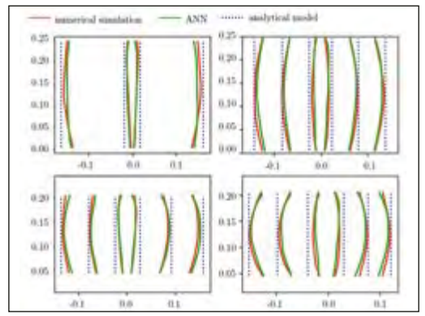

Fig. 4: Comparison of analytical, numerical and ANN predicted plate deformations and velocities

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SiC-based power semiconductor devices for defence applications

The French-German Research Institute of Saint-Louis (ISL) is consolidating and further developing a unique high-power semiconductor device technology based on the semiconductor material silicon carbide (SiC). It is offering widely renowned services in device characterisation with its automated wafer-level test platform. In addition, it is developing compact inductive pulsed-power generators and repetitive SiC-MOSFET (metaloxide-semiconductor field-effect transistor) Marx generators.

Electrically-driven weapon and protection systems require specific pulsed power supplies that are designed to be as compact and efficient as possible. Such systems are currently not commercially available. Extensive research has been carried out at ISL on power electronic components, in particular power semiconductor devices, conventional semiconducting switches based on silicon (Si), and novel semiconducting materials such as silicon carbide (SiC).

Owing to its outstanding physical properties, SiC by far outperforms Si, which is the standard semiconductor material, and allows the fabrication of devices with a higher blocking capability, a tenfold to hundredfold higher power density, and superior switching speed. Bipolar SiC devices are considered key elements of future electrically powered weapon and protection systems. In cooperation with Laboratoire Ampère in Lyon, ISL was the first to succeed in demonstrating light triggering for a SiC thyristor using light emitting diodes. ISL developed an entire fabrication process for innovative and highly efficient 10-kV-class thyristors and consolidated the device technology to a complete 100-mm SiC wafer process (Fig. 1). As part of a project funded by France, ISL focused on electrically triggered amplifying gate thyristors (Fig. 2) and demonstrated a conceptual design inherent to conventional large-area Si phase control and light triggered thyristors. As a next step, the results will be transferred to industrial partners and made available for defence applications in the framework of small-batch manufacturing.

ISL continues to offer widely renowned services in device characterisation with its automated 20-kV wafer-level test platform (Fig. 3). The system enables distinct device inspection from single die to full wafer mapping at elevated temperatures up to 700 K and thus provides relevant information on operation and reliability issues such as breakdown strength and power dissipation.

Rapid developments in semiconductor-based high voltage switching solutions have opened up the possibility of replacing traditional gas discharge-based high-voltage generators (Marx) by semiconductor switch-based models and fulfilling the strong demand for such pulsed power sources for dedicated short-pulse defence applications. The potential advantages are reliability, system readiness on-demand, a higher pulse repetition rate, excellent pulse-to-pulse reproducibility, precise synchronisation, and ease of scalability. On behalf of the Bundeswehr Research Institute for Protective Technologies and CBRN Protection (WIS), ISL is developing switching arrays based on commercially available SiC-MOSFET devices, which are able to meet the requirements for closing switches inside a semiconductor Marx generator. The target is a switching voltage of at least 15 kV at a load current of several kA at a rise time faster than 20 ns. With the help of a dedicated test board (Fig. 4), the necessary technical solutions for a 100-kV class generator were developed: an inductive, galvanic isolation of the SiC MOSFETs connected in series, protection circuits against transient surges, voltage balancing between the SiC MOSFETs, and a dedicated control for a synchronous, active turn-on and turn-off of all SiC MOSFETs.

Fig. 1: 100-mm epi-wafer comprising SiC thyristor devices with varying dimensions

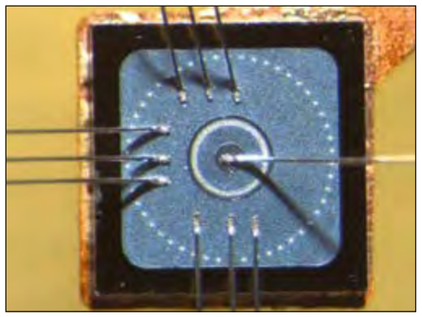

Fig. 2: Micrograph of an experimental, 3.2 x 3.2 mm^2 SiC amplifying gate thyristor in electrical test configuration (wire bonded and rear solder attached). Source: S. Scharnholz et al., https://doi.org/10.4028/p-ztr5d7

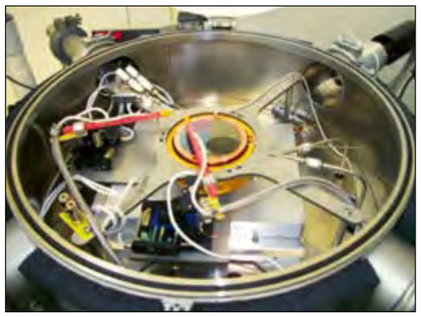

Fig. 3: Interior of ISL's automated 20 kV vacuum wafer probe station

Fig. 4: Test board for studying SiC-MOSFET switching arrays, here equipped with 40 SiC MOSFETs in a (10 x 4)-array

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Defence inflation: The impact of rising prices on the procurement of weapon systems

In consequence of the developments in 2022, the Defence Acquisition & Supply Management (DASM) research group has analysed the effects of increased prices. Inflation in the defence sector has been higher than the general inflation rate, which also has serious effects on purchasing power with regard to the special fund ("Sondervermögen"). Overall, this represents a "cost dilemma" which requires strategic cost management in the future.

The defence sector – like almost all other government and economic sectors – is based on the division of labour. The Bundeswehr commissions companies. In terms of materiel, the operational capability and performance of the Bundeswehr therefore depend on the efficiency of the supply chain.

It is of crucial importance that the customer has strategic cost management expertise to assess the cost structures of suppliers properly. This is the only way to evaluate an offer or to assess cost deviations during the long service life of products. Against the background of the €100 billion special fund and the announcement by the Federal Government to both comply with the two per cent target of NATO and to get one of the best equipped armies in Europe, strategic cost management will be one key to success.

The Federal Statistical Office (Press Releases Nos. 397 and 458) has reported a general inflation rate of 10.4 per cent, and an increase in producer prices of 45.8 per cent. These developments must be taken into account in strategic cost management. Suppliers can no longer cope with these price increases on their own, as their effects can endanger their existence. As such, price escalation could acutely jeopardise security of supply of the Bundeswehr. At the same time, the inflation rate is causing the special fund to melt away. Depending on the inflation rate, there could be a serious loss of purchasing power. Permanent inflation of five per cent means that the real purchasing power of the investment fund will decrease by around a quarter in five years (scenarios in Fig. 1). This creates a strategic cost dilemma in the Bundeswehr supply chain.

The strategic cost dilemma of the Bundeswehr supply chain stems from opposing tendencies of the statutory, static special fund ("budget consistency") and the cost increases in producer prices ("supply cost increase") and can be described using three dimensions:

Dimension 1 describes the declining purchasing power of the fixed fund due to inflation (declining curve in Fig. 2). Dimension 2 describes the simultaneously rising producer prices of the defence industry (rising curve in Fig. 2). This is intensified by the integration of the defence industry into civilian supply chains, e. g. in the semiconductor industry, which results in additional shortages caused by other (civilian and military) customers. There is therefore a risk that the special fund's armaments promise will fall short of its expectations. This will become even more relevant the further in the future the funds are actually spent.

Studies on price increases for defence goods already show high values at ten per cent for the period from the 1950s to the 1970s; if this is extended from the 1950s to the early 2000s, it even rises to 11 per cent. There are many reasons for this, which is why studies distinguish between defence inflation (DI) and (intergenerational) cost escalation (ICE): DI stands for the money that national defence ministries have to pay for all types of goods, including buildings, land, personnel expenses, capital goods, and so on. ICE, on the other hand, describes the price or cost increase effects that result from improved capabilities of new technology generations. The main difference is that with ICE the rising costs are offset by improvements in performance, while DI does not include any positive performance effects.

In general, more attention needs to be paid to the inflation issue again. Precisely because the Bundeswehr is being re-equipped in many areas in view of the current changes in the security situation, precise knowledge of cost and price developments is an important basis for planning. The DASM research group will continue to contribute to this in 2023 with its research.

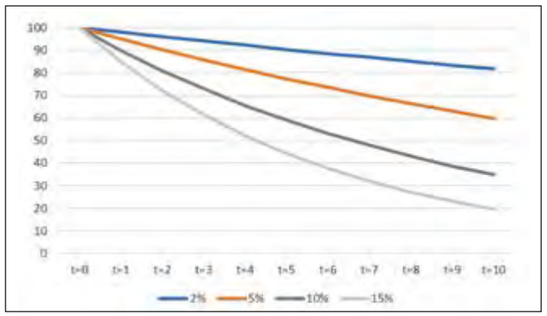

Fig. 1: Indication of potential purchasing power effects of the special fund

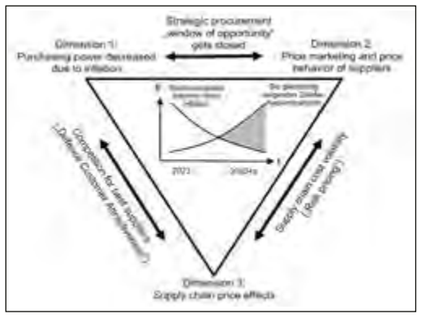

Fig. 2: Strategic cost dilemma

Fig. 3: Bundeswehr University in Munich (library building)

Universität der Bundeswehr München
Forschungsgruppe
Defence Acquisition &
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Fig. 4: DASM research group

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Satellite communications “to go”: Deployable lightweight manpack antenna system

As part of the ILKA project and supported by the University of the Bundeswehr Munich, the HPS company has been developing a new portable antenna system in manpack format. The complete system weighs less than 25 kg and includes a 1.2 m reflector for fast data transmission. Portable and usable in any terrain, it is designed to be used by highly mobile teams.

One of the most important prerequisites for reliable command and control as well as information transfer in the field is communications, and satellite communications is essential for covering long distances. In addition to strategic and tactical links to fixed ground stations, terminals that can be deployed quickly are playing a critical role in a dynamic and highly mobile operational environment. Terminals of the category up to 1.2 m diameter offer data rates of several Mbps and support common frequency bands from X band through Ku band to Ka band. However, systems available on the market today are characterised by their comparatively heavy weight and the time-consuming assembly of the reflectors which usually consist of independent segments. In addition, several cases are usually required for transport, which severely limits mobility.

This capability gap is addressed by the research project ILKA (integrated deployable lightweight manpack complete antenna) which is funded by the Federal Ministry for Economic Affairs and Climate Action. The project includes the feasibility study of a fully equipped deployable communications system with a reflector diameter of 1.2 m including all necessary subcomponents (RF feed, electronics, power supply, antenna alignment technology, tripod, backpack) for X band and Ku band (Fig. 1). Under the leadership of the HPS company, a German consortium has formed including the Blackwave company, the Technical University of Munich (Chair of Carbon Composites), and the mtex antenna technology company in cooperation with the Institute of Information Technology of the University of the Bundeswehr Munich.

Fig. 1: Antenna system in operational configuration

Fig. 2: Antenna system in transport configuration

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The principle of radially extending ribs has already been explored as part of previous work on the KEAN (deployable compact backpack antenna) project and, because of its proven positive aspects, is now also being used as the basis for further development of the communication system in the current project. One person will be able to carry the system with its small pack size and a total weight of less than 25 kg (Fig. 2). In addition to its compactness, the antenna system will also be easy to use, which includes the fact that a satellite link can be set up quickly in less than 15 minutes. In addition to the innovative folding kinematics of the reflector and the miniaturisation concept of the electronic components, this requires a production-ready manufacturing concept for reflector blades made of fibre-reinforced polymer in a lightweight design. An innovative combination of short- and long-fibre-reinforced polymers is used to combine the HF reflection requirements with the necessary stiffness and dimensional stability as well as low weight (Fig. 3).

After development and design have been completed, process development and production of the laboratory prototype are currently underway. Application-oriented end-to-end connectivity tests as well as systems and handling tests are also planned to be conducted at the Munich Centre for Space Communications (Fig. 4), a reference and test facility for satellite communications at the University of the Bundeswehr Munich. The completion of the project in mid-2023 will pave the way for the implementation of a first small series.

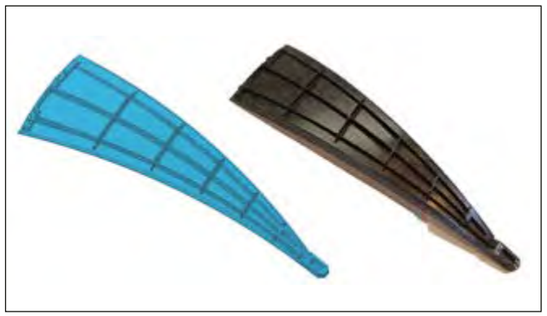

Fig. 3: Stiffened blade backside in CAD (left) and implementation as CFRP component suitable for series production (right)

Fig. 4: Reference and test facility for satellite communications: The Munich Centre for Space Communications

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Aerodynamic characterisation of spin-stabilised projectiles for high-elevation firings

The French-German Research Institute of Saint-Louis (ISL) investigates the flight behaviour of spin-stabilised projectiles for high-elevation firings. In order to determine the aerodynamic characteristics of projectiles flying with large angles of attack, both wind-tunnel tests and numerical flow simulations are conducted. These are required to accurately predict trajectories of projectiles fired with high elevation angles.

Artillery shells are fired with a spin around their longitudinal axis, which stabilises their trajectory and prevents them from tumbling. The concept of spin stabilisation begins to fail when the launch angle (elevation) exceeds 70 degrees. Reduced aerodynamic forces in conjunction with the high curvature of the trajectory cause the angle of attack to increase sharply at the apogee of the trajectory (Fig. 1). Depending on the launch conditions, its aerodynamic characteristics and the wind conditions, a projectile may restabilise in the original nose-forward orientation on its way down, or completely turn over and stabilise in a base-forward orientation so that the projectile base hits the ground first. In some cases, limit cycles may occur, in which projectiles fall to the ground in a more or less stable cyclic sideward motion.

While such high-elevation trajectories are of minor relevance for military operations, they are used for ammunition testing, for example in the context of fuse tests. In these cases, projectiles are intentionally fired with sufficient elevation to cause a base-forward descent in order to prevent damage to the fuse at the projectile tip when the projectile hits the ground. For a safe determination of danger zones, possible trajectories must be calculated in advance. This requires knowledge of the projectile's aerodynamic properties at subsonic speed and angles of attack of up to 180 degrees. These can either be measured experimentally or calculated using numerical flow simulation methods. However, because experimental data for validation are not yet sufficiently available, the reliability of the simulation methods under the present conditions cannot be guaranteed.

For the aerodynamic characterisation of artillery projectiles, subsonic wind tunnel tests are conducted at the ISL using scaled projectile models (Fig. 2). The aerodynamic forces and moments are measured by a six-component force balance integrated into the model. The spinning motion of the projectile surface is realised using an electric motor installed between the force balance and the projectile body.

In addition, flow fields around the projectile are measured using optical methods. Fig. 3 shows the pressure distribution in an axial cross-sectional plane around a spinning projectile, as reconstructed from velocity measurements using Particle Image Velocimetry (PIV). As can be seen in the example shown, the spin of the projectile surface causes an asymmetric pressure distribution on the projectile surface. The phenomenon is known as the Magnus effect and causes spin-stabilised projectiles to experience lateral forces that lead to a side drift of the trajectory and significantly affect the stability behaviour.

Experimental measurements of the flow field not only serve to provide a phenomenological explanation of the measured forces, but also represent an excellent opportunity to validate the predictive capabilities of numerical simulation methods.

In order to capture the prevailing flow phenomena, advanced simulation techniques such as LES or DES are required (Fig. 4).

The combination of force-balance experiments, optical flow-field measurements and numerical simulations provides reliable aerodynamic data for artillery projectiles at large angles of attack. These are required to accurately predict trajectories of projectiles fired with high elevation angles. Taking wind conditions into account, reliable estimations can be made about the danger zones of test firings.

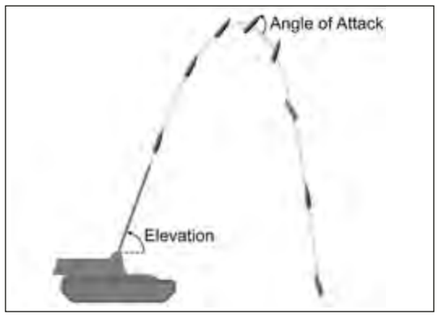

Fig. 1: Typical trajectory of an artillery shell when fired with elevation angles above 80 degrees

Fig. 2: CAD model of the wind tunnel test section model mount, and mounted projectile model

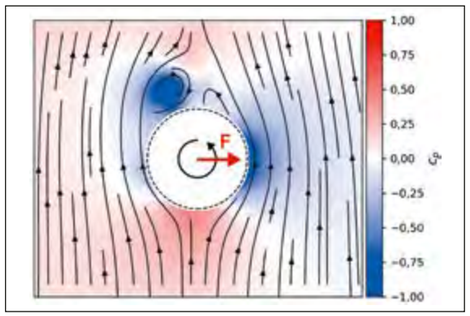

Fig. 3: Pressure coefficient cp reconstructed from PIV measurements of the flow velocity around a spinning projectile at a 40-degree angle of attack, along with the resulting lateral force F and pseudo-streamlines of the planar velocity field. The direction of spin is indicated by a circular arrow

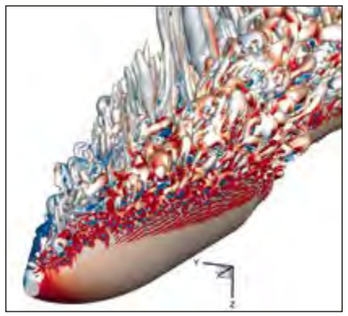

Fig. 4: Vortical structures in detached flow regions on the leeward side of an inclined projectile, computed with scale-resolving large-eddy simulations

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Reactive structural materials: Interdisciplinary and multiscale fundamental research by experiment and simulation

Fragmentation cases made of reactive structural materials can improve the performance of warheads significantly. Upon target impact they release large amounts of chemical energy in addition to their kinetic energy. The French-German Research Institute (ISL) and the Helmut Schmidt University / University of the Federal Armed Forces Hamburg (HSU / UniBw H) conduct simulations and experiments in close cooperation to investigate the complex terminal ballistic behaviour and also develop new methodologies.

Reactive structural materials as replacements for conventional warhead materials have gained substantial interest for their potential, both from the protection and the effector side. However, the underlying mechanisms leading to the release of chemically bound energy during impact are not yet fully understood. In particular, it must be examined what role mechanical and chemical processes and their interaction play. This research requires an interdisciplinary and multiscale approach.

ISL and HSU / UniBw H have combined their individual strengths into a common set of capabilities to facilitate the investigation of reactive materials on different scales and with different methods.

On a macroscopic scale, the terminal ballistic reaction behaviour of individual surrogate fragments is investigated experimentally at ISL far into the hypervelocity range. For this gas and powder guns are used. Explosively-driven reactive material fragments and surrogate charges are tested at the institute's own proving ground. High-speed cameras and

Fig. 1: Perforation of an armour steel plate by a surrogate fragment from left to right, obtained with high-speed imaging. The energy release and expanding reaction zone after perforation are shown clearly

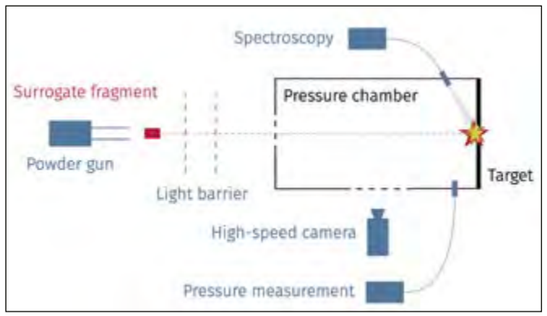

Fig. 2: Experimental setup at ISL with simultaneous recording of flight conditions (light barrier, high-speed camera), quantitative reaction values (pressure chamber), and qualitative reaction values (spectroscopy)

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flash x-ray systems are used for imaging experiments. Vented Chamber Calorimetry (VCC) is used to quantify the release of energy. Spectroscopic studies of the impact zone provide information about the species created during the reaction and help to understand reaction pathways (Fig. 1 and 2).

The required reactive materials can be produced by means of powder metallurgy at ISL and characterised mechanically in terms of their strain rate dependent behaviour. The parameters obtained are used for finite element simulations, which model the fragmentation of reactive materials on a mesoscale.

To aid fragmentation modelling, computer tomography will be used at the Chair for Computational Material Design at the HSU / UniBw H. The required computer tomography machines have been set up as part of dtec.bw. Also as part of dtec.bw, new physical vapour deposition (PVD) equipment is currently being put into service at the HSU / UniBw H. This will facilitate the creation of thin films of reactive materials and reactive-material-based graded materials on a laboratory scale.

At the atomic level, the behaviour of reactive materials is simulated at the Computational Material Design chair using quantum chemical modelling and molecular dynamics. With these methods, any combinations of materials and influences on their chemical behaviour can be investigated, e. g. the influence of impact-induced mechanical strain on the reaction path (Fig. 3). Information on the strains occurring during impact is obtained from molecular dynamics simulations.

Calculations are done with automated workflows using a high-throughput procedure at the new "HSUper" high performance computing cluster of the Bundeswehr University in Hamburg (Fig. 4). This facilitates the identification of promising materials for future applications from a wealth of precursor materials.

In the long term, the obtained results from different length scales will be combined into a multiscale digital twin of reactive materials, ranging from the atomic up to the macroscopic level. The aim is to have a holistic understanding of material behaviour.

This work is financed by core funding of the Federal Ministry of Defence, additional federal contract funding, and third-party funding from the German defence industry.

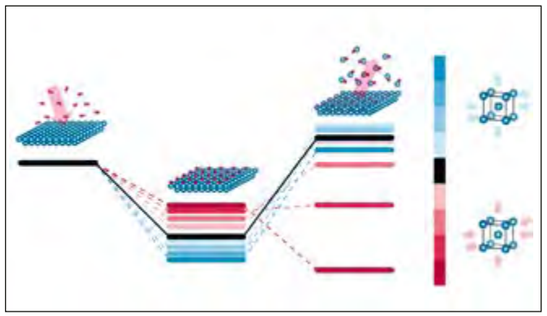

Fig. 3: Surface oxidation and degradation of zirconium in an unstrained balanced state (black), at isotropic compression (red), and isotropic tensile strain (blue). Sufficient compression promotes the release of energy

Fig. 4: Computational resources (HPC cluster HSUper) have been provided by the projet hpc.bw, funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr. dtec.bw is funded by the European Union – NextGenerationEU

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Integration of additive manufacturing into the German Navy

Additive manufacturing in the German Navy is entering the next stage. Last year, after successful experiments on various ship classes such as frigates, corvettes, and combat support ships were performed in 2021, and work on the topic of 3D printing in the Bundeswehr had been done as part of Concept Development & Experimentation (CD&E), the promising results led to the first procurement of material extrusion printers.

In 2023, the training of soldiers will start at the Naval School of Technology near Stralsund. First units will then be equipped with a 3D printer. The aim is to increase the availability of the units by using the new technology. However, the foundations have to be laid for this. These foundations are the training and the correct mindset as well as the establishment of a database for parts. This is to build a digital spare parts inventory within the next few years, which will allow spare parts to be produced on missions at sea in the future.

Because the terms 3D printing and additive manufacturing are generic terms, but technical terms such as selective laser melting (SLM) or fused filament fabrication (FFF) are usually only used by specialist personnel, a new cluster and classification system was developed as part of the research. This is intended to minimise problems with interdepartmental communication.

The integration logic is designed to support temporarily self-sufficient systems. Four levels of additive manufacturing and the corresponding systems engineering were identified

Fig. 1: Level structure for additive manufacturing
(Source: according to Hartig http://dx.doi.org/10.24405/14321)

Fig. 2: CD&E experiment frigate SACHSEN: integration of a Level 2 material extrusion printer

Fig. 3: Additively manufactured filter insert of the sea cooling water system being used on frigate SACHSEN. Only feasible using level 2 3D printers because of the size

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for the German Navy. The basic structure is like a pyramid (Fig. 1), with the horizontal axis representing dissemination and the vertical axis representing complexity. Classification is generally based on the organisational structure together with the usable resources on board. Small material extrusion (MEX) printers with low resource requirements for space and operator training can be used on the vast majority of all units and are classified as Level 1 additive manufacturing.

Larger systems that, for example, require peripherals, use higher strength polymers, can therefore implement more complex applications, and accordingly require personnel with advanced training, can only be used on larger units. This is shown in Fig. 2. The first two levels enable ships to generate parts to cover needs for a short time until the logistics system can resupply.

The availability of this system is optimised by means of the two higher levels. Level 3 of additive manufacturing, which is based, for example, on laser powder bed fusion technology, cannot be used on board due to the availability of resources and the danger to personnel because of the carcinogenic raw material. Use on land, for example in the naval arsenal, is a good way to take advantage of these technologies and to use synergy effects based to the needs of the different units.

In the future, Level 4 additive manufacturing technologies and processes will make the production of certified spare parts possible through collaboration with commercial manufacturers. Until then interim components will be produced for temporary repair. These are used until the required spare part can be supplied via the existing logistics system.

Level 1 of additive manufacturing has now been procured as part of integration and is to be used on all units of the navy at sea as well as ashore. This will basically follow the concept of progressing from simple to complex solutions. Based on the evaluation of the data, the next stage of the integration concept will then be implemented. The units with the necessary available resources such as space, manpower, energy, etc. will be equipped with a more powerful Level 2 additive manufacturing system.

Fig. 4: Additively manufactured trackball retaining ring being used on frigate SACHSEN

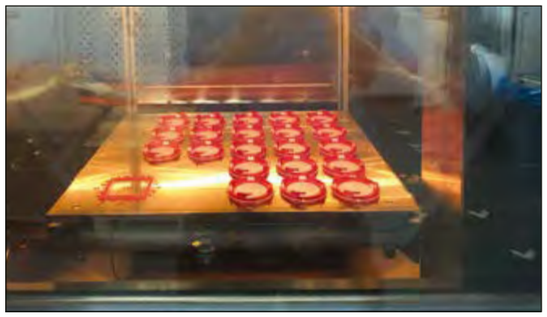

Fig. 5: Production of the trackball holder rings in the build area of a Level 2 material extrusion printer

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Bundeswehr leadership culture in the digital age

The megatrend of digitalisation places special demands on a complex organisation such as the Bundeswehr. We will look at the social process of introducing and using digital tools, with a special focus on the acceptance of and resistance to the use of data-intensive algorithms and their impact on executive decisions.

The increasing availability of large amounts of data and the use of data-intensive algorithms also bring about fundamental changes for the decision-making processes in the area of responsibility of the Federal Ministry of Defence. The focus of our research is on the challenges that arise from this for the command and control processes of the Bundeswehr. In cooperation with Prof. Gabi Dreo, Professor of Communication Systems and Network Security at the Bundeswehr University in Munich, we have combined software engineering with organisational sociological questions and analyse how organisational and technical factors influence the use of analytics tools. Increasing digitalisation has an impact on the leadership and its behaviour and has the potential to change leadership culture. The current leadership culture, however, also has a considerable influence on the processes of digitalisation in the Bundeswehr. Accordingly, we assume that there is a recursive relationship between leadership and data-intensive algorithms (Fig. 1).

Methodologically, a qualitative approach was chosen with the implementation of expert and topic-centred interviews. Initial results show that the Bundeswehr is still in the early stages of cultivating the analysis of large amounts of data and the development and use of AI (artificial intelligence). However, the organisation has extensive databases. This “raw material” (2021 data strategy for the area of responsibility of the Federal Ministry of Defence, p. 4) must be developed in the future and made usable in line with the concept. The fundamental challenge with regard to data analytics is the utilisation of such data, along with the guarantee of data quality and the widespread use of relevant applications. Especially the issue of understanding the results of data-intensive learning algorithms (black box algorithms) and how these results were reached leads to resistance even in the Bundeswehr.

At the same time, there is an awareness that data analytics tools offer great value in the preparation of informed decisions. In a highly hierarchically structured organisation such as the Bundeswehr, leadership can demonstrate willingness to implement digitalisation across all levels and thus serve as a key factor in the digitalisation process. At the same time, as the digital transformation progresses, there is an increasing need to move from the traditional decision-making process to leadership behaviour that includes more agile elements at some points. For the success of the digital transformation, it is of central importance to develop an awareness of the concrete goals, possibilities and limits of digital technologies, so that there is a clear understanding of what certain technologies should be used for, what they are capable of and suitable for, but also what they cannot do and where their limits lie.

Based on the findings from the qualitative interviews, a quantitative survey tool was developed. The online questionnaire to measure the effects of digitalisation on leadership processes will be tested in a next step and can be made available for use in several organisational areas of the Bundeswehr (Fig. 2).

The project on leadership culture in the Bundeswehr runs from April 2021 to December 2024 and is funded by the dtec.bw centre for digitalisation and technology research of the Bundeswehr (Fig. 3).

Fig. 1: Recursivity

Fig. 2: Welcome page of the online questionnaire

Fig. 3: dtec.bw centre

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A l'étranger avec des amis: Satisfaction and commitment of Bundeswehr personnel and their families at the new location in Évreux, France

A project team of the Bundeswehr University in Hamburg investigated for German Air Force Headquarters how satisfied Bundeswehr personnel and their families in Évreux are and drew up recommendations for action to improve integration and quality of life on site. The need for action was particularly evident in terms of medical care for dependents, the range of available accommodation, and language training.

Most Bundeswehr personnel serving abroad are assigned for two to six months. However, the binational squadron being set up in Évreux since 2021 presents a special case: personnel is stationed there for three to six years. They and their dependents face special challenges: They have to find accommodation, get used to language and culture, and rely on local infrastructure. In addition, many soldiers move to France with their families and therefore have to take care of school and childcare for their children as well as consider possible employment opportunities for their partners.

The Bundeswehr University in Hamburg was tasked with providing academic support to the project. The aim was to examine to what extent personnel and their families feel integrated in France, whether they have been sufficiently prepared for their task and the stay abroad, and which factors contribute to satisfaction, integration, motivation and willingness to stay in Évreux for a long period of time. Based on the results, measures should be derived to improve the situation for personnel and their families on site and contribute to their integration and willingness to stay. Expectations and attitudes towards the location were to be positively influenced so that enough personnel will be found for future assignments.

The project team of the Bundeswehr University in Hamburg travelled to Évreux in February 2022 to get a first-hand impression of the situation and to collect data. For this purpose, $n = 51$ members of the German armed forces and $n = 14$ family members living with them in France filled in a standardised questionnaire. This included the assessment of the current working and living conditions, perceived integration in France, as well as job satisfaction, commitment, motivation, health and willingness to stay. In addition, $N = 15$ qualitative interviews were conducted to supplement the quantitative findings.

The Bundeswehr members rated their job, the mission and their leadership very positively and showed a strong commitment to the Bundeswehr and the mission. The quality of life in Évreux (cultural offerings, clubs and associations, surroundings) was rated very positively (Fig. 1 – 4), but other aspects of life in France were rated less favourably, especially by those with dependents. They gave a more negative assessment of medical care, the availability of housing and language courses, as well as preparation and information provided prior to their assignment. Integration so far was perceived as moderately successful, which was mainly attributed to a lack of language skills and insufficient contact with French people outside of work. Even though these factors are associated with negative health experiences (more psychological stress and symptoms), an overall relatively high motivation was reported. Family members gave a similar assessment, but in addition they complained about the lack of job opportunities and the fact that they had to cut back on their careers because of this. However, the children found it easy to make friends. Despite these circumstances, there is currently a high willingness to stay in Évreux for longer.

As the medical care and housing situation were assessed very negatively, there is an urgent need for action in this regard. This should be realised primarily by additional medical and housing support personnel. For good integration and willingness to stay, cooperation and communication with the French are essential, which is why the provision of (more) language courses, also for dependents, is recommended. Other recommended measures include the management of expectations prior to assignments, the centralisation of information, clear responsibilities as well as better planning and organisation of the process of relocation.

Fig. 1: Évreux Cathedral

Fig. 2: Évreux Town Hall

Fig. 3: Picturesque corners in Évreux

Fig. 4: Port of Deauville on the Atlantic Ocean, 1 hour from Évreux

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Power electronics for high-power pulse applications, exemplified by a compact power supply for electric weapons

The Chair of Power Electronics at the Bundeswehr University in Hamburg and the French-German Research Institute (ISL) supervise three doctoral research studies as part of a cooperation agreement. The focus is on high-efficiency capacitor charging systems with high-power density, as well as on a new generation of silicon-carbide power semiconductors for compact high-power pulse generators.

Based on the 2016 framework agreement on cooperation (Fig. 1) between the Bundeswehr University in Hamburg and the French-German Research Institute of Saint-Louis (ISL), the Chair of Power Electronics and the Pulsed Power Technologies group at ISL jointly supervise three doctoral research studies.

The research team at the ISL mainly focuses on the development of compact energy supplies for electromagnetic railguns. Thanks to its unique experimental testing facilities (Fig. 2), the ISL plays a central role within Europe regarding the research and development of this technology. Especially the development of the XRAM generator (Fig. 3), a pulsed power generator based on inductive accumulators with high energy density instead of conventional capacitor banks, received international attention.

The operation of a medium-sized electromagnetic railgun supplied by a 1 MJ inductive energy supply prototype with an energy density of 4.5 MJ/m³ was successfully demonstrated as well as a 13 Hz repetition rate in conjunction with a battery-based energy supply. A key component with this type of high-power generator is a complex electric circuit which relies on high-voltage capacitors to turn off thyristors.

Capacitors and corresponding high-voltage chargers will be a key necessity in the future, regardless of whether capacitive or inductive pulsed power generators will prove to be superior. Consequently, the development of ultra-compact and highly efficient capacitor chargers is a main research topic of the cooperation between ISL and the Chair of Power Electronics, which has a high level of expertise with modern power converters.

The capacitor charging system developed at ISL (Fig. 4), utilises a ferrite-less and fibre-reinforced coil as well as a high-power semiconductor switch due to the extremely high currents. A voltage converter of this design and power range is globally unprecedented. As part of this research cooperation, the partners have already been able to optimise the capacitor charging system on the basis of a detailed analysis of loss parameters (Fig. 5).

The charging power was increased by 180 % to 300 kW by improving the circuit design. This system outperforms comparable, commercially available chargers regarding both efficiency and the resulting power density of more than 4 kW/dm³. However, a comprehensive simulation model we developed has helped to identify limits of the current topology.

Now, this research project aims to increase the already uniquely high power density even further. The goal is a modular and redundant charging system with a total power output of 1000 kW. Cutting-edge silicon carbide (SiC) power semiconductors will be implemented in a resonant converter topology especially adapted to this application, which will facilitate operation at a very high switching frequency. The associated increase in resonance frequency will significantly reduce the volume of the resonant components and the transformer, which will result in a considerable increase in power density. We must strive for high efficiency in order to achieve a compact design of the semiconductor cooling system.

Fig. 1: ISL Directors shake hands with the President of the Bundeswehr University in Hamburg on the extension of the cooperation agreement

Fig. 2: NGL 60 railgun and PEGASUS capacitor-based energy system

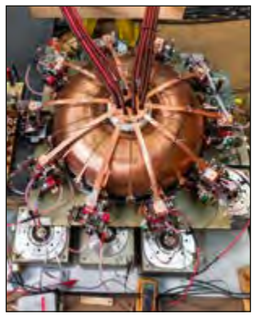

Fig. 3: XRAM generator – inductive pulsed power generator for railguns

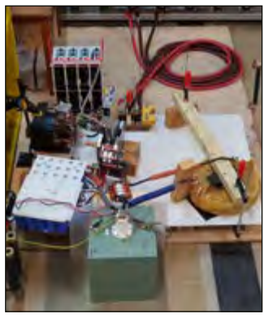

Fig. 4: Experimental set-up of the inverting buck-boost converter topology

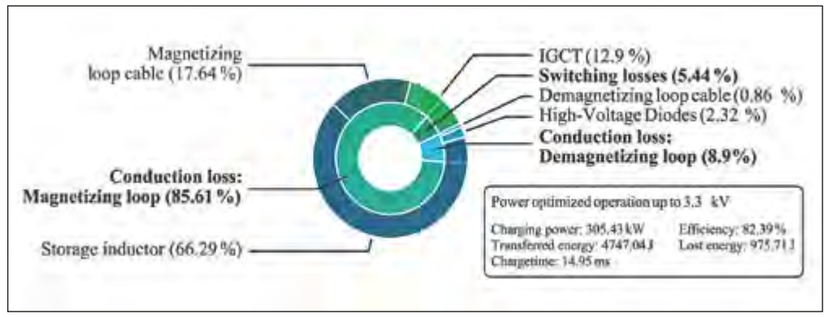

Fig. 5: Loss analysis of the inverting buck-boost converter topology for capacitor charging; inner circle (bold): type of loss; outer circle: circuit component

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Shaping digitalisation: Educational research to empower social resilience in uncertain times

To advance digital competencies and improve resilience, the project Competencies for a Digital Working Environment (KoDiA) – Empowerment for Digitalisation explores how education can help foster resilience in democratic societies. The project is one of 68 projects funded by the Digitalisation and Technology Research Centre of the Bundeswehr (dtec.bw) (Fig. 1) at the Bundeswehr Universities in Hamburg and Munich.

Dtec.bw, the Digitalisation and Technology Research Centre of the Bundeswehr, is a scientific centre funded by the Bundeswehr Universities in Hamburg and Munich and part of the German government's economic stimulus relief package for overcoming the COVID-19 crisis. It is academically autonomous. At both universities, funds for dtec.bw have been used for financing research projects and projects for knowledge and technology transfer. Dtec.bw is funded by the European Union – NextGenerationEU.

Digitalisation has a fundamental impact on how citizens participate in democratic processes and how they obtain information as well as what information they use as a basis for their participation. This includes opportunities (such as easy access to any kind of information) as well as risks (such as "fake news", disinformation, manipulation). Citizens' skills in terms of judging the validity and therefore reliability of digital information are therefore vital.

This is the purpose of the Competencies for a Digital Working Environment (KoDiA) – Empowerment for Digitalisation project: The project will explore the spectrum of interaction in virtual environments through research in different contexts. One of the main questions is how education can support competency development in our digital working and living environments. We have been using an approach based on contextualised research. This means that our research is embedded in different institutional and social contexts to explore theory in real situations of education, formation and training within the Bundeswehr as well as in civil educational contexts.

The first of three main tasks (Fig. 2) of the KoDiA-project is the empowerment of the individual. Responsible participation is vital to strengthen democratic processes and principles and to stabilise the resilience of public and state. Our research approach connects training research within the Bundeswehr and educational expertise in civilian vocational training, integrating official standards on the topic of digitalisation released by the Conference of the Ministers of Education and Cultural Affairs of the federal states and the standard occupational profiles of the Federal Institute for Vocational Education. One example of our research is the exploration of using mixed reality in the training of driving instructors at the Bundeswehr Logistics School, another is to find out how eduScrum can be used as a learning method in hybrid environments.

The second task of the project is the concept of public science, which entails innovative cooperation for the enhancement of communication between scientists and the public.

The Bundeswehr (Education and) Training Congress, which has been a hybrid event since 2022, has been a use case for the topic (Fig. 3). The convention aims to bring together experts from science, economy, public administration, as well as education and training, using the virtual space as an easily accessible meeting place for science and society. The convention uses the Link and Learn internet learning platform of the Bundeswehr. Experiences from using the platform as virtual conference environment directly impact the further development of the Bundeswehr virtual learning environment, which is currently being developed as part of the HERKULES follow-on project (Fig. 4 and 5). The convention aims to create a space of evidence- and science-based information to support coping with digitalisation, make digital participation easier, and improve self-efficacy.

The third main task of the KoDiA-project is about addressing the increasing fragmentation of the science system. The aim is to make research and development processes and findings compatible by interdisciplinary exchange. Our main point of focus has been on the concept of stakeholder balancing. The research context is a network dealing with education for innovative energy transition, created in cooperation with the Freiburg University of Education, which includes scientists from various disciplines as well as experts from economy, industry, vocational training and Bundeswehr.

KoDiA integrates the Bundeswehr research context with the research context of general and vocational education and training at schools, businesses and institutions of higher education, so that findings can be used everywhere.

dtec.bw
Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr
Finanziert von der Europäischen Union
NextGenerationEU

Fig. 1: dtec.bw logo

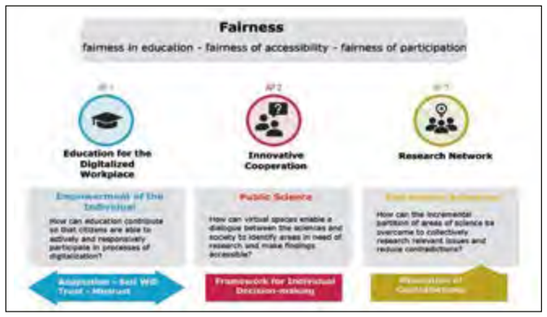

Fig. 2: Overview of the main tasks of KoDiA

Fig. 3: Discussion on digitality, security and resilience, with (from left) R. Kiesewetter, MdB, Prof. Dr. D. Schulz, Moderator Prof. Dr. M. Schulz, M. Çapar und Prof. Dr. J. Schlicht (Source: Fotoarchiv, HSU/UniBw H, Ulrike Schröder)

Fig. 4: Forum on supporting professional competencies by means of adaptive learning systems, with the team of Prof. Dr. S. Hiestand of Freiburg University of Education (Source: Fotoarchiv HSU/UniBw H, Ulrike Schröder)

Fig. 5: Presentation of new technologies for education and training (Source: Fotoarchiv HSU/UniBw H, Ulrike Schröder)

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Conceptual design of a holistic surrogate for testing non-lethal agents in the form of kinetic projectiles

In an expert workshop with various services of the Bundeswehr, research institutes and clinics, the Laboratory of Production Engineering and the Technical Centre for Protective and Special Technologies, Branch 320 (in short WTD 52) have established the requirements for a surrogate for testing non-lethal agents in the form of kinetic projectiles (Fig. 1).

The most important requirement is the validation capability of the human surrogate. It should ideally match the human organism with respect to important mechanical parameters, such as densities, strengths, stiffnesses and measured values. This will be considered based on literature characteristic values, own test setups or data from other agencies / institutes. The geometry should be equivalent to the human body and the tolerance behaviour should be reproducible. Biofidelity should be guaranteed, and the 95 % or 50 % man can be taken as a reference. To achieve this goal, it should have a modular as well as reusable structure of components. From a medical point of view, the design should initially focus on the abdominal and thoracic regions, as this is where the greatest stresses are expected. As a test concept, five stages were worked out according to which the surrogate will be developed (Fig. 2).

In stage 1, tests are carried out on coupons to determine certain characteristic values such as elastic modulus, tensile strength, elongation at break and density. These coupons are test specimens with simple geometry that are manufactured according to existing standards. Findings from tests on human or animal biological material are used as the basis for validation. In Stage 2, tests are performed on existing test setups such as those according to NATO STANREC 4744. In Stage 3, complex geometries similar to human anatomy will be created to investigate the reproducibility of results with a specified number of surrogates. In Stage 4, further details in the form of material combinations and different components of the human body, such as various organs and bones, are to be reproduced. We recommend to map only a subset to keep the cost and effort in check. In Stage 5, larger components such as an entire torso with all organs and blood vessels are created and the developed test setups are used to validate the surrogate. The findings can be used to design new standards for testing projectiles, which then can be used across the services.

Currently, work is underway to develop a surrogate of the human thorax for ballistic testing. For this purpose, the anatomy of the torso and the injury behaviour were first studied. A concept for a modular thorax surrogate is being developed, consisting of several reusable components. The concept is based on a 3D model from a CT scan of the thorax of a male provided by the Department of Biomechanics and Accident Analysis at the Institute of Forensic Medicine, LMU Munich (Fig. 3). We differentiate between subcomponents for the soft tissue, the bone part, the organs and the measurement sensor system. First, we used PUR rubber PMC-770, followed by 20 % ballistic gelatine (Fig. 4).

Criterion	Weighting	Rank
Validation capability	0,19	1
Accuracy	0,17	2
Multiple use capability	0,15	3
Structure of the surrogate	0,13	4
Shaping Mapping of the body shape	0,11	5
Testing capabilities	0,09	6
Material	0,070	7
Manufacturing process	0,050	8
Costs	0,030	9
Boundary layers	0,010	10

Fig. 1: Requirements with weighting for surrogate production

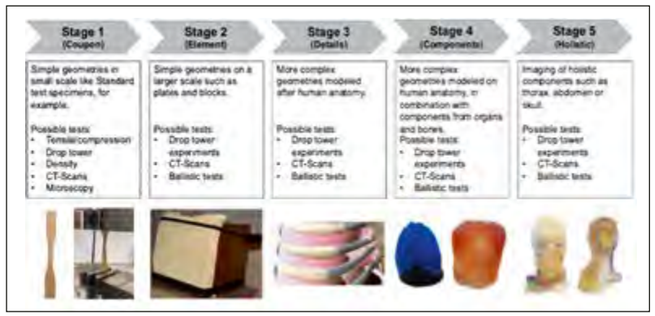

Fig. 2: Planned tests for validation of possible surrogates and materials divided into 5 stages

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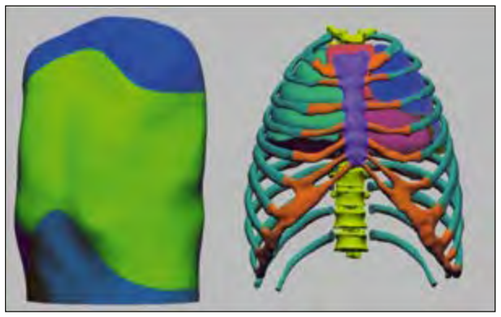

Fig. 3: 3D model of a CT scan of the thorax, provided by the Department of Biomechanics and Accident Analysis at the Institute of Forensic Medicine, LMU Munich

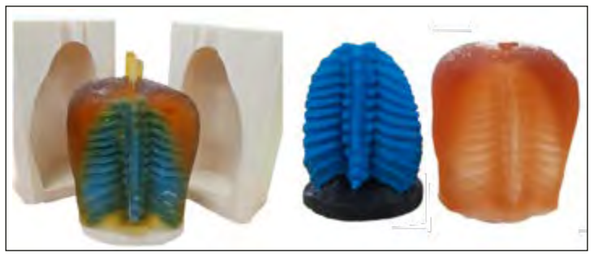

Fig. 4: Casting mould with core, made by additive manufacturing for creating the soft tissue

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Actively controlling the acoustic signature of naval vessels

Reconnaissance methods and civilian underwater noise monitoring can disclose classified signature features of the noise radiated by naval vessels. A ship model made of steel at a 1:8 scale is used to examine the extent to which inertial transducers can modify signatures.

The acoustic signature of a ship comprises the spectral characteristics of waterborne noise generated by different noise sources including machinery, flow-induced and cavitation noise. This signature can help detecting and identifying a vessel using passive sonars or sensors and suitable signal-analysing procedures.

The most important signature features are spectral lines, i. e. narrowband noise components in the spectrum that differ from the background noise. These noise components are usually generated by machines with rotating parts such as combustion engines and radiated as sound into the surrounding water via the ship's hull.

The occurring frequencies of the spectral lines are usually the basic frequency and harmonics of the corresponding rotational speeds of the aggregates or components. The acoustic fingerprint, a combination of frequencies of several lines in one pattern, can lead to a classification and even contain information on the ship's condition.

Fig. 1: Type 148 Tiger-class fast attack craft (Source: Karr 2015, German Navy)

Fig. 2: Fast attack craft model at a 1:8 scale measuring approx. 6 m in length

Fig. 3: Fast attack craft model tied up underneath the WTD 71 measuring station in Lake Ploen

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Passive methods are used to reduce noise transmission on board and signature radiation into the water. They include elastic decoupling of on-board noise generators and the reduction of cavitation in propellers. An adaptive control mechanism for active signature manipulation is used to complement these established systems. Based on data measured on board, they modify the acoustic signature by means of actuators on the hull shell. Crucially, in addition to reducing and amplifying signatures it is also possible to add noise components without increasing the counter-detection range.

For model testing, the Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research (WTD 71) provided a ship model made of steel without deck installations, generators or propulsion systems. This model accurately simulates the Type 148 Tiger-class fast attack craft and bears great similarity in geometry and acoustics (Fig. 1 and Fig. 2).

Following the system design phase and initial trials ashore, the system test is conducted in water at the WTD 71 measuring station in Lake Ploen (Fig. 3). The actual signature which is composed of a sound sequence is introduced at the positions of engine substitute masses via noise generators. Then the signature control mechanism is activated and on-board data measured in real time is used to add noise components to the existing structure-borne sound via eight inertial actuators on the hull shell (Fig. 4). The resulting interference effects lead to measurable signature changes in the previously defined monitor area consisting of six hydrophones around the measurement position (Fig. 5). A specification of the target signature offers a wide range of options and serves as the basis for implementation into a signature management system.

Military signature monitoring as well as civilian subsea environmental acoustic monitoring play an ever greater role and increasingly influence the behaviour of naval vessels. Therefore, this could be a key approach for protecting hydroacoustic signatures from known and unknown detection, identification and classification of reconnaissance procedures.

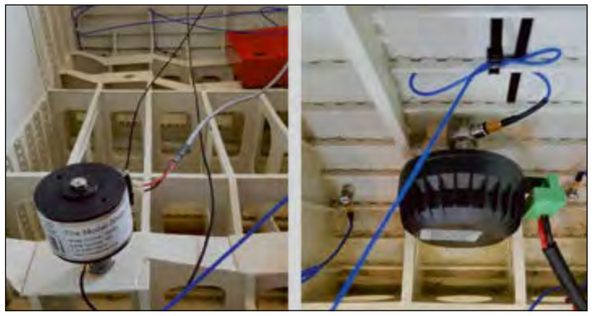

Fig. 4: Inertial actuator in the fast attack craft model to generate the actual signature (left) and inertial actuator and accelerometers on the hull shell to generate the desired target signature (right)

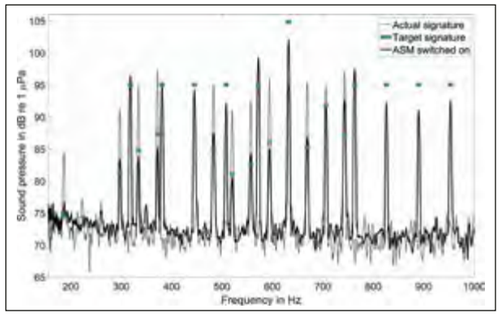

Fig. 5: Measurement result obtained at hydrophones during the active signature manipulation system test at the WTD 71 measuring station in Lake Ploen

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A method of investigating the combustion of synthetic and alternative fuels

The use of alternative and synthetic liquid fuels and NATO's Single Fuel Policy have raised combustion-related issues for the existing diesel engine-powered vehicle fleet. Our method helps to better assess these issues. We also present a method of adapting engines to changing fuel qualities.

Alternative and synthetic fuels are suited to meet some of the requirements for CO_2-neutral and low-emission mobility. They can be used in existing conventional diesel engines without major adaptations if the existing fuel specifications are met. In Europe, EN 590 is the current standard for diesel fuels. It contains specifications for chemical-physical properties such as density or viscosity but also for combustion parameters such as the cetane number which is determined through engine test procedures. Since the cetane number is a measure of the ignitability of diesel fuels (Fig. 1), it has a narrow range to ensure reliable and safe engine operation. The test engine uses an older combustion technology and was designed for the use of fossil diesel fuel. The validity of the cetane numbers set for alternative fuels must be verified because fuels of different origin differ in their chemical structure and composition. This has an influence on diesel engine combustion and emission formation.

The example of paraffin diesel fuels and the applicable DIN EN 15940 shows that fuels deviating from DIN EN 590 can also be used for diesel engine operation and approved by manufacturers.

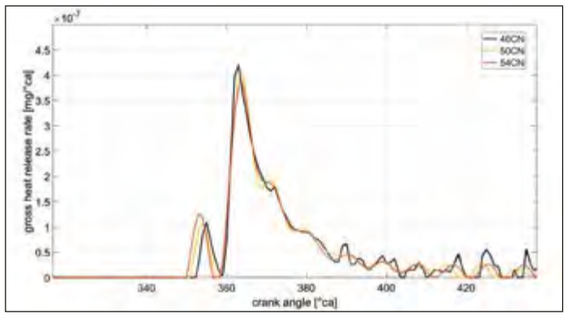

Fig. 1: Gross heat release rates with different cetane numbers (same operation point)

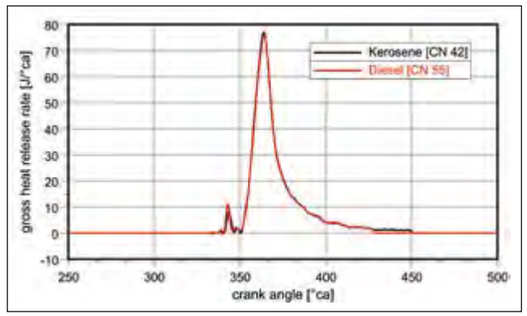

Fig. 2: Gross heat release rates with different fuels (same operation point)

NATO conducted studies on the use of alternative fuels in diesel engines at an early stage. This resulted in the Single Fuel Policy which provides for the use of kerosene in aircraft and land vehicles. The member states are responsible for ensuring compatibility of their aircraft and land vehicles. Previous tests with older diesel engines have shown that they can be used even if they deviate from DIN EN 590. Fig. 2 shows the gross heat release rates of kerosene and diesel in the same operation point. They are almost identical despite different cetane numbers.

The German Armed Forces must also deal with this issue during missions abroad in order to ensure the operational readiness of vehicles and equipment when no diesel or other fuel that meets specifications is available. For example, kerosene samples from operational areas revealed cetane numbers of less than 40 and thus an unusually low ignition quality even for kerosene.

In cooperation with the Bundeswehr Research Institute for Materials, Fuels and Lubricants, a method was developed that allows for a better assessment of non-standard fuels in terms of combustion suitability in diesel engines. The aim was to develop a fast and reliable method that takes into account the testing capabilities of the German Armed Forces. A major advantage of the method is the low use of time-consuming and cost-intensive engine test benches (Fig. 3), since statistical test planning and simulation tools are already used in the test planning phase.

A comprehensive method to assess synthetic and alternative fuels in diesel engine operation is available by using precise cylinder pressure measurements and a subsequent thermodynamic analysis of the engine process as well as the extensive measurement of gaseous and solid emissions.

In addition, we are working on a research project to adapt engine controls to changing fuel qualities by means of specifically developed control and regulation functions in free control units based on fuel data (Fig. 4).

Fig. 3: Single-cylinder test diesel engine

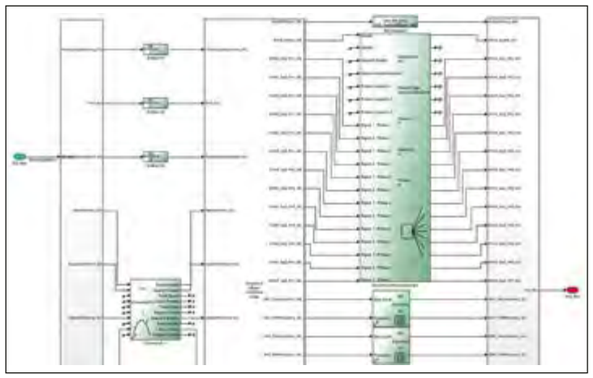

Abb.4: Overview of the injection model at the functional level

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Implementation of a test procedure for evaluating pre-filtration technologies for the treatment of drinking water from surface waters

The German Armed Forces need rapidly deployable water treatment systems to ensure the reliable availability of drinking water in all operational scenarios. Our research results provide the basis for a reproducible test procedure for assessing pre-filtration technologies for mobile water treatment plants with regard to their readiness for use in the field.

While stationary water treatment plants can be specifically designed for the existing conditions of a raw water source, the Bundeswehr needs all-purpose mobile equipment. The plants use the reverse osmosis (RO) principle for the treatment of drinking water of various raw water qualities from crystal-clear water to water from a harbour basin, even in a CBRN environment if required. This technology places high demands on pre-filtration in order to avoid undesired deposits on the RO modules.

The design of mobile drinking water treatment plants is based on the technical requirements in accordance with DIN 2001-3. Borderline cases concerning the contamination of groundwater and surface water to be processed are defined on the basis of inorganic and organic sum parameters. Reliability of the water treatment plant is required.

Highly varying degrees of water pollution with algae, biopolymers and particles pose a major challenge for water treatment.

We examined methods for generating nature-identical test water to assess pre-filtration technologies regardless of the season.

As a first result, we have generated and patented “inorganic particle test water”. It simulates the turbidity of surface waters in a nature-identical manner through the use of suspended test dust from the minerals kaolinite, quartz and iron oxide. A comparison of the particle size distribution of the test water suspension with the values of natural surface waters such as river water, seawater and water from lakes shows that the simulation is realistic.

The patented procedure is now supplemented by “organic test water” which, thanks to extensive research and preliminary studies, can be naturally produced and reproduced from lysed chlorella algae. This test water contains algae cells, cell fragments, biopolymers and humic substances. Ultrasound-based cell disruption (lysis) of microalgae (Laksono 2018) releases the highly molecular organic compounds. In the test water these have filter blocking properties similar to those in surface water contaminated with algae (Fig. 1). Reproducible batches of the “organic test water” can be prepared and used to determine the performance of pre-filtration technologies by means of defined process and test conditions and relevant parameters (Fig. 2).

Topping up the algae lysate (Fig. 3) helps to maintain the organic load even for long-term tests. Thus, a test procedure at pilot plant scale is available for performance testing also of backwashable pre-filtration procedures (Fig 4). In addition, first applications over several days have confirmed the successful applicability of the combined test waters.

Further steps include designing a basin for larger test water quantities and furthering the automation of the test procedure.

Our test method is the first method to facilitate a reproducible assessment of the performance of pre-filtration technologies in accordance with the DIN 2001-3 standard. Particular focus is on future-oriented backwashable pre-filters. This improves our capability to assess pre-filtration technologies and to give advice with regard to the modern technical design of mobile water treatment, which contributes significantly to improving reliable water supply.

Fig. 1: WIS test pond with algae

Fig. 2: Organic test water in a basin with agitator

Fig. 3: Algae lysis container and lysate

Fig. 4: Backwashable plant during testing with organic test water with clear filtrate and backwash basin

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“BundesWEAR“ digital outfitting of clothing

For the digitalisation of the outfitting of clothing to Bundeswehr military personnel, an AI-based image processing system has been created. It identifies soldiers’ body measurements and creates their digital twins. A smartphone app with these functionalities allows automated clothing size allocation. This results in a more effective and efficient clothing management approach.

3D body scanning captures body measures and dimensions. In concert with the usage of an AI-based image-processing system, which deduces body data from pictures or videos, this technology will support the digitalisation of clothing management. This will not only lead to the development of superior fitting clothing but also to more efficient and effective logistical processes. Thorough digitalisation can transform the outfitting of clothing from the currently labour- and resource-intense logistic process towards a more user-friendly and efficient one.

Partnering with BWI, an app was developed. Besides functions such as body scanning, it entails options for managing processes of ordering, replacing, and returning products. The primary body scan is gathered through a short video in which users perform a full rotation captured by a smartphone’s front camera subsequently processed by the respective mobile device. Building on AI-enabled image processing software, calibrated through an anthropometric database, relevant body measures are deduced. This process for the most part is not influenced by the clothes worn during body scanning. Combined with specific personal information of the user, the system is able to leverage captured data to precisely and automatically choose the optimal item of a portfolio (such as required personal equipment) of mass-produced articles. This innovative ordering system (Fig. 1) is named BundesWEAR. It was tested in an extensive experiment at WIWeB in which 63 persons participated (23.8% ♀ and 76.2% ♂) (Fig. 2).

Fit was objectively assessed for ten combat clothing articles in a range of different configurations. During fit evaluation, users had to perform several standardised poses that aim to mimic typical movements of soldiers. Concurrently, all test persons were scanned in a 3D body scanner to validate the body data calculated by the smartphone app. Additionally, researchers of the Bundeswehr University in Munich surveyed and interviewed all test persons in order to collect data on the individuals’ subjective assessments in terms of comfort, acceptance of the BundesWEAR technology, and wearing preferences.

Juxtaposing the calculated body data of the smartphone app with the 3D body scanner measurements indicated that results are equally precise for both genders. 91 % of each individual body zone (such as chest circumference), were measured sufficiently precise to allow for size allocation. However, the algorithm-based size recommendations for men substantially outperformed the results for women (Fig. 3). This is mainly due to the fact that unisex articles worn by both men and women have originally been designed for a male target audience without taking the anatomic specifics of women into consideration. Additionally, one size code for female combat clothing represents two standard size codes which amplifies the clothing’s poor fit for women.

The results have shown that the digitalisation of the outfitting of clothing by means of an app is already possible. The experiment revealed enormous potential for significant improvements of logistical procedures such as providing the armed forces with clothes.

The BundesWEAR system is part of extensive ergonomics and digitalisation research of the System Soldat innovation laboratory at WIWeB. The focus is on paving the way for novel opportunities for developing and distributing clothes through the usage of digital twins.

Fig. 1: BundesWEAR online ordering portal (left in front) – smartphone scan (right in front) – list of the determined body measurements (right in the background) and the automatically assigned clothing sizes (left in the background)

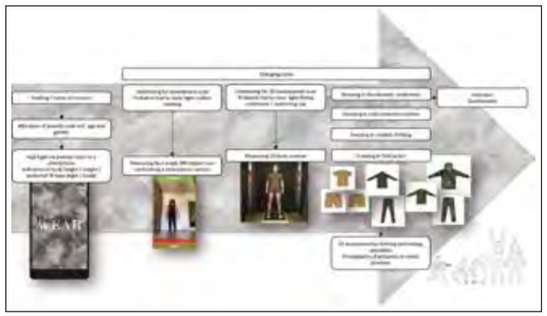

Fig. 2: Experiment schedule

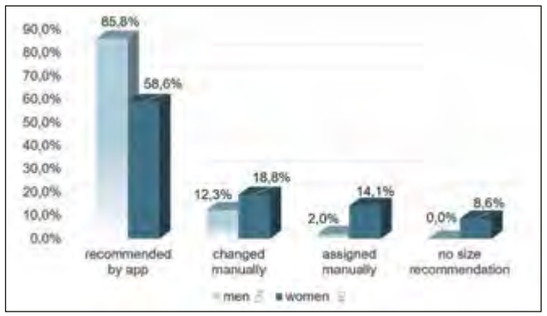

Fig. 3: Automated sizing results (relative frequencies in %)

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Additive manufacturing of ultra-high molecular weight polyethylene

Ultra-high molecular weight polyethylene (UHMWPE) is a high-performance plastic which is used for protective applications. The material properties are significantly influenced by the processing and / or the manufacturing process. The research project will investigate the potential of additive manufacturing processes of UHMWPE for protective applications.

Ultra-high molecular weight polyethylene (UHMWPE) is a plastic with an extremely high molecular weight. Among other things, UHMWPE is characterised by high wear resistance and impact strength. It is therefore suitable for a wide range of applications, e. g. for sliding components in mechanical engineering, implants in medical technology or as a composite material for ballistic protection.

Due to its high molecular weight, UHMWPE has a high (melt) viscosity, which makes it difficult to process by injection moulding or extrusion. Therefore, UHMWPE is mostly pressed into semi-finished products, such as blocks or rods, and then mechanically processed. Fibres made from UHMWPE are produced by gel spinning, for example, and then further processed. The manufacturing process and the process parameters used have effects on the morphology, i.e. the orientation of the molecular chains, and significantly influence the material properties.

An alternative for processing UHMWPE would be additive manufacturing, which would result in enormous freedom,

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especially in terms of geometry. The investigation of additive manufacturing processes and the evaluation of the associated printed products as well as the material properties are a research project at the Bundeswehr 3D Printing Centre at the Bundeswehr Research Institute for Materials, Fuels and Lubricants (WIWeB). As part of this project, different raw materials (e. g. powders, pellets and fibres) and their processing are being assessed (Fig. 1). The aim is to develop knowledge about the specific material properties and the influences of process parameters and to evaluate the potential for protective applications.

In addition to commercially available fibres, powders and granulates of pure UHMWPE with different average molecular weights, pre- and post-treatment options are also being investigated, such as physical pre-treatment with decalin.

As a basis for filament-based processes and to assess an extrusion process, we produced our own filaments by using an extruder. By varying the parameters during extrusion, the properties of the UHMWPE filaments were significantly changed. The strength of the filaments already was increased by up to 50 %, with individual (positive) outliers with an increase of up to 215 % showing that an even greater change in the material properties is possible (Fig. 2 and 3). To investigate additive manufacturing processes, initial process parameters for Selective Laser Sintering (SLS) and Fused Filament Fabrication (FFF) processes were experimentally determined. Tensile specimens were fabricated and tested to evaluate the mechanical properties (Fig. 4).

First results clearly show that the processing procedures and parameters influence the morphology of the plastic and its properties. We successfully processed UHMWPE using additive manufacturing at the specimen level. We therefore think that use in the field of protection is possible, but further research is required and will be pursued in the project. For example, the individualised production of ballistic protection plates or the production of (shape-)adapted protection structures in field camp construction would be conceivable.

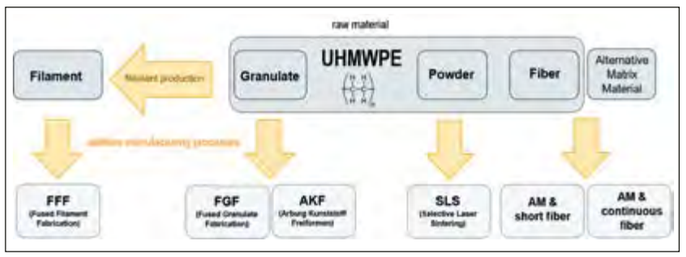

Fig. 1: Schematic representation of the raw materials and additive manufacturing processes under assessment

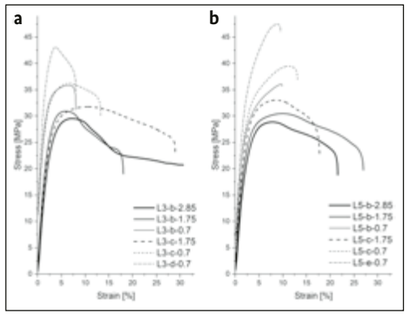

Fig. 2: Stress-strain diagrams of representative filament samples of UHMWPE, prepared from granulate, with an average molecular weight of 0.9 x 10^6 g/mol (Fig. a) and with an average molecular weight of 2.3 x 10^6 g/mol (Fig. b)

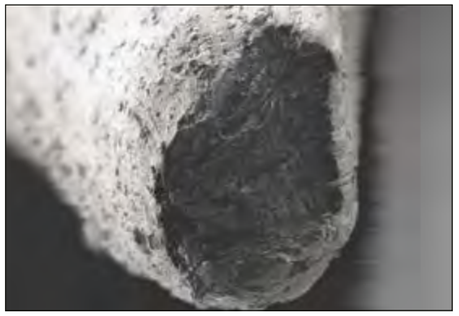

Fig. 3: Fracture surface of a filament made of UHMWPE with increased strength (SEM image, voltage 0.805 kV, working distance 2.1 mm)

Fig. 4: Creation of a tensile specimen of UHMWPE using FFF

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The Engine Mission Simulation System: Engine simulation within the virtual flight mission

In designing future aircraft, the entire system including airframe, propulsion system, energy management and mission control must be considered in a coupled approach at an early stage. The Engine Mission Simulation System allows parallel simulation of the propulsion and power supply system of the aerial vehicle in a virtual mission. This facilitates the development of innovative technologies as well as their quick and cost-effective evaluation.

Especially for unmanned aerial systems, the development cycles are constantly shortening, while the requirements of the armed forces for the aircraft are increasing. To be able to simultaneously develop and evaluate the increasingly complex, novel technologies quickly and efficiently, the concurrent assessment of the flying platform with its propulsion and energy system as part of several representative missions is necessary. For this reason, the Institute of Jet Propulsion at the Bundeswehr University in Munich, together with the Bundeswehr Technical Centre for Aircraft and Aeronautical Equipment (WTD 61), is developing a multidisciplinary simulation framework for the investigation and evaluation of the propulsion and power system of flying systems.

The basic program structure of the Engine Mission Simulation System (EMSS) is shown in Fig. 1, including the most important data connections. In order to be able to exchange or extend individual software parts or replace them with hardware in the future, special emphasis was placed on modularity. By using a variety of software such as NPSS, MATLAB/Simulink® or X-Plane 11, a multitude of interfaces are available, which allow the efficient use as well as the easy further development of the software.

We mostly use models of unmanned aerial vehicles in the range of up to two tons maximum take-off mass as virtual research platforms in EMSS, as shown in Fig. 2. In order to be able to verify or calibrate the physical representation of these aircraft in the EMSS, we use numerical flow solvers to perform calculations at exemplary points in the flight envelope. The result of such a calculation is shown in Fig. 3, where on the surface of the aircraft the pressure distribution is plotted in black and white, while in the cutting plane in the symmetry axis of the UAV the Mach number distribution is shown in colour.

Currently the EMSS is already being used for various investigations focusing on integration aspects of the propulsion system and its energy management. Regarding the propulsion integration into an existing aircraft, the effect of inlet disturbances on engine performance and intelligent nozzle design are of particular research interest. To investigate inlet disturbances, the institute relies on its many years of experience in experimental and numerical investigation of aerodynamic phenomena in highly bent inlet systems. A typical disturbance pattern of such an engine inlet is shown in Fig. 4. This extensive database is transferred to the EMSS via dimensionless parameters, where its influence on the propulsion and thus aircraft performance is investigated in various flight conditions. At the same time, research is also being conducted at the other end of the engine. Building on detailed CFD analysis, the influence of fluidic thrust vectoring systems on both trim drag and the impact on the propulsion system is examined in the EMSS.

The EMSS provides time-resolved data of the propulsion system, the flight condition and the aerodynamics for all simulations. Based on this data, conclusions can be drawn about the performance and possible areas of application of a technology at an early stage of development at any time during the flight mission.

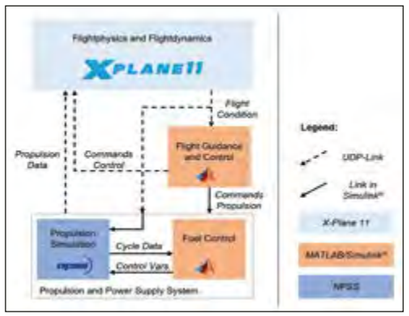

Fig. 1: Programme structure of the Engine Mission Simulation System

Fig. 2: Rendering of a study of an Unmanned Propulsion and Energy Research Aircraft

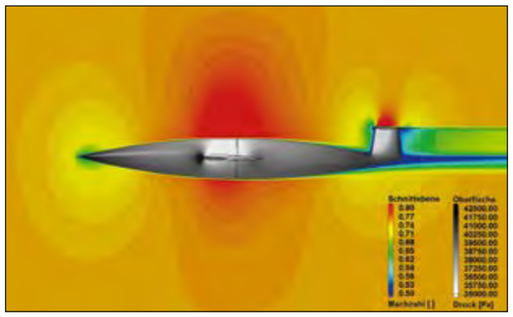

Fig. 3: CFD simulation of a simple UAV design

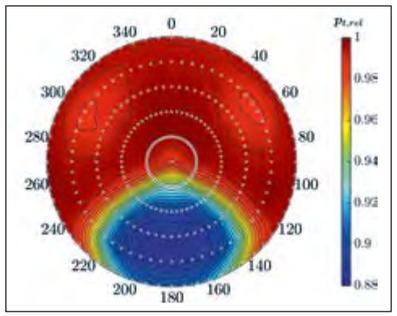

Fig. 4: Typical pressure distortion pattern at the engine inlet plane after a bent inlet

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Parametric estimation of power spectra for the analysis of hydroacoustic time series

Time-resolved recordings of sound propagating in water provide hydroacoustic time series, the analysis of which plays an important role in maritime reconnaissance or in the operation of sonar systems. At WTD 71 a class of modern algorithms for time series analysis, known as "state space modelling", is employed and further developed, which allows improved estimation of the power spectrum.

While electromagnetic waves in water only propagate to a very limited extent, acoustic sound waves can do so over much greater distances. Therefore, the measurement and recording of hydroacoustic signals by means of appropriate sensors (hydrophones) is suitable for passive military reconnaissance, as well as for underwater communication. Even when operating active sonar systems, there is a need to analyse and filter the recorded time series. Hydrophones may be employed individually, for example in data recording buoys, or as drifting or towed arrays.

As a result of recording sound in water, time series are obtained; if several hydrophones are used within a horizontal or vertical array, beamforming can be used to focus on certain specific spatial directions. An individual hydrophone records all sound sources in the vicinity, including surface and underwater vessels, but also marine mammals and weather effects.

Time series nowadays are collected and analysed in many disciplines of science; time series analysis has matured into a separate field within statistics. Various algorithms for analysing time series have found widespread application, such as the estimation of power spectra by means of the Fourier transform, by which the power contained in the time series is represented as a function of frequency. For time-varying time series, a time-dependent estimation of the power spectrum can be carried out, the result of which is called a spectrogram. If in a spectrogram the broadband background is removed so that only narrowband components (lines) remain, this is called a lofargram.

Modern algorithms for time series analysis employ a parametric modelling approach instead of the Fourier transform; a very powerful class of parametric models is known as "state space models". The Centre for Waterborne, Structure-borne and Airborne Sound at WTD 71 is working on the development of corresponding modelling algorithms and their application to hydroacoustic time series. As a result of such modelling, parametric estimates of the power spectrum are obtained.

Research into algorithms for time series analysis also includes the generation of suitable data sets during experiments at sea. In such experiments, for example, a research vessel sails on a specific course past a deployed recording system, in order to be able to investigate the range of components of signatures (Fig. 1).

As an advantage of spectral estimation by means of parametric modelling, we mention improved noise suppression (Fig. 2), which increases the detectability of weak signals. Furthermore, in appropriately structured state space models, it is possible to separate and reconstruct individual components from signal mixtures; this is also possible for components with time-varying or poorly defined frequency. Following the separation of components, selective filtering is also possible. As an example, Fig. 2 (lower panel) shows the result of parametric estimation of the power spectrum of a time series recorded during the passage of a research vessel past a deployed recording buoy (Fig. 1): The blue line shows the entire power spectrum, while the red line shows only the part of the spectrum that is generated by the line comb of the ship's diesel engine, with a line spacing of 15 Hz.

Because in a state space model the properties of the components, such as the main frequency, are explicitly represented by model parameters, parametric lofargrams can be generated directly from these models; these can be used to track selected components of signatures. An example is shown in Fig. 3.

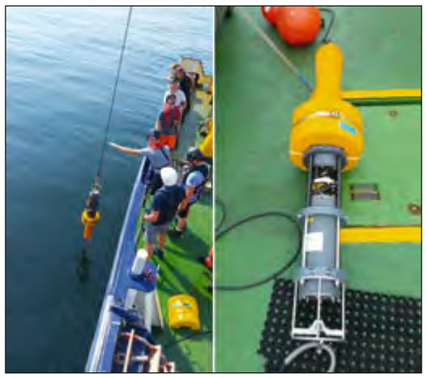

Fig. 1: Recording buoy, produced by Jasco Applied Sciences Ltd., with single hydrophone (right); deployment of buoy from research vessel ELISABETH MANN BORGESE (left)

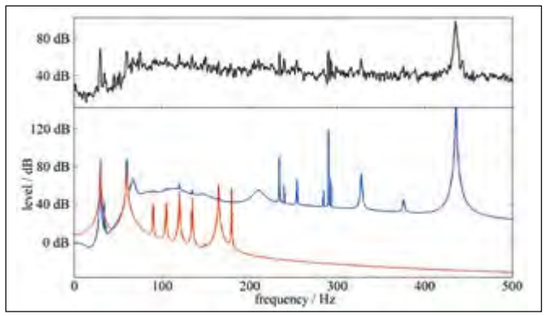

Fig. 2: Example for the estimation of the power spectrum of a time series, recorded by a buoy deployed in the Baltic Sea, which contains ship lines of RV ELISABETH MANN BORGESE, using Fourier transform (upper panel, black), and using parametric state space modelling (lower panel, blue); in the lower panel the portion of the power spectrum generated by the ship diesel's line comb is shown (red).

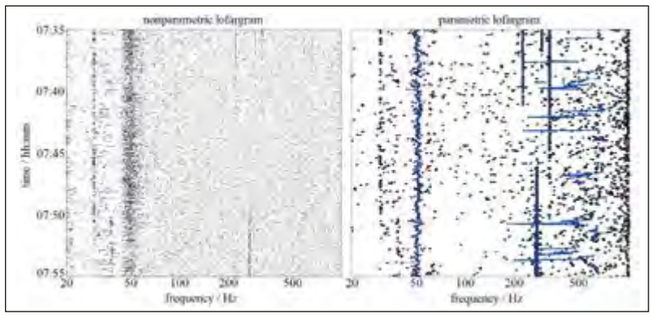

Fig. 3: Conventional (non-parametric) lofargram (left) and parametric lofargram (right), for a 20-minute time series, recorded by a buoy deployed in the North Sea. The visible signature lines belong to two ships, including RV ELISABETH MANN BORGESE.

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Demonstrator for simulating bistatic and multistatic anti-submarine warfare

The prediction of acoustic probabilities of detection is essential for Anti-Submarine Warfare (ASW). This is done by simulation programs for sonar performance analysis which compute sound propagation for a given scenario. Modern ASW employs bistatic or multistatic methods, where transmitter and receiver are spatially separated. This leads to new challenges for the simulation.

Because of their longer range under water, ASW uses sonar systems based on sound waves instead of electro-magnetic sensors. With a simulation program for sonar performance analysis, the probability of detection for a given scenario can be calculated. This means that it is possible to determine whether a hostile submarine is detectable within an area around the own ship. Vice versa, it can also be determined whether own units can be discovered by a hostile ship.

Modern ASW is often done jointly as a group. For the detection of a hostile submarine (target) via an actively sent sonar ping, the transmitter of the ping and the receiver of the ping reflected by the target are not necessarily on the same unit. This is called a bistatic or, if more than two units are involved, multistatic scenario. Therefore, to predict probabilities of detection, the simulation programs have to be capable of computing sound propagation in these scenarios, too.

For monostatic scenarios, the Navy uses the German simulation program MOCASSIN (Monte-Carlo Schallstrahlen Intensitäten), maintained and further developed at WTD 71, for the sonar performance analysis. Due to the large quantity of single calculations, an extension to bistatic and multistatic scenarios poses higher demands on computational power and on the graphical presentation of the results. Furthermore, more sophisticated models are needed for bistatic scattering at boundaries and for three-dimensional target strength (reflection properties of the target). This requires the development of a new simulation program. Within a demonstrator, the concept of a web-based approach, facilitating a separation of model server and application client, and a suitable graphical presentation of the results are being examined.

To this end, the FORTRAN core model of MOCASSIN was taken apart, modernised and new components were added. This C++ program library for all computations necessary for a multistatic scenario, together with the GUI (graphical user interface) backend, runs on a high-performance model server. It is accessible via a website in a browser on an undemanding client device.

In addition, the demonstrator contains a database server which provides environmental data such as water depths, sediment properties and sound speeds which are required to compute sound propagation. To this end, a PostgreSQL / PostGIS database with data available freely on the internet from EMODnet and Copernicus was chosen as a first step. Later on, this will be replaced by classified Navy databases, if applicable.

The third component of the demonstrator is a local tile server for providing map data (e.g. based on Open Street Map) and overlays (e. g. bathymetry) which in an operational context must be able to work without an internet connection.

Via mouse clicks, the user can place several units at chosen positions. This automatically triggers the computation of sound propagation in range-depth slices around each position. Selecting two units as transmitter and receiver leads to a combination of the individual computations and, by taking ambient noise, bistatic reverberation and target strength into account, yields a prediction of the probability of detection. The results are presented directly on the map for a chosen target depth.

This allows for the user to determine interactively suitable positions and courses with a low probability of detection or to ensure a timely detection of possible threats.

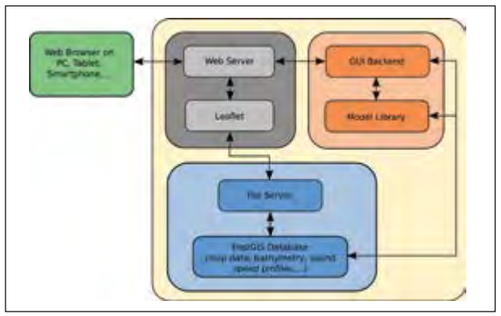

Fig. 1: Concept of the web-based demonstrator for bistatic and multistatic sonar performance analysis

Fig. 2: Screenshot of the user interface in a web browser: presentation of environmental data (here sediment type) as overlay and sound speed profile at the chosen position. The sound speed profile influences sound propagation significantly

Fig. 3: Screenshot of the user interface in a web browser: monostatic acoustic (one-way) propagation loss for several positions

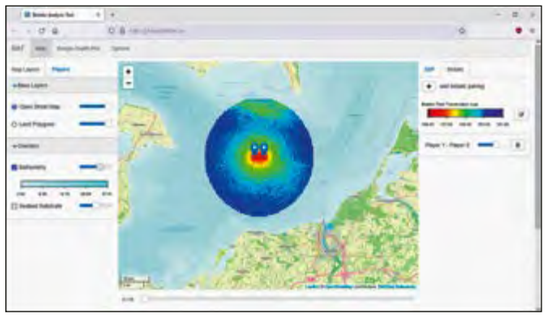

Fig. 4: Screenshot of the user interface in a web browser: bistatic acoustic propagation loss for a transmitter-receiver pairing

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Post-fossil energy management in the Bundeswehr: Bundeswehr-relevant energy storage systems and energy converters for renewable energy

With the Federal Climate Protection Act's entry into force, a reduction of greenhouse gas emissions by 2045 including the replacement of fossil energies is mandatory. This will also concern the Bundeswehr. The aim of the study "Innovative Sustainable Energy Systems" (INES-Bw) therefore is to design the Bundeswehr energy transition with maximum energy security and energy resilience as quickly as possible by means of a scientifically sound strategy.

In the context of the energy transition, the Bundeswehr is also confronted with challenges regarding the energy security and resilience of its properties and mobile systems with their special capability and performance profiles. The increasing share of volatile renewable energies (wind and solar) and the elimination of conventional power plants require the integration of electricity storage systems into the energy grid that compensate for seasonal and circadian generation gaps. In addition, fossil fuels must be substituted by climate-neutral synthetic and biogenic energy sources by 2045.

The net electricity consumption of Bundeswehr properties was most recently around 1 TWh annually, and the heat consumption around 2.9 TWh. Of this, 61 % (electricity consumption) and 11.4 % (heat) were covered by renewable energy sources in 2019 (Fig. 1). CO_2 emissions were 0.82 million tons in infrastructure and 0.63 million tons for military mobility.

Systems for generating and storing renewable electricity from the volatile energy sources of sun and wind represent an option for supplying electrical energy to Bundeswehr properties and are the subject of various projects and studies (Fig. 2). Furthermore, processes and plants to produce climate-neutral, NATO-SFP-compliant liquid fuels were assessed regarding military-specific requirements and needs (NATO Single Fuel Policy).

For short-term electricity storage (circadian or "short-term storage"), lithium and redox flow batteries (RFB) were identified as technologies with the highest potential under military conditions and recommended for practical evaluation.

For longer-term efficient storage (seasonal or "long-term storage"), hydrogen produced by electrolysis followed by methanisation (PtG) is particularly suitable. The methane can be reused for heat generation at Bundeswehr properties. Fuel cells, stationary combustion engines or micro gas turbines offer direct resilient reconversion of the chemically bound energy.

To produce climate-neutral liquid fuels (e-fuels) from electricity, hydrogen, and carbon dioxide (PtL), Fischer-Tropsch systems based on microreactors were assessed; they are already commercially available for lower outputs. Compared to the storage options presented, they have a lower technological maturity and do not yet have the necessary military robustness. Climate-neutral PtL fuels will have to replace carbon-based fossil fuels such as NATO-SFP compliant ones in the foreseeable future, because for many military applications there will be no alternative energy carrier with the required volumetric energy density (Fig. 3).

Results of the study were documented in a digital architecture model to provide a common basis for understanding and comparison. For this purpose, the Bundeswehr modelling framework "Architecture Data Model of the Bundeswehr" (ADMBw) was used. This way, an effective and cost-efficient development of military capabilities is supported (NAFv4).

We would like to thank all partners of the project, in particular the colleagues of the IUD I and IUD II 5 departments at the German Federal Ministry of Defence, the Bundeswehr Research Institute for Materials, Fuels and Lubricants in Erding, the Bundeswehr University in Munich, as well as the Federal Office of Bundeswehr Infrastructure, Environmental Protection and Services and the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support.

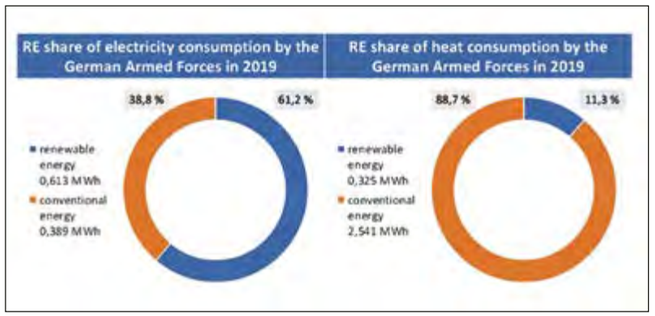

Fig. 1: Share of renewable energies in the Bundeswehr's electricity and heat consumption in 2019 (Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support (ed.) (2019): Bundeswehr Energy Report 2019)

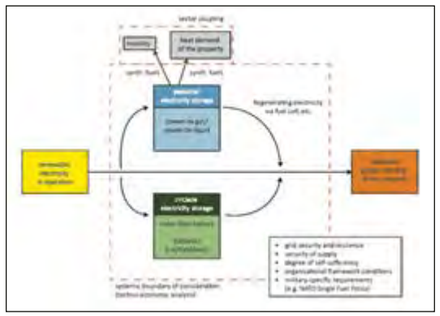

Fig. 2: Building blocks for an innovative energy system of the future

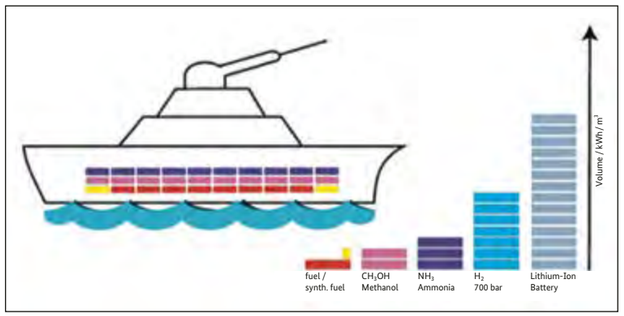

Fig. 3: Space requirements of different energy carrier tank systems on an ocean-going patrol vessel (18 MW main propulsion) (according to Chatterjee, Daniel (2021): Power-to-X a key element of the energy transition. Workshop Rolls-Royce and PlgABw. PlgABw, 05.10.2021)

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Performance-enhanced underwater explosives

Fraunhofer ICT has many years of experience in the development, production, processing and characterisation of plastic-bonded explosives for pressed or cast charges. Specialised mixing technologies and new components are used to produce charges with improved performance and reduced sensitivity, for underwater applications.

Underwater explosives are used for a variety of purposes, including countermeasures against mines. Previously, active charges based on trinitrotoluene (TNT) predominated, such as the SSM TR 8870 explosive used by the Bundeswehr. However, these can now be replaced by plastic-bonded charges (PBX) based on ammonium perchlorate (AP) and aluminium, which have a low sensitivity and high performance.

To achieve the required reaction of the explosive charge under water, sufficient oxygen must be available for the detonation reaction. AP is used in the formulation as an oxidiser, i. e. AP can release oxygen during a reaction. The use of the new oxidiser ammonium dinitramide (ADN) is a promising development in underwater explosives. Unlike AP, ADN does not contain chlorine, so no hydrochloric acid can be generated during detonation – it can therefore be considered environmentally friendly. ADN also offers advantages in formulation. It is not only an oxidiser but also an explosive. Depending on the density and formulation, the detonation velocity is in the range of 5000 to 6000 m/s, which is favourable for energy transfer to seawater.

Fig. 1: High explosives for underwater application

Fig. 2: Witness plates from initiation tests

To evaluate the potential use of ADN compared to AP in underwater explosives, thermodynamic data were calculated using the ICT thermodynamic code. Calculations were made for a variety of possible formulations, including the pressure and temperature immediately after the reaction. Furthermore, the detonation velocity and the heat of detonation, which is a measure of the energy released during detonation, were calculated.

This made it possible to narrow down the selection of possible formulations. After checking the compatibility of all the raw materials used, nine formulations were developed based on plastic binder / plasticiser / ADN or AP / hexogen and aluminium. For this purpose, all the components had to be adjusted so that, after the mixing process, a low viscosity of the compound could be achieved despite the highest possible filler content, enabling the mixture to be processed by casting. Fig. 1 shows sample charges with a diameter of 21 mm.

First, initiation tests were used to determine the diameter above which initiation of the explosive charge could occur. If initiation is successful, a hole appears in the witness plate, as shown in Fig. 2. Charges with different diameters were then produced to determine the diameter above which the detonation velocity is independent of the charge diameter. At the same time, a plate dent test was performed to make a relative comparison of the explosiveness of the different formulations. Here, the depth of the dent in a steel block was evaluated, as shown in Fig. 3.

50-mm copper cylinder tests were conducted to evaluate the performance of a formulation. The mixed formulation was poured into a copper tube with a diameter of 50 mm. Using a laser, photonic Doppler velocimetry was then applied to determine the wall velocity of the expanding copper tube during detonation. Based on these experimental data, parameters for an equation of state were determined and implemented in a numerical simulation procedure to calculate different scenarios involving underwater explosives, as a function of ignition depth, charge size, or distance to the target. Compared to reference charges, the results confirm the promising properties of ADN in underwater explosive formulations.

Fig. 3: Results from plate dent testing

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Modern performance determination of explosives

Fraunhofer ICT is the only research institute in Germany to cover all aspects of explosives research. A major focus is on the development of methods for determining the performance and safety for small quantities. The combination of new and established methods covers the entire range – from synthesis in the laboratory to system-related applications.

One of the established methods is the copper cylinder test, in which the expansion velocity of the copper tube filled with explosives is recorded with time resolution using photon Doppler velocimetry (PDV). This uses the Doppler effect (comparable to the frequency change in sound) to determine velocity. The expansion work calculated from this allows the equation of state of the explosive to be determined, which can then be used in simulations for any application. Fig. 1 shows the setup of the copper cylinder test for 50-mm-diameter explosive charges with adapted PDV measurement technology. The cylinder test developed at the ICT combines state-of-the-art measurement technology with an evaluation method developed at the ICT, which allows for the precise determination of equations of state.

In order to better characterise the blast effect of explosive charges, ICT developed a modular lance (Fig. 2) which brings up to three blast pressure sensors to within 1 m of the explosive charge and can also be used in the event of fragmentation. This allows even small charges of 100 g to be characterised with high resolution. The equation of state from the cylinder test also provides an interface between simulation and experiment, as exemplified for a blast pressure curve in Fig. 3.

Fig. 1: 50-mm copper cylinder test

Fig. 2: Pressure lance for incident blast pressure measurement

The determination of the detonation velocity as an essential performance parameter normally requires quantities of explosives in the range of kilograms. Using a method newly developed at the Fraunhofer ICT, validated measurements on an explosive charge with a mass of only 150 mg over a running length of a few millimetres have already been performed. Printed circuit boards are used for this purpose, which form an array of 16 short-circuit contacts, each with a spacing of only 0.4 mm. This allows the determination of the detonation velocity also on detonators and booster charges.

The detonation pressure defines the initial state of isentropic expansion. It can be accurately determined in experiments by means of PDV. For this purpose, a thin metal foil is accelerated by detonation, and the free surface velocity is determined. Using mass and momentum conservation as well as known material parameters of the metal, the pressure on the explosive side – the detonation pressure – can be calculated. Fig. 4 shows the combined experimental setup for detonation pressure determination and detonation velocity measurement for a typical explosive mass of approx. 20 g.

The initiation of explosives by shock waves is a physically complex process for which, depending on the application, it must be known in particular how far the initiation stimulus is from the threshold value (Go / No-Go). For safety barriers in ignition systems, for example, the aim is to ensure that the impulse is not transferred to the main charge in the event of an erroneously triggered ignition. For this purpose, Fraunhofer ICT quantifies the initiation in simulations and by modelling, which is exemplified for the James model in Fig. 5 for two cases (with and without barrier). With a barrier, the threshold is reliably not reached, so that initiation is safely prevented.

In the future, the development of new explosives will continue to require the established methods with high quantities of explosives. The new experimental and numerical methods form a supplement to established procedures that can be used at an early stage of development, which speeds up the process, reduces costs and guarantees optimum effect.

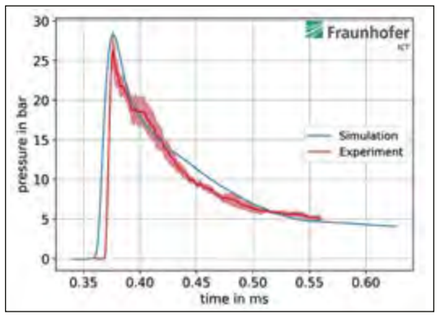

Fig. 3: Measured and simulated blast pressure profile

Fig. 4: Experimental setup for combined measurements of detonation velocity and detonation pressure

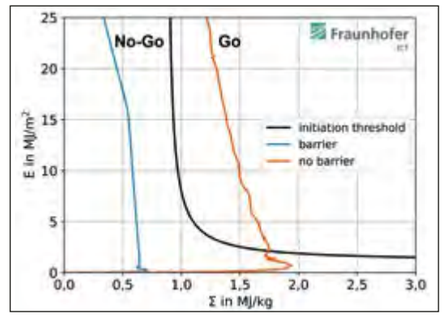

Fig. 4: Initiation stimulus with and without barrier

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Meaningful human control of automation and AI in weapon systems

Novel artificial intelligence technologies, increasing requirements, and demographic changes lead to a growing number of tasks in modern weapon systems being automated and assisted. The consequent and essential question is: despite all this technology, how can a human maintain meaningful control in an environment of intelligent machines?

Motivated by the current worldwide political situation, for example the Russian war of aggression against Ukraine, and pushed by technological progress, the weapon systems of the Bundeswehr are constantly being upgraded and improved. In this, conflicting priorities of fighting power, agility, protection and safety of the own troops and civilians must be considered.

In addition to aspects of increasing the fighting power at reduced manpower, the use of artificial intelligence (AI) and automation and therefore meaningful human control (MHC) play an essential role.

Modern combat systems such as the Future Combat Air System (FCAS) or the Main Ground Combat System (MGCS) are relevant use cases for AI, automation, and MHC in which manned and unmanned platforms will be combined. Fig. 1 shows the use of augmented reality in the Joint Operational Demonstrator for Advanced Appliances (JODAA) of the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support. Smart and loitering ammunition are highlighting a further application of high automation which must be monitored and controlled permanently by a human operator located at a base station.

MHC on the one hand is influenced by situation awareness, usability, and transparency, and on the other by ethical and legal guidelines. Understanding and guiding the precise interplay of these factors is the aim of several scientific research projects and discussions which are in desperate need of national and international coordination.

As part of government-funded research on cooperative movement control as well as within the „Human systems integration for MHC over AI-based systems" NATO Research Task Group 330, the department of balanced Human Systems Integration, together with experts from the US, Netherlands, Great Britain, France, Italy and Germany, has been conducting research on organisation, structure, law, ethics, validation, and verification. In 2022 preliminary results of this military working group were compared with those on the civilian side. They are being published in 2023 in the "Handbook of Meaningful Human Control". Fig. 2 shows the basic model of cooperative control, which adds the cooperation between natural and artificial agents to Boyd's 1995 observe-orient-decide-act (OODA) cycle, but at the same time further develops the signal-detection-theory towards a dilemma model describing cooperative signal detection and action.

Fig. 3 shows that the challenge of MHC is not limited to a single weapon system of crew and AI/automation, but also connects our military personnel and weapon systems with the organisations in charge such as the Bundeswehr and NATO as well as the general society and their political and judicial institutions.

Only an intact and efficient chain of capability, authority, trust, control and responsibility can make MHC over powerful defence systems work.

The next step is the translation of this general model into verifiable requirements which can be utilised for valid and verified future combat systems such as FCAS and MGCS with regard to the MHC aspect, without hindering the efforts to meet the challenges and accumulated demands that have become apparent because of the Russian war of aggression against Ukraine. A first step is shown in Fig. 1, the development and evaluation of novel combat management systems in a demonstrator vehicle, with controllability at the very heart of this activity.

Fig. 1: Left: Joint Operational Demonstrator for Advanced Applications (JODAA). Right: Interior view with augmented reality overlays in the camera-monitor vision system, developed by Fraunhofer FKIE

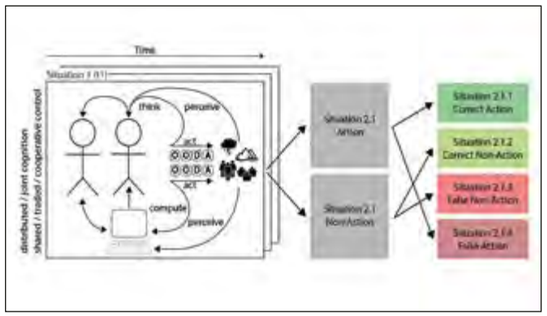


Fig. 2: Joint Signal Detection and Action Model (dilemma model) as a basis for MHC

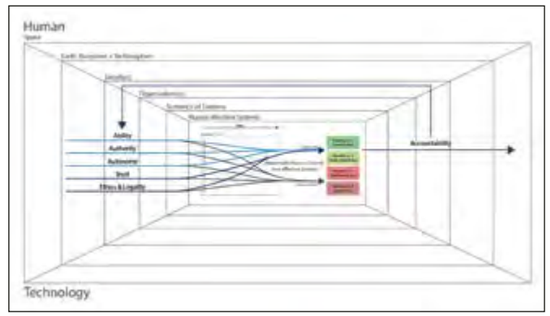
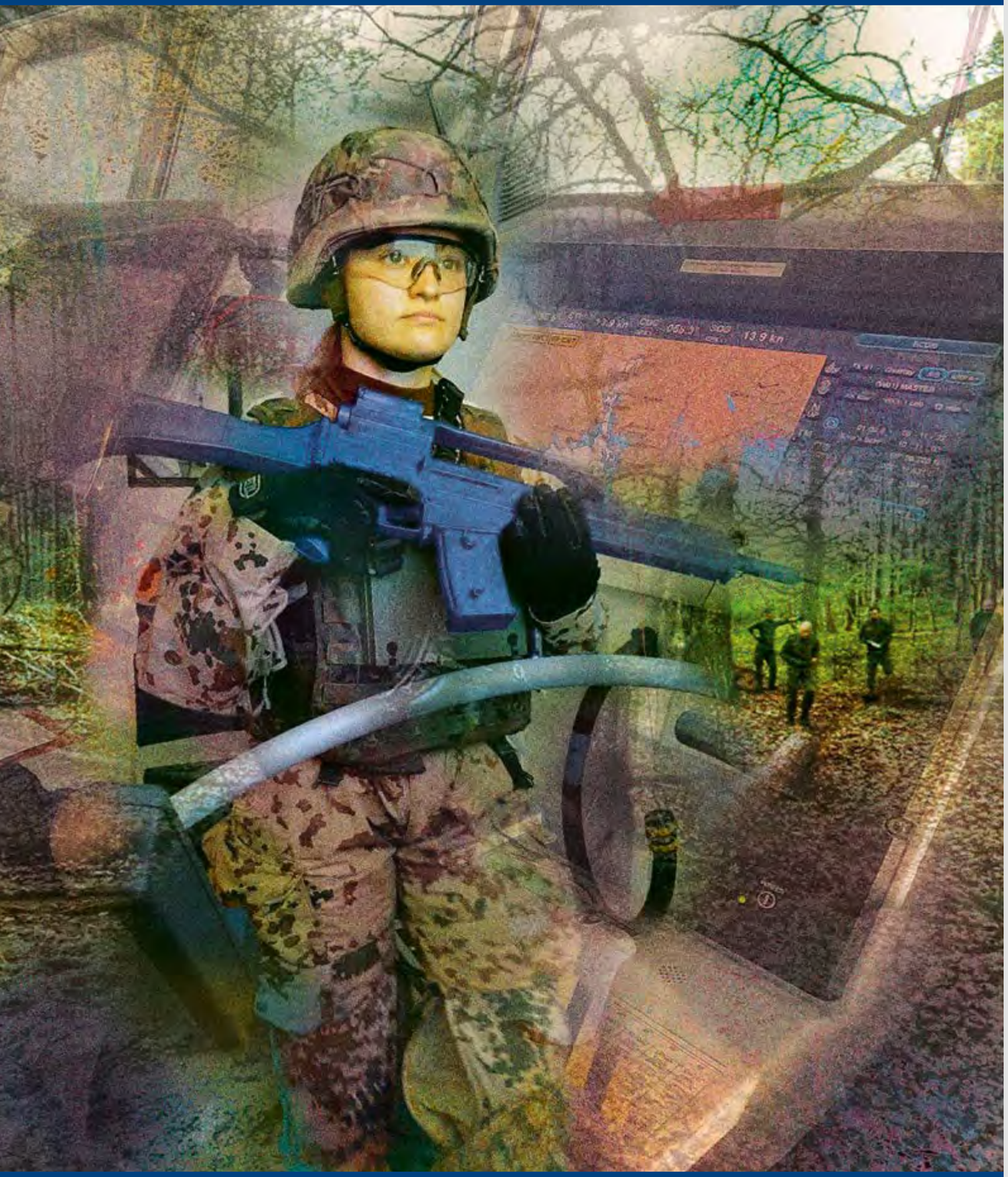


Fig. 3: Holistic bowtie model of MHC



2

Military Medical and Military Psychology Research

In 2022, German security policy underwent a historic watershed moment in the wake of the Russian invasion of Ukraine. This change was also reflected in military medical research. This is apparent in a variety of contributions on CBRN medical defence, the effects of intense stress in military service, the optimisation of emergency medicine and long-term rehabilitation after mental stress or illness.

The Bundeswehr Institute of Radiobiology examined the long-term effects of a nuclear weapons explosion by analysing medical records from the aftermath of accidental exposure to early fallout during the “Castle Bravo” atmospheric nuclear weapons test. The Bundeswehr Institute of Microbiology presents a new diagnostic capability for the rapid detection of *Yersinia pestis* based on receptor-binding proteins of bacteriophages. Alternatives to animal testing methods remain an important focus of military medical research, to which the Bundeswehr Institute of Pharmacology and Toxicology contributes a study on the establishment of human liver spheres and liver toxicity studies.

The Bundeswehr Institute of Preventive Medicine has contributed a study on the dangers of heat stress in protected vehicles and associated challenges and solutions. Unmanned aerial vehicles play an ever-increasing role in current and future conflicts. The Air Force Centre for Aerospace Medicine is conducting an empirical study on the psychological stress and mental health effects among HERON 1 UAS drone pilots, operators and imagery analysts. The Naval Institute of Maritime Medicine presents a trial and evaluation of circadian sea watch systems for the German Navy. The Bundeswehr Hospital in Hamburg is studying the effects of physical and mental stress during combat swimmer training from the perspective of sports medicine and sport psychology.

A number of Bundeswehr hospitals are focusing on emergency medicine this year. The Bundeswehr Central Hospital in Koblenz describes the use of a photon-counting CT scanner in a trauma room setting to optimise the diagnosis of polytrauma patients. The Bundeswehr Hospital in Berlin is studying patient safety in emergency medicine by conducting a risk analysis of latent information loss. At the Bundeswehr Hospital in Westerstede, the Human Extremity Recovery Ordnance (H.E.R.O.) project focuses on limb preservation through ex-vivo perfusion of extremities for successful replantation and transplantation.

In its report on the Research Alliance South, a collaboration between the Bundeswehr Hospital Ulm and the Bundeswehr University Munich in support of future university research into trauma care, the Bundeswehr Hospital in Ulm highlights the potential of the close connection of medical informatics and trauma care.

The Bundeswehr Psychotrauma Centre at the Bundeswehr Hospital in Berlin reports on its evaluation of a medically guided and service-oriented rehabilitation training programme for mental illness aimed at getting soldiers mentally fit back so they can return to service.

Another contribution by the Psychotrauma Centre reports on a longitudinal study focusing on the first occurrence of mental disorders after deployment abroad. As part of the study, soldiers who experienced a critical event while on deployment are compared with fellow soldiers on the same deployment who were not exposed to such an event.

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Rapid detection of *Yersinia pestis* based on receptor-binding proteins of bacteriophages

At the Bundeswehr Institute of Microbiology, viruses that specifically infect bacteria (bacteriophages) are utilised to detect highly pathogenic bacteria. For the rapid microscopic detection of *Yersinia pestis*, the causative agent of plague, receptor-binding proteins of these phages are biotechnologically produced in the laboratory and used as probes for fluorescence microscopy.

Plague is the highly contagious infectious disease caused by the bacterium *Yersinia pestis*, which is transmitted between rodents and their fleas. Through fleabites, the pathogen can also infect humans and cause bubonic plague. If the pathogen enters the bloodstream, this can result in plague sepsis and secondary pneumonic plague through infection of the lungs. Unlike other forms of plague, pneumonic plague is also transmissible from person to person via droplet infection. Infected individuals develop primary pneumonic plague, which is usually fatal after a few days if left untreated. Although plague is considered an eradicated disease in Western Europe, natural plague outbreaks continue to occur, especially in the Global South, and pose a risk of infection for soldiers on foreign missions and of spreading the pathogen to Europe. What is more, *Y. pestis* can be used as a biological warfare agent. The plague pathogen thus continues to pose a risk to military operations and public health.

The fulminant course of plague infection can only be countered by immediate antibiotic therapy. This requires rapid and definitive identification of the pathogen. Polymerase chain reaction (PCR), detection of the F1 capsular antigen (usually with rapid assays), and culture-based pathogen identification are considered standard procedures. Alternatively, diagnostic bacteriophages (or phages, for short), i. e. viruses that infect bacteria, can be used to identify *Y. pestis*. Although highly specific, these classic phage assays require pure cultures of the pathogen and thus evaluation of their results may take several days – which is simply too long, especially for diagnosing acute pneumonic plague.

We have thus developed detection assays that take advantage of the high specificity of diagnostic phages but produce results within minutes. For this purpose, we used the receptor-binding proteins (RBPs) of these phages, which are responsible for recognising and binding to the bacterial host (*Y. pestis*).

The proteins are biotechnologically produced as a fusion with a reporter protein and purified. The protein fusions (RBP + reporter) can then be used to detect *Y. pestis* and thus to diagnose plague, as the RBP part of the fusion protein binds specifically to the *Y. pestis* cells and the reporter part generates a quantifiable signal (Fig. 1).

Depending on the combination of reporter protein and RBP, different applications are possible, such as using a fluorescent protein as the reporter (Fig. 2), which allows the binding of RBPs to *Y. pestis* cells to be verified by means of fluorescence microscopy. The specific binding of the RBP-reporter fusions to the cells results in fluorescent labelling (Fig. 3) if *Y. pestis* cells are present in the sample. If not, the protein is washed out. Fig. 4 shows an assay of a sample containing *Y. pestis* cells. Bacterial cells can be seen in transmitted light microscopy on the left, but their shape alone does not confirm *Y. pestis*. When the fluorescence signal of the sample is recorded, however, the red labelling of cells by the RBP fused with the fluorescence protein on the right confirms the presence of *Y. pestis* cells in the sample.

The newly developed assay is highly specific yet easy and quick to perform, with results available in as little as 10 minutes. The method can thus be used for rapid confirmatory identification of *Y. pestis* in order to initiate targeted therapy with antibiotics as soon as possible and thus to improve the probability of survival of infected individuals in a natural outbreak or following a deliberate release of the pathogen.

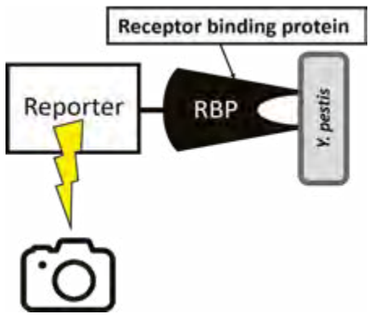

Fig. 1: Application of receptor-binding proteins of bacteriophages to detect *Y. pestis*: While the RBP part of the fusion protein binds specifically to *Y. pestis* cells, the reporter part generates a signal that can be picked up by a detector such as a fluorescence microscope

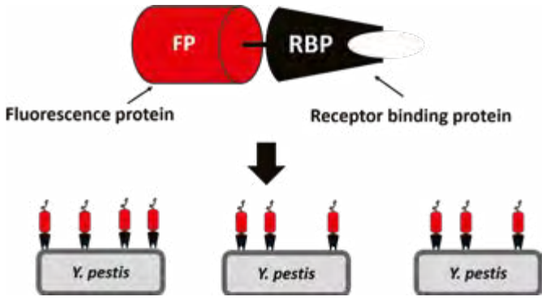

Fig. 2: Fusion of fluorescent protein with phage RBP: A fluorescent protein is used as a reporter protein, which, after being excited with light of a certain wavelength, emits light at a different wavelength. After binding to *Y. pestis* cells, this signal can be picked up by a fluorescence microscope

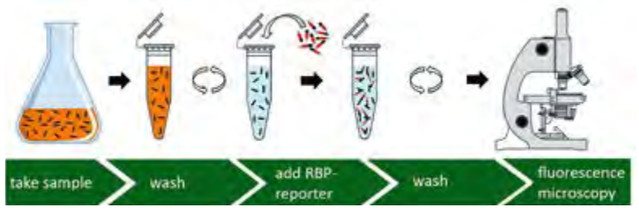

Fig. 3: Schematic overview of the process of testing samples for the presence of *Y. pestis* cells using RBP-fluorescent protein fusions and fluorescence microscopy

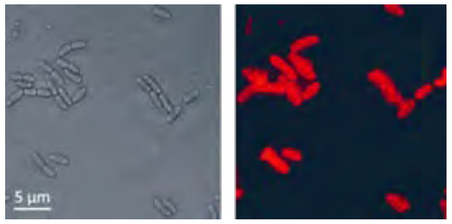

Fig. 4: Typical result of RBP-reporter-based detection using fluorescence microscopy: The RBP-reporter was added to a sample containing *Y. pestis* cells, which was then analysed microscopically. On the left, the image shows bacterial cells in a visible light image. On the right, the image shows the same section of the sample under fluorescent light.

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Alternatives to animal experiments: Studies on hepatotoxicity with human liver spheroids

Human in-vitro models are required to minimise the need for animal experiments. The Bundeswehr Institute of Pharmacology and Toxicology has established liver spheroids to investigate the potential hepatotoxic effect of oximes, a mainstay in the therapy of organophosphorus compound poisoning. Hepatotoxicity could not be determined at therapeutically relevant oxime concentrations.

The liver plays a key role in metabolic processes and adverse drug reactions. Modern pharmaceutical research increasingly provides animal-free methods based on human tissue to achieve better transferability of study results to humans and to reduce animal experiments. Human cells or tissue are cultivated in vitro outside an organism and are exposed to drugs or other substances.

Such three-dimensional tissues consisting of various cell types facilitate the simulation of the effects of different substances or medications on individual organs and allow for an initial toxicological risk assessment.

Treatment with the reactivator obidoxime (Toxogonin®) to treat organophosphorus pesticide poisoning has fallen out of favour due to case reports involving liver toxicity. The potential hepatotoxic effect of obidoxime and three other oximes (pralidoxime, MMB-4, HI-6) was investigated at the Bundeswehr Institute of Pharmacology and Toxicology.

Three-dimensional liver spheroids were produced from the hepatic cell line HepaRG and primary hepatic stellate cells, both of human origin (Fig. 1). Storage methods were optimised to the point that liver spheroids could be stored for up to 72 hours.

Drug-induced hepatotoxicity was investigated with a known hepatotoxic substance (diclofenac) and oximes. Exposure to diclofenac resulted in decreased viability and increased release of the liver damage parameters AST and ALT (Fig. 2 and 3). Our research showed that treatment with obidoxime, if dosed as recommended, does not result in liver toxicity.

Different organ models are currently being established at the Bundeswehr Institute of Pharmacology and Toxicology. Tissue from different organs can be cultivated on a chip in separate compartments connected with microfluidic channels (Fig. 4). Microfluidic circulation is ensured through a micropump and supplies organoids with cell culture medium. Organ-on-a-chip models offer an innovative approach for the study of the toxicity and efficacy of drugs in a more physiological context (Fig. 4 and 5).

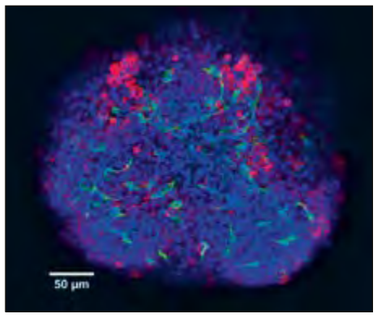

Fig. 1: Immunohistochemical study of liver spheroids: overlay image of cytokeratin 8/18 in HepaRG cells (red), vimentin in stellate cells (green) and nuclear staining with 4',6-diamidino-2-phenylindole (DAPI, blue); scale bar: 50 µm

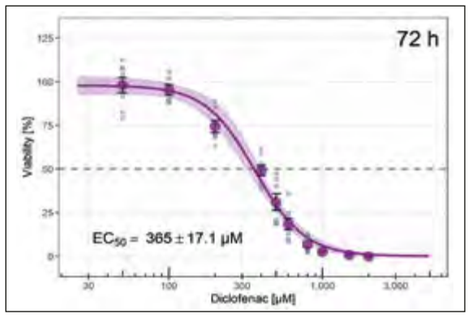

Fig. 2: Cell viability of liver spheroids after diclofenac exposure for 72 h: Viability was normalised to the corresponding solvent controls; data are presented including mean ± SEM (purple circles and black error bars), single data points (blue squares) and 99% confidence intervals (purple ribbon)

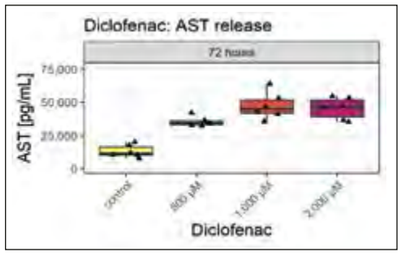

Fig. 3: AST release from liver spheroids after exposure to diclofenac for 72 hours: AST release [pg/ml] after exposure to solvent control, 500 µM, 1,000 µM and 2,000 µM diclofenac; data are presented as boxplots; single data points are shown as black triangles; significance compared to corresponding solvent control, **: p < 0.01 vs. control

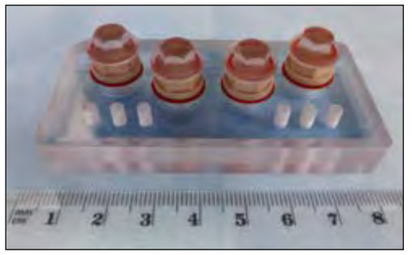

Fig. 4: Multi-organ-chip for the cultivation of two different organ models

Fig. 5: Control unit for the organ-on-a-chip platform

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Heat stress in armoured vehicles: Challenges and solutions

Heat stress poses a significant risk to the health and performance of soldiers. Critical heat stress can occur in protected or armoured vehicles and tanks despite the use of air conditioning. Various complementary solutions are currently being developed for this complex, mission-relevant problem.

Reports from soldiers suggest that significant heat stress can occur despite air conditioning in protected or armoured vehicles and tanks not only in hot areas of operation but also under weather conditions as they prevail in central Europe. The issue is further compounded by the high thermal insulation provided by military clothing and the modular ballistic protective and carrying equipment. Such working conditions can lead to dangerous heat stress as well as critically reduced physical and mental performance during operational training and deployments. Although this mission-relevant problem is not new, published findings on the extent of heat stress in military vehicles are sparse.

In order to develop evidence-based solutions to this complex problem, the first step was to obtain baseline data from technical workplace analyses. In cooperation with the Bundeswehr Technical Center for Land-Based Vehicle Systems, Engineer and General Field Equipment (WTD 41), various protected and armoured vehicles were exposed to desert and tropical climatic conditions in an environmental chamber and the resulting interior climate was measured.

Fig. 1: Examination of the EAGLE V in the climate chamber at WTD 41

Fig. 2: Dummies developed to simulate the heat and moisture emitted by vehicle crews alongside the measurement technology for recording WBGT values

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The previously used test setup was revised to properly account for the hitherto underestimated input of moisture and heat by crew and electrical devices in the different vehicles. The inclusion of these factors is crucial for an accurate physiological evaluation. Specialised dummies were developed in-house to simulate the heat and moisture emitted by personnel during the test runs. Air temperature, relative humidity and thermal radiation are important parameters for evaluating the effect of climate on humans. The effect of these combined factors can be described in climate indices such as the Wet Bulb Globe Temperature Index (WBGT), which allow for a better assessment of heat stress.

Using the revised test setup, WBGT values of up to 37° C were recorded. Heat can already affect physical and mental performance and pose a threat to health at a WBGT of 30° C.

These results prove potentially high heat stress for vehicle crewmembers and highlight the need for preventive countermeasures. The Institute is pursuing several solutions to reduce heat stress in vehicles:

1. Rapidly available technical ad hoc measures (e. g. Barracuda net, tinted vehicle windows) are being tested using the revised setup in cooperation with the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support and with WTD 41.
2. The Institute is currently reviewing a potential change in strategy, away from merely cooling the vehicle interior towards directly cooling personnel. The effectiveness of an air-flow cooling vest is currently being tested in a setup involving subjects on simulated patrols in desert and tropical climates. The garment is worn under the ballistic protective vest with dry, tempered air flowing through it during the simulation in order to promote sweat evaporation as the most effective way of heat dissipation. The concept is based on a body cooling method for full-body protective suits, which was developed and patented at the Institute.

These examples show that this complex problem can only be tackled using interdisciplinary, interdepartmental, and innovative approaches.

Fig. 3: Test subject wearing a bodycooling vest specifically adapted to fit underneath the SK4 vest; the cooling vest was developed and manufactured together with the Bundeswehr Research Institute for Materials, Explosives, Fuels and Lubricants (WIWeB)

Fig. 4: Test subject during the test inside the climate chamber to investigate the effectiveness of the body cooling vest

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Assessment of medical findings after the accidental exposure to early fallout resulting from the Castle Bravo atmospheric nuclear weapon test

An analysis of the medical data of victims of the accidental exposure to early fallout from the atmospheric nuclear weapon test code-named Castle Bravo clearly shows that external irradiation poses the greatest danger. Only in the thyroid was the absorbed radiological dose primarily caused by incorporated radioiodine, with ingestion likely being the primary route of entry.

The bombings of Hiroshima and Nagasaki are examples of nuclear airbursts with many fatalities caused by prompt effects (blast, burns, initial ionising radiation), but they produced little fallout. The nuclear test code-named Castle Bravo on the Marshall Islands (1 March 1954, 15 Mt) caused no casualties by prompt effects, but the inhabitants of the nearby atolls and the crew of a Japanese fishing vessel (Lucky Dragon) were affected by large amounts of fallout within a few hours (Fig. 1). The Castle Bravo case thus permits the study of health hazards resulting from early fallout alone.

The inhabitants of the Rongelap Atoll were found to have been exposed to external irradiation at a dose of 1.6 Gy (threshold for symptoms: 1 Gy). Based on haematological data (Fig. 2) and the METREPOL classification system, their level of acute radiation syndrome can be categorised as “mild” (H1 on a scale from H0 to H4). Blood transfusions or antibiotics were not required and there were no short-term fatalities. The dose accumulated in the thyroid, however, resulted primarily from internal irradiation after radioiodine incorporation and was estimated at 7.6 Gy (Fig. 3). The long-term effects were thyroid abnormalities, including thyroid failure, nodules, and malignant tumours.

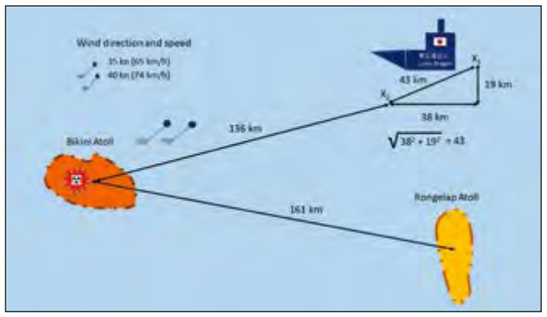

Fig. 1: Simplified map showing the Bikini Atoll (detonation site), the Rongelap Atoll, and the possible positions of the Japanese fishing vessel Lucky Dragon (X1 or X2; different latitudes and longitudes have been given for the ship at the time of detonation): the wind direction from south-west (indicated by the staff parts of the wind barbs) to north-east (indicated by the dot end) and its speed (one long feather: 10 knots) are given for a height of 10-12 km using the standard symbols on weather maps

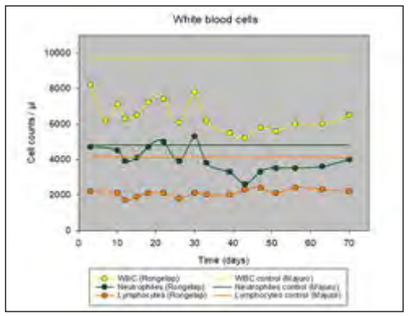

Fig. 2: Time course of the mean cell counts of total white blood cells (WBC), neutrophils, and lymphocytes in the inhabitants of the Rongelap Atoll, who were most exposed to fallout: the first blood samples were taken after evacuation three days after the beginning of fallout exposure (Source: Cronkite et al., 1954; figure adapted from Rump et al., in press)

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The Bundeswehr Institute of Radiobiology owns a database that includes detailed individual clinical and laboratory data from the 23 Japanese fishermen aboard the Lucky Dragon. These men were exposed to fallout earlier than the Rongelap victims and at higher doses (2.9 Gy). The evolution of their haematological parameters over time shows lower blood cell counts and their level of acute radiation syndrome, on average, can be categorised as moderate (H2). The data show remarkable interindividual variability, with clinical severity ranging from no acute effects (H0) to severe radiation injury (H3) (Fig. 4). Victims were treated with blood transfusions and antibiotics. Several developed jaundice. In the 1990s, many surviving crewmen were diagnosed with hepatitis C (likely incurred from blood transfusions) and died from hepatocellular carcinomas. There were no reports of thyroid dysfunction, possibly because the food and water stored on board were not contaminated and / or because the iodine-rich diet typical in Japan confers natural, albeit very limited, protection against radioiodine accumulation in the gland.

One Japanese crewman died six months after the incident, having shown symptoms of subacute liver failure. Autopsy confirmed liver atrophy with inflammatory cell infiltration as well as pneumonia. A radiochemical analysis showed only his bones to be contaminated with fission products. Although the cause of death was not determined with absolute certainty, findings are consistent with liver failure due to transfusion hepatitis rather than radiation hepatopathy.

The Castle Bravo case confirms that, compared with global fallout, early fallout after a nuclear weapon detonation mainly consists of larger particles and is rich in short-lived radionuclides associated with a very high initial activity that decreases rapidly. The main danger results from external irradiation by penetrating gamma radiation, and sheltering is the most important protective countermeasure. Only in the thyroid does internal irradiation prevail. Avoiding contaminated food and water offers the best protection. Thyroid blocking with stable iodine may be a useful additional measure but is definitely of secondary importance compared to sheltering.

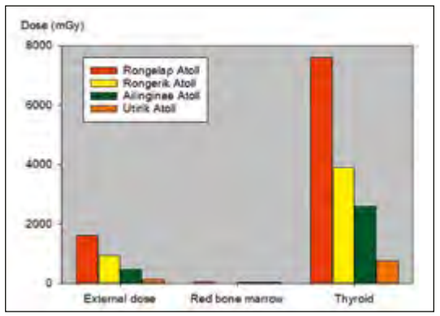

Fig. 3: External and internal radiation doses absorbed by the red bone marrow and thyroid of victims in different atolls of the northern Marshall Islands: the Rongelap Atoll is closest to the Bikini Atoll (site of detonation) and the Utirik Atoll is furthest from it (Source: Simon et al.,2010; figure adapted from Rump et al., in press)

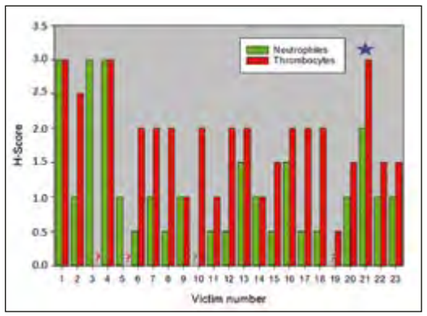

Fig. 4: The severity of acute radiation syndrome expressed as H-score of the METREPOL system based on neutrophil or thrombocyte cell counts in the peripheral blood of the 23 crewmen of the Lucky Dragon: H0: no acute effects; H1: mild; H2: moderate; H3: severe; H4: serious/fatal; where the choice of two classification levels was unclear, the mean was given (H1-H2: score 1.5); ? = available haematological data did not permit clear and final classification; blue star on victim no. 21: short-term fatality who died in September 1954 (Source: SEARCH database)

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Mentally fit to return to duty: Evaluation of a medical and service-oriented rehabilitation training for mental illnesses

The Psychotrauma Centre of the Bundeswehr is evaluating a low-threshold rehabilitation training programme. The programme's methods and content have been adapted based on initial findings. The medical and service-oriented rehabilitation training (MDOR) is already proving to be an effective and efficient rehabilitation module for patients with no or limited fitness for duty as a result of mental illness.

If treatment for mental illness (depression, deployment-associated anxiety disorders, etc.) is protracted, the resulting inability to return to work can affect the recovery process. Long periods of disability leave lead to significantly reduced quality of life, reduced social support and the persistence of psychiatric symptoms. Prolonged inability to work also proves to be a significant obstacle in the provision of further care by medical and psycho-social services. Chronic mental illness accounts for more than 83 % of initiated proceedings to determine unfitness for service and the majority of initiated proceedings to determine service-related disability.

The 23-day rehabilitation training (Fig. 1) for military personnel with mental illness included three core measures such as work-related psychoeducation groups (13 sessions of 120 min each), occupational therapy (8 sessions plus a project day, 10 units of therapeutic physical exercise developed and monitored by sports psychologists, etc.) and additional support measures such as social counselling and individual therapy sessions as well as a joint final project (Fig. 3).

Fig. 1: Schematic overview of rehabilitation modules

Fig. 2: In addition to sport, ergo- and occupational therapy, group and individual and individual discussions, nature-related activities are carried out to promote mental and physical well-being

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The evaluation was based on semi-structured feedback from participants and quantitative information on their fitness for duty (hours on duty per week, number of days of sick leave) as well as psychometric procedures. Data were collected at the beginning (t0) and end of group training (t1). Catamnestic follow-up data were collected 3 (t2) and 6 months (t3) after the intervention.

The average number of days of sick leave decreased significantly between t0 and t2, from 30.1 before training to 11.8 days at follow-up ($Z: -2.511$, $p = .012$). The average number of hours on duty per week increased significantly between t0 and t2, from 15.6 hours before to 21.3 hours three months after training ($Z= -2.805$, $p = .005$). There were signs that vocational rehabilitation training in the Bundeswehr is a useful addition to an overall treatment plan. In addition to increased hours on duty and decreased days of sick leave, there were also positive developments in terms of increased confidence with regard to successful reintegration into the service, improvements in daily structure, increased service satisfaction and increased self-esteem.

Based on the experiences of the pilot study, a research programme with three main focus areas was developed. The modified rehabilitation training is currently being evaluated in a controlled, standardised main study. In an additional project, the measure will be adapted into a basic module that can be implemented at the regional medical treatment facilities of the Bundeswehr Medical Service. Qualitative interviews and focus groups are already being held to collect data on the needs of patients and caregivers in the context of interdisciplinary patient-centred rehabilitation teams (IPR) in order to make future rehabilitation measures even more practice-oriented and user-specific.

Fig. 3: Almost daily sports training also serves to promote the participants' individual basic skills (IGF). The "Battle Rope" exercise shown here promotes strength, endurance and coordination

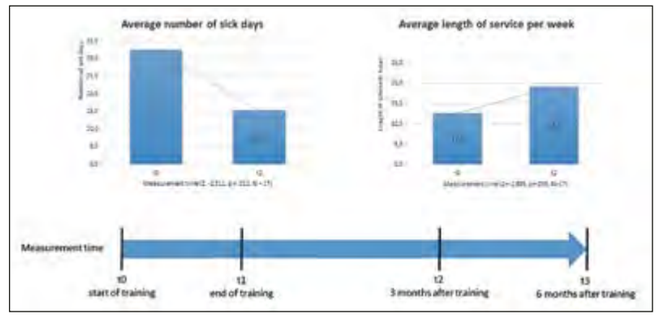

Fig. 4: Initial results of the evaluation show significant effects on fitness for duty and time spent on duty

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Mental health of German UAS HERON 1 drone pilots, operators and imagery analysts: An empirical study

The ability to conduct image-based reconnaissance is a vital requirement for gaining information to compile a current situation picture. From a perspective of military psychology, both the work situation of the military personnel deployed for this purpose and the psychological stress that results from this type of work are relevant for the early detection, prevention and treatment of resulting mental health issues.

As part of the EU MALE RPAS (Eurodrone) definition study, an analysis of the workplaces of UAS HERON 1 operators and pilots was carried out to acquire specific insights into the design of the future Eurodrone ground control station as perceived by those who will work there. The analysis revealed that mental health assessments of operators, pilots and imagery analysts will also be necessary. This requirement was highlighted by the PTSD commissioner (Post-Traumatic Stress Disorder) of the Federal Ministry of Defence and implemented in the present study in accordance with a directive from the Surgeon General of the German Air Force (Fig. 1).

A total of 131 participants took part in the survey, which corresponds to a response rate of 41 per cent, with 125 complete data sets included in the analysis. The sample consisted of 92.4 % male and 7.6 % female participants. Of these participants, 26.4 % were pilots, 27.3 % were tactical operators and 45.5 % were imagery analysts (Fig. 2).

The survey was conducted as an empirical cross-sectional study, which participants completed in an online format on their work computers. For this purpose, established and validated psychological questionnaires were used to collect data on somatoform disorders, psychosocial stress, depression, anxiety / panic disorders, substance abuse (specifically alcohol), post-traumatic stress disorder and adjustment disorder, which were then subjected to quantitative (closed formats) and qualitative (analysis of responses to open question formats) evaluation. The results of the study show that the sample exhibits a significantly higher stress level overall than the average German population, with imagery analysts most severely affected out of all three groups.

The majority of pilots in the study are affected by psychosocial stress (Fig. 3), as are operators, albeit to a significantly lesser extent. Operators are more often at risk of substance abuse, however (Fig. 4). Imagery analysts, on the other hand, exhibit high rates of psychosocial stress, somatic symptoms and depression (Fig. 5). The present study cannot provide information on any causal relationship between these mental health issues and the work of UAS HERON 1 pilots, operators and imagery analysts, although our analysis of free-text responses to open questions revealed tendencies towards certain occupational and psychosocial stress factors, including psychosocial and familial factors such as separation, health issues, conflict within the family or workplace as well as financial problems. Employment-related factors primarily involved dissatisfaction with the work environment and the work itself (27.9 %) as well as problems in coping with deployment experiences (19.9 %). Placing these results in the context of general military stress in the Bundeswehr would require a sufficiently large control sample, which is currently not available.

Overall, the study provides a significant contribution to the evaluation of psychological stress and its impact on German UAS HERON 1 personnel and thus highlights opportunities for prevention and general improvements.

Fig. 1: Research into UAS HERON 1

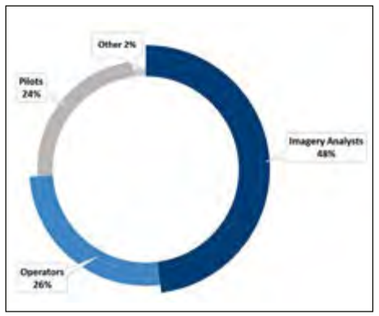

Fig. 2: Sample composition

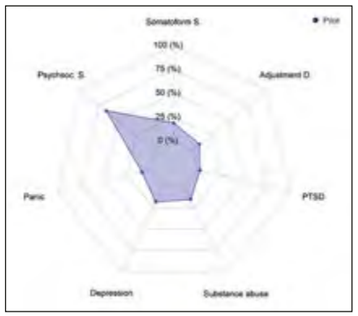

Fig. 3: Stress profile of UAS HERON 1 pilots

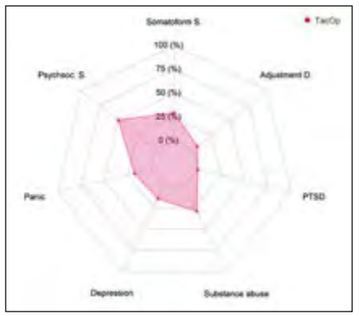

Fig. 4: Stress profile of UAS HERON 1 operators

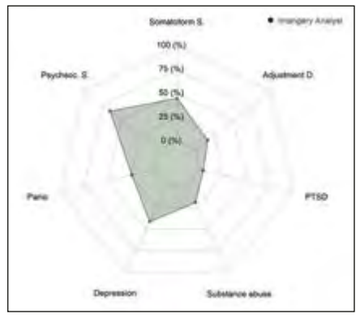

Fig. 5: Stress profile of UAS HERON 1 imagery analysts

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Testing and evaluating circadian sea watch systems for the German Navy

The Naval Institute of Maritime Medicine in Kronshagen aims to soon serve as a central competence centre for advice on watch scheduling and fatigue management. Since 2021, intensive research efforts have been made to be able to show how watch systems optimised to match the circadian rhythm can affect the performance and regeneration of crews aboard naval units.

Some of the watch systems currently used in the German Navy do not reflect the current state of knowledge about the human circadian rhythm nor current guidelines for the design of watch systems. The German Navy is thus conducting tests to study traditional watch systems and optimised systems that reflect guidelines for circadian-based watch systems. The systems, which consist of two, three or four shifts, are compared in terms of how they affect the well-being, sleep and performance of crews. The primary question regarding two-shift-systems is whether an improvement in well-being and performance can also be achieved with waking and resting periods that are shorter than eight hours. For the three-shift systems, the focus will be on the advantages and disadvantages of rotating vs. fixed wake and rest times.

Study participants wear actigraphs on their wrists to monitor their physical activity and thus their waking and sleeping phases during the experiment (Fig. 1). Subjective sleepiness and fatigue are assessed with standardised questionnaires. Vigilance, defined as the ability to reliably detect and quickly respond to a stimulus that occurs at an unknown time, was assessed using a three-minute psychomotor vigilance test. The test was integrated in and administered through the actigraph (Fig. 2) and conducted at the beginning and end of each watch.

Two different watch systems were tested as part of a special research project aboard the minehunters DATTELN and FULDA in the Baltic Sea from 4 to 23 February 2022. The traditional watch system used by German minesweepers was compared with a circadian-based watch system optimised to reflect the current state of research (Fig. 3).

In the standard watch schedule of minesweepers, there is a change of watch every six hours, starting at midnight. The new watch cycle allows for longer sleep phases and for both watch sections to get periods of sleep during the night, which is when sleep is most restorative. Both units participating in the study followed the same mission profile in the same sea area of operations but with different watch systems. After one week (during a stay in port), the two units switched the watch systems and the experiment continued for another week (Fig. 4).

The concluding survey showed that some crew members felt more rested and were more productive during the day while on the circadian-based watch system. In the end, 42 % of participants favoured the new circadian-based watch system.

The actigraphy and vigilance test data are currently being evaluated. Whether the participant's subjective perceptions and assessments concur with the objective data thus remains to be seen.

Fig. 1: Participant wearing the actigraph over his uniform

Fig. 2: Conducting the 3-minute vigilance test with the actigraph

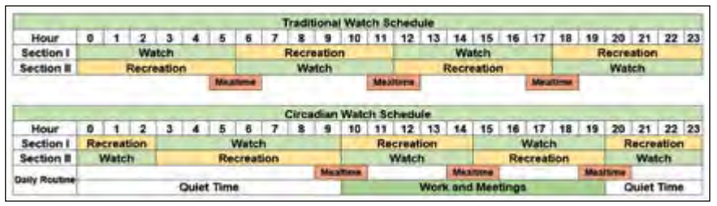

Fig. 3:
Top table: traditional watch cycle (6-6-6-6 change of watch, starting at midnight)
Bottom table: circadian-based watch cycle (7-5-5-7 change of watch, starting at 3 a.m.)

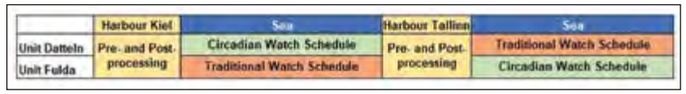

Fig. 4: Test setup for studying the 2-section watch system aboard the minesweepers FULDA and DATTELN

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Patient safety in emergency medicine: Risk analysis of latent information loss

Loss of information is a known cause of patient harm. In order to identify latent risks of miscommunication in day-to-day work, participants from all areas of emergency medicine were interviewed. Based on the results, adaptations are being evaluated in order to use the NATO 9-line MEDEVAC request as a possible template for safe communication in a civilian setting.

Although critical incident reporting systems (CIRS) and work process analyses can help identify and address incidents, they do not sufficiently meet the various information needs of the different emergency care professions and cannot identify organisational problems or imbalances between professions. As part of the study, group interviews were thus conducted with 39 participants from pre-hospital and in-hospital emergency care (Fig. 1) to evaluate situations and working conditions in which information loss may occur. Causes of failures to follow proper procedure for safe information transfer were also evaluated. The ultimate aim was to determine whether the NATO 9-line MEDEVAC request (Fig. 2) could be adapted to create a civilian reporting format for structured information transfer and resource requests, which is currently lacking in civilian prehospital emergency care. The aim of the study was to identify latent patient hazards in everyday work in order to adapt training and care structures and to improve communication across care professions.

Participants were recruited specifically from areas with a high information density. They included both physicians and non-physician employees of a military emergency department and the ambulance service (civilian and military participants), medics of specialised police forces and staff of a civilian emergency dispatch centre. All participants had to have received training in specific communication and handoff techniques to reduce the risk of miscommunication.

The results of the study suggest that personnel with military training can more confidently apply structured protocols in dynamic emergency response scenarios. The participants in the focus group analysis perceived communication risks that differ from the findings of CIRS and work process analyses. Specifically, the felt that causes of information loss often go unrecognised – existing preventive and training measures for patient safety are either implemented inconsistently in daily practice or personnel is insufficiently trained for their employment in a high-risk environment.

Ten risk factors for information loss were identified and can be subsumed into the following categories: organisational factors (deficits in training / education, interfaces, technical /standardised requirements); factors related to the surrounding environment; interpersonal factors (hierarchy and lack of information); and factors specific to individuals (stress / fatigue, stereotyped thinking, lack of focus, and misjudgement /misinterpretation). Different professional groups cited different main reasons for miscommunication. Paramedics, for example, cited a stressful environment (lack of focus), while nursing staff of the emergency department cited poor interface communication. Any standardised protocol for communicating information from prehospital emergency care and requesting (additional) resources should therefore be intuitive, structured, and easy to implement. It must be able to clearly reflect and communicate special operational situations. A core benefit of using the 9-line design is that information is communicated in a standardised manner. Participants also cited disadvantages to using the protocol in civil emergency care, however (Fig. 3). Various requirements need to be considered in the creation of a protocol: I) content, design, and training requirements; II) critical information relative to the operational region, situation, and information recipient; III) adaptation to special operational situations (e.g. breakdown of communication infrastructure), different medical conditions, and security situations.

Adapted military reporting protocols can serve as a template for civil emergency medical personnel to improve interface communications.

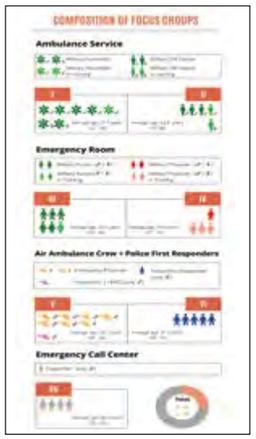

Fig. 1: Composition of focus groups

NATO 9 LINE MEDEVAC REQUEST

1. Location (grid of pic up zone)			
2. Call sign/frequency			
3. Number of patients (by type)			
P1 (urgent - 1 h):	P2 (priority - 4 h):		P3 (routine - 24h):
4. Special equipment required			
A: None	B: Host/winch	C: Extraction	D: Fan
5. Number to be carried laying/sitting			
L (Litter):	A (Ambulatory):		E (Escort, e.g., child):
6. Security at Pick-up Zone			
N: No Enemy	E: Enemy in Area	P: Possible Enemy	X: Hot pick-up zone
7. Pick-up zone marking method			
A: Panels	B: Pyro	C: Smoke D: None	E: Other
8. Nationality/status			
A: Coalition Forces	B: Coalition Civilian	C: Non-Coalition Force	D: Non-Coalition Civilian
9. Pick-up zone terrain obstacles:			

Fig. 2: NATO 9-line MEDEVAC request

Fig. 3: Advantages and disadvantages of the 9-line MEDEVAC request

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The Human Extremity Recovery Ordnance (H.E.R.O.) project: Ex vivo perfusion of human extremities for successful replantation and transplantation

Limb loss has a drastic impact on a patient's life, and extremity trauma is still a major concern in conflicts. The current lack of replantation possibilities and high rates of amputation can be addressed with the development of a portable ex vivo limb perfusion device. Ex vivo limb perfusion can likely be used to overcome critical clinical time limits and enable the development of large-limb transplant programmes.

A 2008 study in the US predicted a 72 % increase in the number of amputations by 2050. The socio-economic consequences of limb loss are considerable. Amputees often experience job loss, financial and social problems as well as depression.

The outcome of replantation surgery varies depending on the cause of amputation, patient condition and the quality of specialist care provided. Recent evidence highlights the advantages of allotransplantation of limbs over prosthetic limb replacement in terms of functional outcome and patient satisfaction.

Replantation is a highly complex microsurgical procedure that requires a high degree of interdisciplinary cooperation in an experienced team as well as specialist aftercare. The first line of treatment is thus limb salvage, although this is not feasible in every case. The technical complexity of surgical treatment is often not the only limiting factor, however, as the short time frames for replantation permitted by cold ischaemic time also need to be kept in mind. The incidence of polytrauma involving life-threatening extremity injuries is increasing. Especially

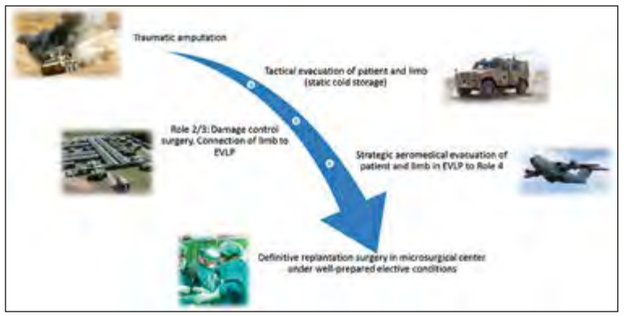

Fig. 1: Potential application of the H.E.R.O. system following a combat injury

in these cases, the strategy of "life before limb" damage control surgery immediately after amputation and during cold ischaemic time affects replantation rates.

This approach is common in both civilian and military medical trauma care. Treatment of traumatic amputation in the military setting is further affected by the realities of tactical evacuation in combat, which leads to longer cold ischaemic times. The amputated limb is often highly contaminated with debris and dirt. Blast injuries in particular are associated with a high degree of soft tissue trauma and significant loss of tissue. Data from registries and recent studies show that around half of all combat injuries in modern warfare affect one or more extremities. For severe injuries, amputation or limited limb salvage are the only options in a combat surgical setting, as replantation surgery is far too complex and time-consuming under these conditions.

Promising data published recently suggest that ex vivo limb perfusion (EVLP) can be an essential factor in overcoming these challenges. However, all animal studies thus far involved perfusion times of no more than 24 hours, which is too short for the military setting, where longer perfusion periods are highly likely due to the need for strategic evacuation to a Role 4 facility in Germany. In our experience from missions in Afghanistan, the average time between damage control surgery in a Role 3 facility and strategic evacuation to a Role 4 facility in Germany was 48 – 72 hours. Fig. 1 shows a possible use case scenario for the H.E.R.O. system.

The aim of the H.E.R.O. project is to close the current replantation capability gap in military operations, which are associated with high rates of amputation. To this end, a clinically applicable EVLP device is being developed and tested on porcine and human models (Fig. 2). Fig. 3 shows a rudimentary prototype of an EVLP device that is already being used for research purposes. The introduction of EVLP promises many benefits:

- extension of the critical ischaemia time;
- additional options and flexibility for surgeons;
- microbiological treatment options such as high-dose antibiotic and antifungal treatment;
- mitigation or prevention of life-threatening ischaemia-reperfusion injury;
- assessment of tissue function;
- allotransplantation and immune-conditioning during ongoing perfusion.

The successful conclusion of the H.E.R.O. project would provide the Bundeswehr Medical Service with internationally unique levels of tactical and strategic flexibility in the treatment of severe injuries to the extremities. The rates of combat-related amputations would be drastically reduced. In civilian settings, EVLP can pave the way for structured vascularised composite tissue allotransplantation, such as of the hand and face.

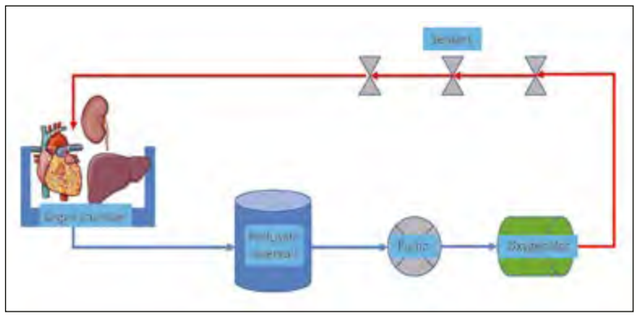

Fig. 2: Schematic overview of an EVLP device

Fig. 3: Clinically applied prototype

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The Research Alliance South: A collaboration between Bundeswehr Hospital Ulm and the Bundeswehr University in Munich on future trauma research

Information technology (IT) and thus computer science have pervaded all areas of life, including medicine. Modern science and research seem unthinkable without IT support. IT is not just an essential enabler in the implementation of research projects but can also be the subject of medical research itself.

The close connection of medical informatics and trauma care offers the potential to increasingly "merge" the two disciplines of informatics and medicine. Simulation in particular is a key aspect that will play an important role in the Research Alliance South. The supporting pillars of the Research Alliance South are clinical trauma research at the Bundeswehr Hospital in Ulm and medical informatics teaching and research at the Bundeswehr University in Munich (UniBw M) (Fig. 1). The goal is to become involved as equal partners in the yet to be established Centre for Multidimensional Trauma Sciences at Ulm University.

In 2020, Colonel (MC) Dr Neuhoff, Colonel (MC) Prof. Friemert, Prof. Dr Hofmann and Dr Melnyk first discussed the idea of a network. They quickly came to an understanding on how expertise in simulation and artificial intelligence (AI) could successfully be applied to traumatological issues. The potential of successfully integrating expertise from the areas of clinical research, AI research and simulation into clinical care provided as part of Bundeswehr health care (General (MC) Dr Backus) and civilian health care was evident.

Fig. 1: Core elements of the Research Alliance South

In the spring of 2021, a working group was thus formed at the Bundeswehr Hospital in Ulm in order to fully digitise the TDSC table-top game so that different training situations involving a mass casualty incident will be available as simulations for operational and civilian training (Fig. 2). The leading institutions in this regard are the hospital's Department of Trauma Surgery and Orthopaedics as a driving partner in clinical care as well as its research management and the Smart Digital Health research centre at UniBw M.

In the area of preclinical research, Bundeswehr Hospital Ulm and UniBw M have also joined forces to work on future projects. A research consortium consisting of both partners as well as two private businesses submitted an application with a starting date of June 2023 on the topic of "Stress resilience through exposure in simulated triage" in response to a call for proposals on "Research for Civil Security" by the Federal Ministry of Education and Research. The aim is to create a demonstrator for the purpose of stress training of doctors and paramedics in preparation for a mass casualty incident and to train the correct courses of action.

A third research area is being established between the Department of Nuclear Medicine at Bundeswehr Hospital Ulm and the Artificial Intelligence Research Group of UniBw M. In this collaboration, AI will be used to better and more quickly interpret radiological imaging after diseases and vitality diagnostics in trauma care.

The Research Alliance South continues to intensify its focus on content and resources. In 2023, three additional research positions will be advertised in the fields of clinical and basic research as patient-oriented areas as well as trauma research using AI and simulation. These positions will be able to build on research collaborations with Ulm University and other institutions. The research area of AI in trauma care will establish and strengthen a research alliance with UniBw M and launch research initiatives with similarly oriented groups at Ulm University.

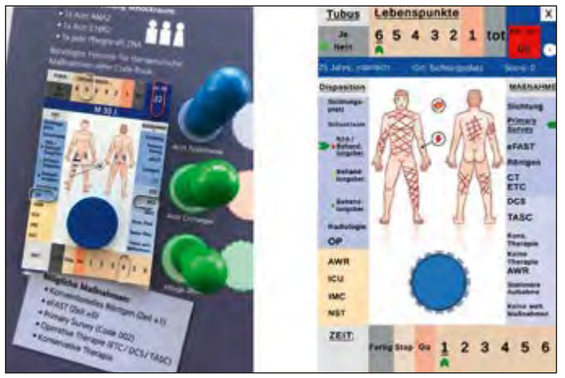

Fig. 2: A patient card from the TDSC® table-top game (left) and the corresponding "virtual" patient card in the electronic codebook (right); images courtesy of Wehrmedizinische Monatsschrift

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Impact of physical and psychological stress during combat swimmer training from a sports medicine and sports psychology perspective

Combat swimmers undergo a physically and mentally demanding training programme. Few candidates apply for the selection procedure and many of them fail. This study is the first to document and scientifically evaluate medical issues relating to combat swimmer training based on chemical analyses as well as psychological questionnaires and physiological measurements.

The Bundeswehr Hospital in Hamburg, the University of Kiel, the University of Hamburg, the Maritime Medicine Section of the Naval Institute of Maritime Medicine in Kiel Kronshagen and the Navy Special Operations Forces Command in Eckernförde are working together to implement the study. Combat swimmers are professionally trained special operations forces of the German Navy who have to perform their mission efficiently under extreme environmental conditions and under high physical and mental stress.

The selection of these soldiers, who are also known as "tactical athletes," is based on strict criteria. These include physical exertion at different times of day and night with sometimes very short periods of regeneration and sleep in between, deliberate food deprivation during some phases of training, deliberately induced high levels of stress, and a lack of close supervision from experts in sports and nutritional medicine. Only a small number of very fit soldiers usually pass this first phase of training as part of the selection process and go on to train as combat swimmers in the following three years.

Fig. 1:
Combat swimmer in a diving pool

Fig. 2: Combat swimmer training

The aim of the study is to investigate the effects of the high levels of physical and psychological stress that candidates experience during the first stage of combat swimmer training (physical training and indoor pool phase) on their body composition, adaptive thermogenesis, endurance, explosive strength of the lower extremities, physical regeneration capacity and psychovegetative symptoms. The results will be used to derive recommendations for the areas of sports physiology and psychology as well as nutritional medicine in order to optimise training.

In terms of methodology, the study is set up as a prospective observation study with a pre/post design, focusing on combat swimmers in training during the first training phase (physical training and indoor pool phase) at a minimum of eight independent time points over a period of eleven weeks. Anthropometric data are collected and bioimpedance analyses, quantitative magnetic resonance imaging (EchoMRI), air displacement plethysmography (ADP), and heart rate analyses (HRV) using a pulse watch will be performed as part of the study. Additional tests to determine resting energy expenditure (indirect calorimetry) as well as blood counts and tests to determine levels of urea, electrolytes, thyroid hormones, leptin, testosterone, cortisol, and insulin will be performed regularly. Standardised questionnaires will also be used to assess sleepiness (Stanford Sleepiness Scale) and subjective-mental feelings of exertion (Recovery and Exertion Questionnaire Sport).

One of several aspects of this study is to aid in the selection of candidates who are suitable for the demanding profession of combat swimming, which is why the participants are deliberately pushed to their physical and mental limits – and sometimes even beyond. It is still unclear whether the soldiers may reach a dreaded state called overreaching syndrome (OR), which can lead to overtraining syndrome (OTS) and to months-long breaks in training or even the end of a competitive athlete's career. The COVID-19 pandemic led to delays in data acquisition, which is why the first results of the study are now expected in 2023.

Fig. 3: Combat swimmer

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Photon-counting CT scanner in the emergency room: Improving assessment of polytrauma patients

Severely injured patients receive initial medical care in the emergency room and trauma is evaluated with computed tomography. A new generation of CT scanners now offers faster imaging with higher resolution. Their high diagnostic confidence, clinical applications and impact on therapeutic decisions for high-quality patient care are investigated.

The Bundeswehr Central Hospital Koblenz has 506 beds for its approximately 20,000 inpatients per year and, as a hospital providing specialised care, carries out about 220,000 outpatient procedures. As a supra-regional trauma centre, it must provide precise and rapid diagnosis of severe injury patterns as an absolute prerequisite for targeted therapy.

Emergency room imaging diagnostics is primarily based on computed tomography, which creates a three-dimensional image of the patient using X-rays that are attenuated in the body and received by a detector.

The Bundeswehr Central Hospital in Koblenz was one of the first institutions in the world to implement a new generation of CT scanners (Siemens Healthineers Naeotom Alpha) in a trauma room setting for severely injured patients (Fig. 1).

This photon-counting CT scanner (PCD-CT) directly detects and counts each X-ray photon and its energy level using an active detector layer made of a cadmium telluride crystal (CdTe). Conversion to visible light as a previously required intermediate

Fig. 1: Photon-counting CT scanner in the trauma room setting

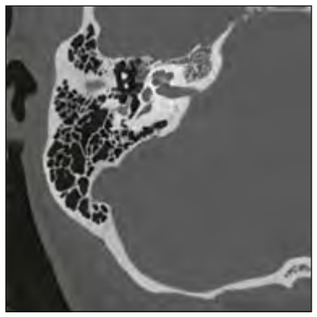

Fig. 2: Ultra-high-resolution image of the temporal bone

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step in conventional CT detectors and the associated loss of information are completely eliminated.

Based on the new spectral information, different materials in the body can be identified and differentiated from one another. Even the number of required scans can be reduced by virtually removing the contrast agent typically injected in advance. A quicker diagnosis means that treatment can begin sooner. Radiation exposure is reduced by up to 45%, which has a positive impact on routine examinations such as lung cancer screenings.

Photon-counting technology also allows for ultra-high-resolution scans with a spatial resolution as low as 0.2 mm without increasing the reference radiation dose. Delicate injuries to complex anatomical structures such as the petrous bone (Fig. 2), which houses the inner ear and conduction structures in a very small space, can thus be visualised. As a result, researchers at Bundeswehr Central Hospital Koblenz were able to achieve the first ever research results on postoperative imaging of these structures using PCD-CT after cochlear implant (CI) surgery. Interpreting conventional detector CT images in such cases is usually difficult due to metal artefacts. PCD-CT imaging has proved to be a promising technology for CI imaging, with improved spatial resolution and better visualisation of small structures than conventional CT (Fig. 3). This improved diagnostic technology opens up numerous new possibilities in almost all clinical areas.

Researchers at the Bundeswehr Central Hospital in Koblenz will continue to investigate the potential for optimisation and to evaluate new clinical possibilities and the role of the quantum counting CT scanner in clinical decision-making, especially in emergency medical care for severely injured patients. To this end, algorithms and AI methods are also being developed in the context of research collaborations, such as with Siemens Healthineers, to accelerate and improve the diagnosis of severely injured patients.

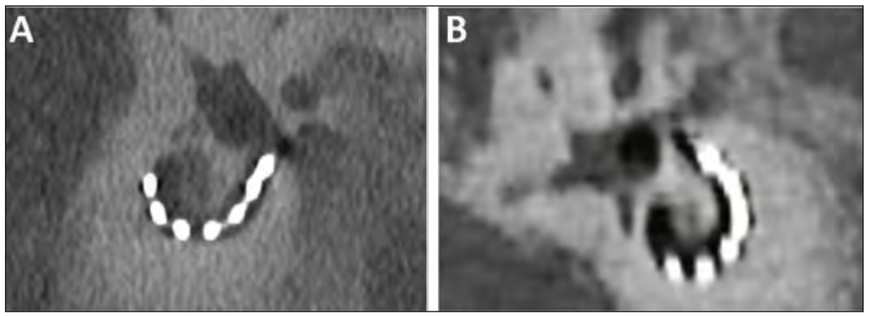

Fig. 3: Comparison of the quality of visualisation of a cochlear implant and the surrounding temporal bone with improved metal-to-bone contrast in PCD-CT images (A) vs. conventional detector computed tomography (B)

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New results of a longitudinal study on mental disorders among German military personnel after Bundeswehr missions abroad

In a new approach, the occurrence of mental disorders after foreign deployment is examined longitudinally. Military personnel with and without experience of a critical event during deployment are matched and compared. The risk of developing a mental disorder was six to seven times higher in the group who had experienced a critical incident.

Despite clear international differences, extensive studies show a significant increase in mental disorders among military personnel after deployments abroad. Military personnel deployed abroad are typically compared with military personnel who served in their home country during the same period. Both groups are surveyed for mental disorders before and after military deployment or a period of service in the home country. The difference in newly occurring mental disorders (with vs. without deployment) can thus be attributed to the assignment abroad.

The present study, which was carried out in cooperation between the Psychological Service of the Bundeswehr, the Psychotrauma Centre at the Bundeswehr Hospital in Berlin, King's College London and the Bundeswehr University in Munich, compares soldiers deployed on the same mission in Afghanistan. The distinction lies in whether or not they experienced a critical event that was specific to the military mission while on deployment. Since general parameters, such as absence, a changed security situation, constant readiness, etc., are similar for everyone on deployment, any newly occurring mental disorder can be traced back to the critical events experienced during the deployment. The general threat situation and other adversities are considered an additional burden generally associated with active service in the military.

For the purposes of this study, a previous survey of a combat force with N = 361 participants before and after an Afghanistan mission (ISAF) in the years 2013 – 2014 was re-evaluated. Of the 361 participants, 81 reported having experienced an exceptionally threatening critical event while on deployment; 280 did not. The presence of mental disorders was determined by a clinical interview (mini-DIPS) before and after the ISAF mission. This made it possible to determine who developed a new mental disorder during this period.

In the overall group of all soldiers deployed abroad (deployments abroad with and without a critical incident, which corresponds to the previous setup without a control group), the incidence rate of anxiety disorders was 5 %, while post-traumatic stress disorders (PTSD) and depressive episodes newly occurred at a rate of 2 % each. This is largely consistent with the results of an earlier study carried out in the Bundeswehr. In our new evaluation, the two groups with vs. without experience of critical events during the assignment were compared with one another. The incidence rate of anxiety disorders was 16 % (with a critical event) vs. 3 % (without a critical event), while that of PTSD was 6 % vs. 1 %, and that of depressive episodes was 7 % vs. 1 %. This demonstrates that it is not the deployment itself that influences the development of mental disorders but rather the events experienced during the deployment. For every one of these mental disorders, the risk (odds ratio) of new onset is 6 - 7 times higher for soldiers who have experienced critical operational events than for those who have not.

Based on these results, the increase in mental disorders can now be attributed to critical events experienced on deployment and not to the deployment per se. These findings should be taken into account in the psychological preparation for deployment and in de-stigmatisation programmes. This evaluation strategy likely also makes the results of international studies more comparable as it takes into account the very different levels of direct risks faced on operations.

Fig. 1: A sergeant hugs his wife (Source: Bundeswehr/Eisner 2004)

Fig. 2: Paramedics practice picking up and transporting a wounded soldier at Camp Marmal in Mazar-e Sharif/ A fghanistan
(Source: Bundeswehr / Torsten Kraatz)

Fig. 3: A sergeant with PTSD (Source: Bundeswehr / Jonas Weber)

3

Military History and Social Science Research

The Bundeswehr Centre of Military History and Social Sciences conducts research on behalf of the Federal Ministry of Defence. Its findings in the fields of military history and social sciences help enrich public and scientific debate on issues of military and security policy in Germany. The Centre applies established methods and standards of historical research to the study of German military history and takes into account interrelationships between the military, politics, the economy, society and culture.

With its work in the social sciences, the Centre contributes to the further development of the field and is able to provide scientifically sound advice to policy-makers. By bringing together history and the social sciences, it opens up new avenues for research and the application of research findings to the teaching of history.

The Bundeswehr Centre of Military History and Social Sciences contributes to an understanding of the role of the armed forces in a pluralistic society. Thematically intertwined with military history, the social sciences help us to analyse and explain new conflicts and special operational scenarios of the Bundeswehr.

Researchers at the Bundeswehr Centre of Military History and Social Sciences are part of the scientific community. They are in close contact with organisations, institutions and agencies in Germany and abroad as well as with university and non-university research facilities. Cooperation with other Bundeswehr institutions that train, research, and teach is becoming increasingly important. The Centre supports Bundeswehr operations by providing analyses from the fields of history and the social sciences.

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Catholic peace work during the Cold War, with a particular focus on East and West Germany

The Cold War period was a time of controversial discourse on peace ethics and security policy. For some years now, the focus of research at the Bundeswehr Centre of Military History and Social Sciences in this regard has been on the two German states – East and West Germany – and on civil-military relations in particular. A new study emphasises the involvement of the Roman Catholic Church in peace work during this period.

The first Assembly of the World Council of Churches took place in 1948 and famously declared that "War is contrary to the will of God", a theological statement that three years earlier had been expressed in the United Nations Charter as the principle of the non-use of force under international law. In the wake of two world wars, the use of weapons of mass destruction, and a high number of civilian victims, the churches rejected the unconditional right to wage war and morally condemned the very act of war itself. In the late 1940s, the churches now felt the need for new form of commitment to peace.

The end of World War II marked a turning point in the ethics of peace and conflict in Europe and beyond, yet conflicts and tensions remained and led to a "cold" war, which would shape foreign and security policy and profoundly influence much of the culture and society of the states affected by the East-West conflict.

From a perspective of comparative history and relational history, this study examines the actions of the Roman Catholic Church in this conflict by analysing previously unpublished sources from state, church and private archives. A divided Germany takes on a symbolic role as an emblem and a focal point of the Cold War. The foundation of the two German states resulted not only in boundaries, borders and separate evolutions – complex connections and relations continued to develop and profound commonalities remained. Christians in both states in particular continued to maintain existing connections and forge new ones. The Catholic Church, which never officially recognised the division of Germany, provided important contributions in this regard.

The study will also examine civil-military relations based on the assumption that civil society actors such as the Christian churches served an important role in the interpretation and events of the Cold War, and that this was also reflected in the military. Furthermore, the Catholic Church not only publicly commented on issues relevant to the military but also was in direct exchange with the armed forces through its military chaplaincy work.

A recurring theme of the discourse is the debate over the legitimacy and limits of military force. On this matter, the Catholic Church was torn between criticising and clinging to the doctrine of just war (bellum iustum), which seemed less and less suited to offering answers to questions arising in response to changing images of war and newly emerging threat scenarios of the Cold War. This includes criticism and recognition of nuclear weapons as instruments of modern technological warfare and as a means of exerting political pressure. The ethical assessment of nuclear deterrence as well as the fear of the use of nuclear weapons and greater awareness of their devastating effects were important aspects in Catholic peace work. The correlations between past experiences of war, current threat perceptions and religious theories of conflict are highlighted.

The question of how one can reconcile military service with one's conscience is another point of discussion. The example of the Catholic Church and its changing theological stance on personal matters of conscience show the tremendous shifts in attitudes towards the armed forces and military service. The study shows how – far beyond the Cold War period – this discourse not only changed attitudes towards conscientious objection but also led to military service becoming closely associated with matters of conscience.

Fig. 1: Millions of people took to the streets as part of the West German peace movement of the 1980s to protest the NATO double-track decision. The cause was widely supported by the Christian churches. Within the Catholic Church in Germany, the "Pax Christi" organisation demonstrated its commitment most clearly (Source: IMAGO / Sven Simon)

Fig. 2: Logo of the independent peace movement in East Germany with the slogan "swords to ploughshares". Although the image at the centre of the logo shows a sculpture that had been a gift from the Soviet Union to the United Nations, people who displayed the logo in East Germany were discriminated against by representatives of the state (Source: Ecumenical Peace Decade)

Fig. 3: Catholic soldiers in the Bundeswehr have shown their commitment to their Church's peace work in many ways. Some of them did so publicly in a number of publications throughout the 1970s and '80s

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The ZMSBw population survey as a measure of public opinion on defence policy

Surveying and studying public opinion on Germany's Armed Forces and German security and defence policy is tremendously important to the Bundeswehr because, in a democracy, armed forces are dependent on public support. The annual population survey by the Bundeswehr Centre of Military History and Social Sciences gauges the Bundeswehr's legitimacy, relevance and integration in society.

Since 1996, the results of the population survey conducted by the Bundeswehr Centre of Military History and Social Sciences have been used to assess the relationship between the Bundeswehr and society and to evaluate the Bundeswehr's public relations work. With its wide variety of high-profile publications on these results (Fig. 1), the Centre also makes an important contribution to the public discourse on German security and defence policy and the armed forces, which serves the goal of integrating the Bundeswehr in society through leadership development and civic education. The survey data are also published in top-tier peer-reviewed scientific journals and are used in dissertations and university teaching.

The data are collected in computer-assisted one-on-one interviews with our stratified random sample that is representative of the German-speaking resident population aged 16 and over. Every year, the final sample comprises more than 2,000 respondents. The central topics of the survey are threat perceptions, attitudes toward German's foreign, security and defence policy as well as attitudes toward the Bundeswehr and its missions. The Bundeswehr Centre of Military History and Social Sciences conducts the only survey on security and defence policy of its kind in Germany to allow reliable trend analyses over long periods of time.

This unique analytical value of the Centre's population survey was particularly apparent in 2022. The results show that Russia's war of aggression against Ukraine has led to a historic shift in German public opinion on defence policy. More respondents than ever approve of increases in funding and personnel for the Bundeswehr (Fig. 2). Whereas foreign and security risks were the least of the public's concerns before, they now have the greatest impact on the average German's sense of security. The German public's previously ambivalent feelings towards Russia have given way to the realisation that Russia poses a threat to Germany's security.

For many years, there was a discrepancy between widespread approval of the principle of collective defence on the one hand and a low willingness to provide concrete military support to NATO's eastern partners on the other. This gap was by and large closed in 2022. These points clearly reflect the historic shift in German public opinion on defence policy.

For many years now, the German public has already taken a positive attitude toward the Bundeswehr as an organisation of the state and an institution of society (Fig. 3), and so there was much less room for improvement in this regard than there was on controversial issues such as Germany's bilateral relations with Russia. In another respect, however, the Bundeswehr's return to national and collective defence in response to the war in Ukraine could lead to improvements in the relationship between the German armed forces and the public: the mission of the Bundeswehr is once more understood and supported by the majority of the German people.

The findings of the population survey conducted by the Bundeswehr Centre of Military History and Social Sciences are widely discussed in the media, the strategic and scientific communities, and the Bundeswehr. In 2022 in particular, the Centre and the results of its population survey were mentioned in more than 40 media reports. The Centre thus succeeded in its ambition to provide a meaningful contribution to the social discourse on Germany's foreign, security and defence policy and the role of the Bundeswehr through reliable empirical research findings. Research reports on the population survey are freely accessible at zms.bundeswehr.de.

Fig. 1: The Bundeswehr Centre of Military History and Social Sciences uses a wide range of formats to communicate the results of its survey to the public

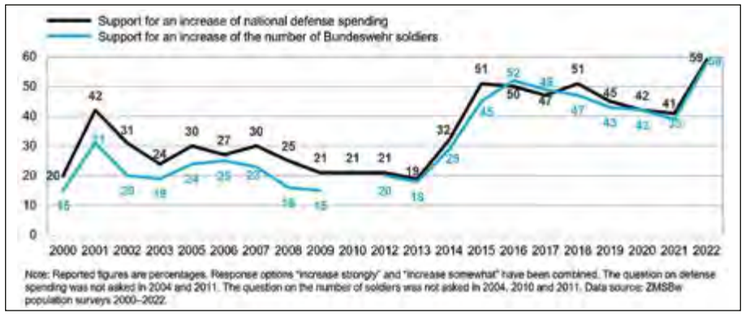

Fig. 2: Development of approval rates for increases in defence spending and Bundeswehr personnel strength, 2000-2022 (Source: ZMSBw)

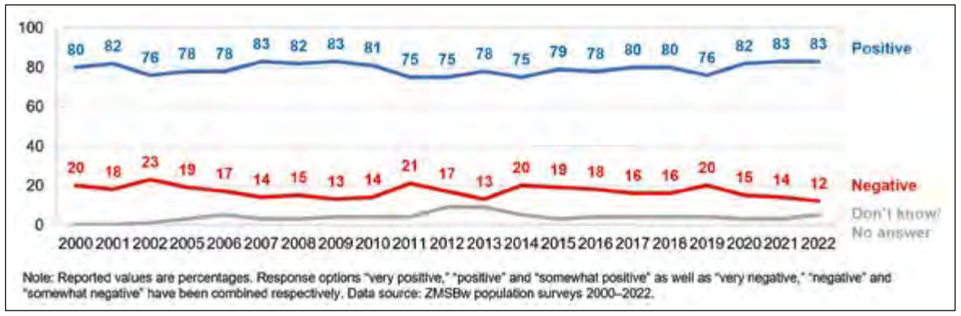

Fig. 3: Development of personal attitudes toward the Bundeswehr, 2000-2022 (Source: ZMSBw)

4

Geoscientific Research

Geoscientific research plays a key role in ensuring a functioning geoinformation service in the Bundeswehr. As a scientific specialised service, the Bundeswehr Geoinformation Service must be capable at all times of providing scientifically sound contributions to situation pictures as well as competent answers to any questions about current issues.

The Service focuses on a range of diverse geofactors from a total of 18 (geo)scientific disciplines, which together affect the planning and conduct of military operations in a variety of ways and across different time scales.

In order to live up to this challenge, we naturally need a certain lead time to gather the right information and intelligence in order to be able to share them at the right time or, better yet, to have the relevant product or service available in our portfolio.

For some time now, a researcher at the Bundeswehr Geoinformation Centre has been studying ways of predicting off-road terrain accessibility for military vehicles for the strategic and operational levels. Her work has already been highlighted in previous issues of this publication. Given current developments in the situation, it is little surprise that this field has come to form a core part of the advisory work of the Bundeswehr Geoinformation Service.

That is why we are using this opportunity to share an update on the project and its progress, both in terms of its scientific approach and its technical implementation.

We also highlight the MoGLi (monitoring GNSS integrity by simple traffic lights) software tool, which performs integrity analyses of GNSS (global navigation satellite systems) data in near real-time. The automatically generated products provide important information on the accuracy and reliability of these systems for everyday military use.

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Cross-country movement maps with CCMod (Cross-Country Model)

Awareness of off-road trafficability is a strategic advantage, not only with regard to the safe deployment of our own forces but also as it allows assessing the enemy's axes of movement. A new feature in the Cross-Country Model CCMod uses higher-resolution SoilGrids data in combination with weather forecasts, information on land use and relief data.

Cross-country maps have always been of great military importance. Not only are they an important asset for getting own troops safely to the theatre and back again as well as for safeguarding the manoeuvrability of own vehicles in the field, they also offer a strategic advantage in that they facilitate estimating the enemy's possible axes of movement and potential axes of attack. The Bundeswehr Geoinformation Service trains soldiers to conduct GIS analyses of terrain and its trafficability. In addition to information on land use, CCMod also takes into account terrain elevation data and especially the current weather and forecasts for precipitation, snow and frost (Fig. 1).

Soil data, particularly estimated soil moisture over the coming days, is also highly relevant to trafficability. Such assessments are challenging because in-depth information on hydrological and soil conditions is required to assess whether the moist or wet soil is trafficable for vehicles with a specific weight and ground contact area. The data required for the calculation are obtained from public sources such as the German Meteorological Service, the Federal Agency for Cartography and Geodesy and the Federal Institute for Geosciences and Natural Resources. The vehicle-specific data are obtained from Bundeswehr databases that are not publicly accessible.

As an upgrade in the current CCMod version, the soil data is based on SoilGrids, a uniform set of global maps of soil properties at 250 m spatial resolution (https://soilgrids.org/). SoilGrids map soil horizons to a depth of up to 60 cm and provide information on sand, clay, silt and gravel content, and bulk density. SoilGrids data on soil organic matter were unrealistic in places and were only used in terms of relative distribution across the four horizons. The total amount of soil organic matter was taken from the Global Soil Organic Matter (GSOM) layer (http://54.229.242.119/GSOCmap/). The use of SoilGrids in combination with GSOM facilitates trafficability analyses even for areas that have not yet been subject to pedological mapping. These analyses can then be used as an initial planning basis.

To address the complex soil moisture problem, the new SoilGrids CCMod tool for ArcGIS Pro automatically calculates seven different scenarios of soil moisture and corresponding trafficability, ranging from extreme dryness to maximum moisture, as static layers based on the SoilGrids data (Fig. 2).

The area of interest is divided into sub-areas and for each sub-area, a CCMod run determines which soil moisture scenario is to be expected for the next day, for example. As a next step, the sub-areas, which in large areas are usually diverse, are combined to form an overall picture of trafficability. In this way, it is possible to calculate the estimated next-day trafficability even for large areas such as the whole of Germany.

Prior to the introduction of CCMod, trafficability maps were manually created in the GIS. Soil composition and moisture were barely considered, if at all. Owing to the increasing complexity of the input data, this approach will be replaced by an automated, standardised GIS procedure (Fig. 3). CCMod-trained users from the Bundeswehr Geoinformation Service will thus be trained to quickly generate standardised terrain trafficability maps for the next three days for planning areas at division and brigade level. Based on the CCMod maps, Bundeswehr Geoinformation Service advisory personnel can provide information in briefings on which areas are passable and which areas require closer examination by pioneers to assess their trafficability.

Ultimately, this is about providing valid geoinformation to help protect our soldiers on operations.

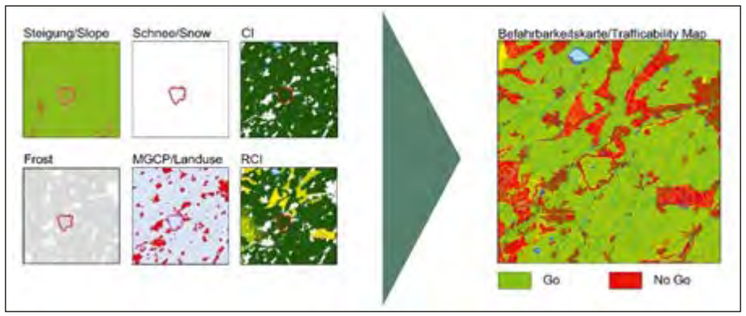

Fig. 1: From input data to trafficability maps: CI and RCI maps describe the resistance (cone index) of the prevailing soil type against deformation caused by single (CI) and repeated (RCI) crossing

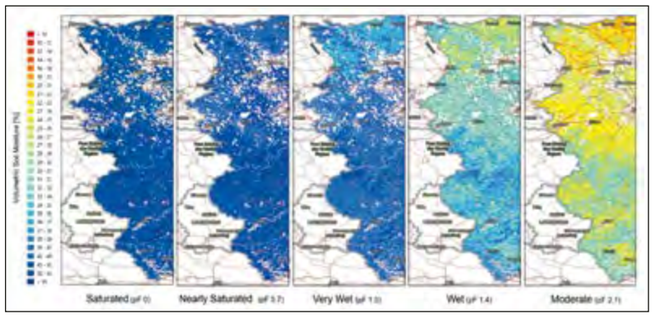

Fig. 2: Five soil moisture scenarios for an area of interest (approx. 150 x 350 km) in western Germany

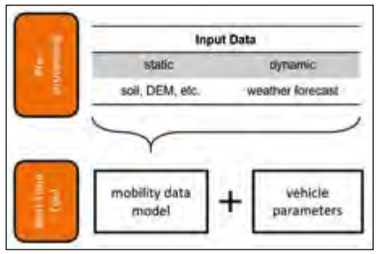

Fig. 3: The CCMod workflow: Static and dynamic input data are merged in a pre-processing step to obtain a mobility data model that serves as the basis for the subsequent real-time step, for which a vehicle of interest is selected. The result map is specific to the selected vehicle and not applicable to other vehicles

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MoGLi: An application for GPS integrity analysis

Global navigation satellite systems (GNSS) are a modern positioning technology. The Bundeswehr Geoinformation Centre in Euskirchen hosts the Bundeswehr's GNSS information and observation system (GIBSBw). The MoGLi software tool (Monitoring GNSS integrity by simple traffic Lights) performs integrity analyses on the basis of observation data from stations in Germany and in countries of deployment.

GNSS are routinely used both in civilian life and in the Bundeswehr in a wide variety of applications with different accuracy ranges. The GIBSBw (Fig. 1) is located at the Bundeswehr Geoinformation Centre in Euskirchen. The facility was established because GNSS users in the Bundeswehr are particularly reliant on a functional working condition of the space segment and minimal interference in the signal from satellite to receiver. There is also a growing demand for geospatial information advisory services for GNSS users and the option of detecting and analysing efforts to jam GNSS signals, especially in the context of navigation warfare.

On the hardware side, GIBSBw consists of different receiver and antenna types of the central monitoring station at the Euskirchen site, which ensure redundant monitoring of the different GNSS signals. The real-time data streams of the mobile or portable reference and monitoring stations in the areas of operations are another component. The continuously recorded observations and all satellite parameters of the GNSS receivers are merged by GIBSBw to be included in analyses for permanent real-time monitoring of GNSS as well as in the MoGLi integrity analysis and other detailed examinations. To complete the situation picture, especially in the Bundeswehr areas of interest, organic Bundeswehr sensor systems are supplemented by observation data from the observational network of the International GNSS Service (IGS) and the European Permanent GNSS Network (EPN).

The central integrity check using the MoGLi analysis tool is a core component of GIBSBw and is based on the analysis algorithms of the Bernese GNSS software. This scientific software package consists of a large number of individual program routines that users can structure according to their individual requirements. A visualisation tool and the presentation of results in accordance with the traffic-light principle (Fig. 2) were developed in-house.

The first parameters to be analysed are the availability of civilian and military signals at the observation stations and the accuracy of absolute position determination by comparison with target coordinates as a direct indicator for the assessment of the GNSS operational status (Fig. 3). To that end, typical Bundeswehr accuracy levels are examined, which differ by satellite path information used (broadcast or precise orbit data) and signal types used with or without ionosphere-free linear combination.

For the core part of the integrity check, the correctness of the transmitted information of the satellite orbits and clocks is analysed by including IGS information such as precise satellite orbit (Fig. 4) and clock information in the evaluation. Finally, the influence of ionospheric refraction (which delays the signals and thus may significantly affect or distort the observations) is studied, with results of the analysis (issued by country) known as vertical total electron content (VTEC).

There are comprehensive analyses of all previous-day observations of the US-owned and -operated GPS as the primary navigation system used in the Bundeswehr. All available observations of the past hour are also analysed in near real-time. All results are evaluated according to the traffic-light principle and published directly in the GeoInfoPortal for the timely information of users. They also serve as a basis for GNSS advisory services in response to user requests and for warnings. An extension to include additional GNSS is possible.

The MoGLi GPS integrity analysis tool originates from a technical project in cooperation with the University of Bonn and, since its operationalisation for GIBSBw, has been working on a permanent and fully automated basis.

Fig. 1: GIBSBw-Logo

Fig. 2: MoGLi evaluation page from the GeoInfoPortal (11 November 2022)

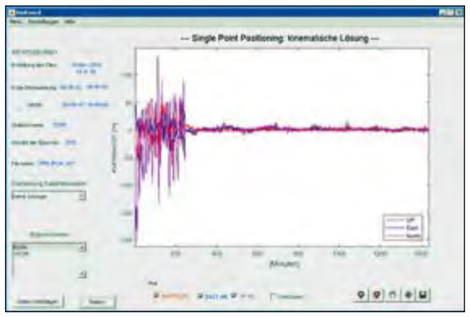


Fig. 3: Analysis of coordinate accuracy using the example of the deactivation of SA on 2 May 2000

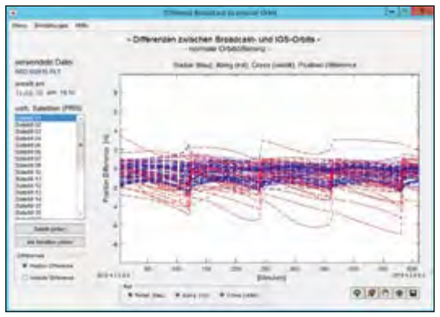
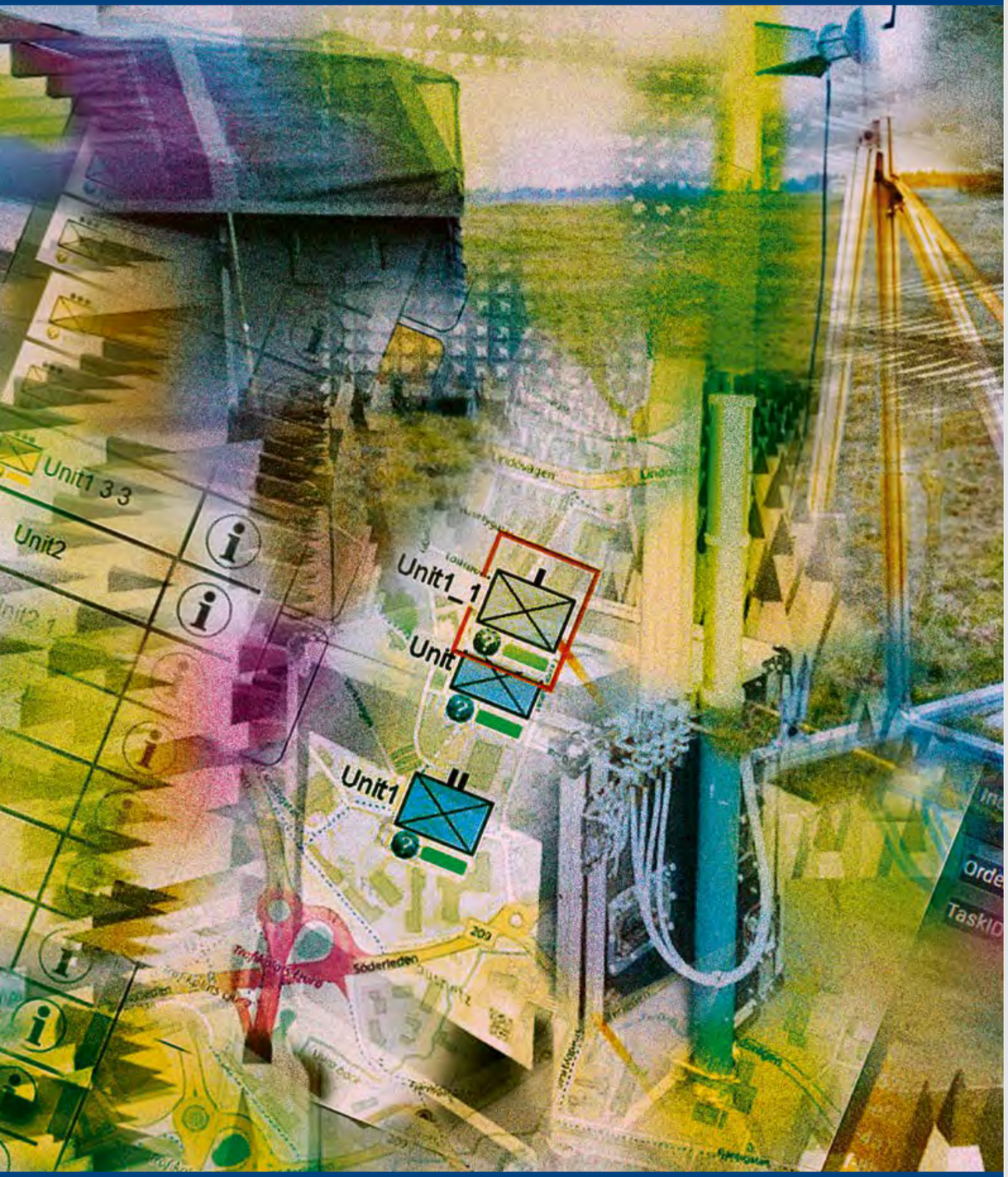


Fig. 4: Analysis of the GPS broadcast orbit with its update rate



5

Cyber and Information Technology Research

Military research on cyber and information technology is guided by civilian and disruptive innovations such as artificial intelligence. It must also take into account the specific characteristics of current and future conflicts, which will be increasingly hybrid.

What follows are several examples from the broad spectrum of research in this field. These include international standardisation activities, specific IT security studies and the use of civilian mobile communications technologies in the military sector.

The aim is to use as much civilian technology as possible, which will be adapted for military uses if needed. Automation is a common theme in all areas of defence research.

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Commercially available 5G mobile technology for tactical communications

The 5th generation (5G) standard of mobile networks is suitable for many requirement profiles and also seems to be an attractive option for military applications. The requirements for civilian and military radio systems, however, differ considerably in some respects. The project will thus analyse if and how 5G is suitable for highly mobile tactical operations and in networked command posts.

The global network rollout for 5th generation mobile networks is making rapid progress, and 5G will be the predominant mobile access technology within no more than 5 years. The new mobile network standard was designed for three applications with very different requirements:

- Enhanced Mobile Broadband (eMBB) for data rates of more than 10 Gbit/s,
- Massive Machine Type Communications (mMTC) to connect up to one million sensors over an area of one square kilometre, and
- Ultra Reliable Low Latency Communications (uRLLC) for both high reliability and low latency of less than one millisecond.

This makes it an extremely attractive option for many military applications as well. Network slicing allows these competing features to be realised simultaneously in a single network.

To ensure that the transmission system can be adapted to the requirements of the application, the air interface can be configured far more flexibly than with the predecessor LTE (Long Term Evolution). The usable frequency range was significantly extended to millimetre waves (up to 44 GHz) so that the required transmission capacity can be realised with channel bandwidths of up to 800 MHz. In addition, gaps in IT security identified for LTE have been closed (e. g. in the protection of subscriber identities, mutual authentication). Multi-antenna systems with MIMO (multiple input, multiple output) for beamforming and spatial multiplexing are an integral part of 5G.

In a military radio system, additional requirements such as high reliability under difficult environmental conditions, robustness against jamming, and the prevention of reconnaissance of radio units are of overriding importance. The project "Rapidly available Modules for Interoperable Capable Networking in 5G" (RAM ICON 5G) aims to shed light on the role that 5G can play in communications for highly mobile tactical operations and in networked command posts.

The development of the civil mobile communications standard did not focus on military operational scenarios. Nevertheless, 5G is less susceptible to interference than LTE. Twice the interference power is required to interfere with the synchronisation signals, for example.

Because of path attenuation at very high carrier frequencies, jamming and reconnaissance are only possible at short distances, which is why the extent to which millimetre waves are suitable for communication in networked command posts is being investigated. Due to the short wavelength, so-called massive MIMO antennas with a large number of antenna elements can be produced in a very compact format. These antennas can be pointed at multiple remote stations at very narrow angles, making jamming and reconnaissance from all other directions much more difficult.

Initial field tests have been conducted to determine how, for example, vegetation or tent and camouflage fabrics affect 5G reception in different weather conditions. Fig. 1 shows an experimental setup during testing using an inflatable tent for command posts. The dry tent fabric is transparent to the tested frequency range up to 28 GHz, even if camouflaged. When it rains, the wet tent fabric attenuates the signal's millimetric waves by almost 5 dB. Measurements with a mobile base station (this time in snow, Fig. 2 and 3) confirmed that at 3.6 – 3.8 GHz, transmission is not likely to be affected either inside or behind the tent. At the time of the experiment, equipment for higher frequencies was not yet available.

As the project continues, the behaviour of a 5G mobile communications system will be systematically analysed for further operational scenarios over a frequency range of 600 MHz – 28 GHz.

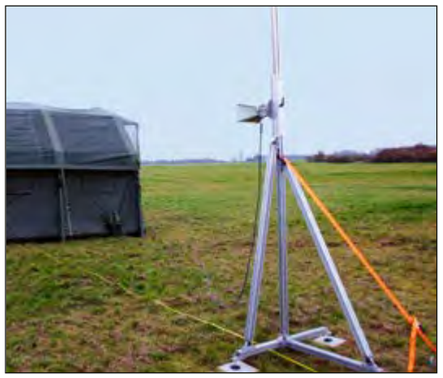

Fig. 1: Setup for measuring the frequency-dependent attenuation properties of tent fabric on an air-supported tent for command posts

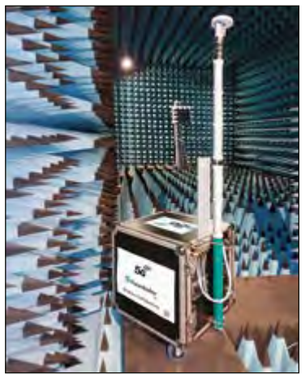

Fig. 2: Mobile base station for 5G campus networks in the n78 frequency band n78 (3.7 – 3.8 GHz)

Fig. 3: Setup for measuring the influence of an inflatable tent for command posts on 5G communications

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Establishing the C2SIM information standard for NATO

A central goal of the NATO Federated Mission Networking (FMN) initiative is to build interoperable systems to support NATO joint operations. Simulated joint exercises are facilitated by standardised communication among command and control systems and simulation systems. This was validated at the 2022 Coalition Warrior Interoperability eXploration, eXperimentation, eXamination eXercise (CWIX).

With the "NATO-C2SIM 2022" study at the Bundeswehr Technical Centre for Information Technology and Electronics, the Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE), together with its international partners in the Simulation Interoperability Standards Organization (SISO), the NATO Modelling and Simulation (M&S) Group 201 "Modelling and Simulation in Federated Mission Networking (FMN)", and NATO Modelling and Simulation Group 194 "Employing the C2-Simulation Interoperation (C2SIM)", furthers the goal of establishing the "Standard for Command and Control Systems – Simulation Systems Interoperation" (C2SIM) for NATO.

SISO developed the C2SIM standard and continues to release improvements. These include updates to the C2SIM ontologies, additional transformation mechanisms that facilitate the creation of C2SIM schemas, and mechanisms for better user support. The C2SIM ontologies serve as a knowledge base (Fig. 1) for initialising a system-of-systems of command and control systems and simulation systems (Fig. 2). The current standard provides a model for land operations, with potential for expansion to other domains and use in multi-domain operations.

In an effort to support current and prospective NATO C2SIM users, training sessions and workshop series are offered regularly, most recently at the Modelling and Simulation Centre of Excellence (MSCoe) in Rome, Italy. Efforts by the NATO groups have also ensured that C2SIM will be established as a STANAG and included in the FMN Spiral 5 "Service Instructions for Modelling and Simulation" and the FMN Spiral 5 "Procedural Instructions for Mission Rehearsal" specification documents.

Another important step in the process of establishing C2SIM involves testing and validation in the context of a mission rehearsal. This took place at the CWIX 2022, which was hosted by the NATO Joint Force Training Centre (JFTC) in Bydgoszcz, Poland. The important capabilities of each of the partner systems were outlined and a total of 84 test cases for evaluating inter-system interactions were defined. Each test case was designed to evaluate the effectiveness of basic C2SIM features in the context of a shortened mission rehearsal (Mini MR) that emulated a joint multinational mission. This mission tasked a joint brigade—comprised of battalions from three nations with additional air force support—with defending the fictional state of Bogaland against an attack from a neighbouring state.

Fig. 1: C2SIM ontologies with class subordination and property restrictions to define classes

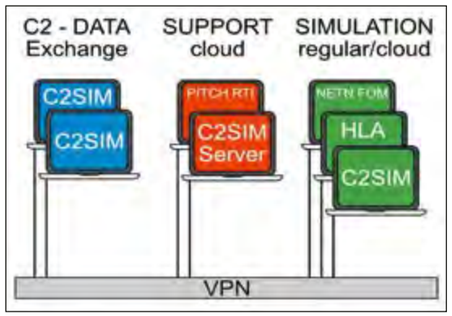

Fig. 2: System-of-systems for communication between C2 and simulation systems

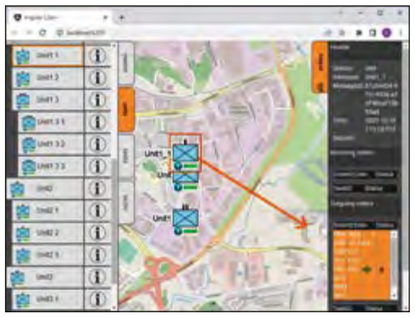

Fig. 3: Tasking in FKIE C2LG GUI

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The battalions took to their assigned places in the field and successfully avoided an ambush. Throughout the mission rehearsal, the Fraunhofer FKIE command and control system (C2LG GUI) acted as both provider and consumer. In the provider role, the C2LG GUI issued C2SIM orders to a range of multinational simulation systems (Fig. 3). Each of the simulation systems executed the orders and responded to the control systems with C2SIM reports. The C2LG GUI then assumed the role of the consumer and processed the reports, updating the situation picture accordingly. These evaluations highlighted the ways in which C2SIM enables interoperability between M&S systems. The C2LG GUI was able to fulfil all of the test requirements. Only a few tests were deemed unsuccessful due to gaps in the C2SIM implementation in some simulation systems. Based on these tests, NATO's Modelling and Simulation Group 201 will conduct a further test round at the CWIX 2023 and integrate additional simulation systems into the system-of-systems.

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Analysis of smartphone malware (smartphone forensics)

The role of digital forensics involves determining whether a system is infected with malware. This study, conducted in cooperation with the Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE), examines this issue in more detail, specifically with regard to mobile devices. It shows the current threat situation, presents a workflow for analysing smartphones to detect infection and assesses the workflow's applicability.

While malware has been a problem for desktop computer users for years, it has recently also begun affecting smartphones (Fig. 1). Because of the amount of personal data stored on them, they have become an attractive target for attacks, as the case of Pegasus spyware on devices running iOS illustrates. That is why it is important to reliably identify the effects of malware and the traces left when smartphones are compromised. To this end, a three-stage workflow was developed as part of this study to serve as a basis for analysing potentially infected smartphones (Fig. 2).

The first step of the workflow is the direct detection of malware infection based on established indicators such as IP addresses, domain names and hash values. The presence of such indicators on a smartphone suggests an attempted or even successful infection of the device. Amnesty Tech's Mobile Verification Tool (MVT) has proved to be a suitable tool for this step of the analysis. Using several modules, the MVT can extract various artefacts from Android and iOS devices and match them against known indicators. This process relies on such indicators of an existing infection being present, however. If they are not, or if indicators behave very dynamically, this first step of the analysis quickly reaches its limits.

The second step is an attempt to detect anomalies on the device instead of specific indicators, which will determine the focus of further analyses. To this end, the MVT performs initial evaluations of extracted artefacts and warns the user of any suspicious application permissions or outdated operating systems, for example. What constitutes an anomaly, however, is often heavily dependent on the use case and the basic state of a device. That is why it may be useful to establish a baseline for the infection-free basic state of the device. Static artefacts, such as a list of installed applications, as well as dynamic artefacts, such as network connections established over time, can be used for this purpose. A comparison of the actual state of a device with its previously established baseline can thus highlight anomalies that can then be further analysed.

Based on any indicators or anomalies uncovered, more detailed investigations are carried out as the last step of the workflow, with the main focus being on analysing any suspicious applications. As part of the study, a sandbox environment will be developed akin to the options available for desktop systems, in which applications can be analysed securely and specifically, as illustrated in Fig. 3. An important question that will be evaluated in this context concerns the execution of applications and whether simply starting an application is enough to trigger its relevant behaviour, for example, or whether more advanced methods are required. While the application is being run, various dynamic features, such as file access and established network connections, will then be secured, logged and presented to the analyst. Finally, the presented sandbox environment will be evaluated on the basis of different benign and malicious applications and examined for its applicability. The aim is to gain insights that can be used to quickly and simply identify malware or malicious characteristics. This also offers the possibility to determine indicators of an infection for use in future analyses.

Fig. 1: The FluBot malware as an example for malware on Android

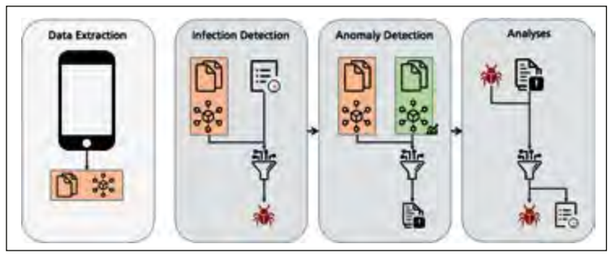

Fig. 2: Workflow for the analysis of a potentially compromised smartphone

Fig. 3: Sandbox environment for the analysis of smartphone malware


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NAVOTOM Alpha
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sporttherapy
own abilities
own resources
Group dynamic processes
military abilities
enhancement of own performance
direct contact to the units
and talk to executives
reflection in the group
coaching &
social competence training
engagement &
motivation
own resources
self-confidence
focused working
afternoon group activities
own responsibility
group cohesion
relatives &
goup project
group dynamic processes

6

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© Ökumenische FriedensDekade	128
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